Nordic Branch Meeting

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Höfn in Hornafjörður, Iceland, October 29-31 2009

Abstract volume

Jökulsárlón (The Glacier Lagoon) in front of Breiðamerkurjökull, SE-Iceland
Photo: Oddur Sigurðsson

UNIVERSITY OF ICELAND IGS Icelandic Meteorological Office

NIGS 2009 **http://www.raunvis.hi.is/NIGS-09**

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NIGS 2009 - List of participants

	Name	Institute
1	Adomas Lukas	University of Oslo
2	Alia Lauren Khan	University of Oslo
3	Amandine Auriac	Institute of Earth Sciences, University of Iceland
4	Anne Lien Moree	University of Oslo
5	Arttu Polojärvi	Helsinki University of Technology
6	Astrid Suzanne Ruiter	University of Oslo
7	Áslaug Geirsdóttir	Institute of Earth Sciences, University of Iceland
8	Bergur Einarsson	Icelandic Meteorological Office (IMO)
9	Bjarki Friis	Institute of Earth Sciences, University of Iceland
10	Carmen Vega	Uppsala University
11	Daniel Schwindt	Geographisches Institut, Universität Würzburg
12	Denis Samyn	Glaciology Research Group, Uppsala University
13	Emilie Beaudon	Arctic Centre, University of Lapland
14	Etienne Berthier	OMP-LEGOS, Toulouse
15	Eyjólfur Magnússon	Institute of Earth Sciences, University of Iceland
16	Finnur Pálsson	Institute of Earth Sciences, University of Iceland
17	Geir Moholdt	Department of Geosciences, University of Oslo
18	Guðfinna Aðalgeirsdóttir	Danish Meteorological Institute
19	Helgi Björnsson	Institute of Earth Sciences, University of Iceland
20	Horst Machguth	GEUS
21	Hrafnhildur Hannesdóttir	Institute of Earth Sciences, University of Iceland
22	Hreggviður Norðdahl	Institute of Earth Sciences, University of Iceland
23	Ida Fossli	University of Oslo
24	Inka Koch	Arctic & Alpine Research Group, Univ. of Alberta
25	Ívar Örn Benediktsson	Institute of Earth Sciences, University of Iceland
26	Jennifer Matthews	University of Oslo
27	Joanna Rainska	University of Oslo
28	Johan Striberger	GeoBiosphere Science Centre, Lund University
29	Jon Ove Hagen	University of Oslo
30	Jouni Peltoniemi	Finnish Geodetic Institute
31	Jukka Tuhkuri	Helsinki University of Technology
32	Karlijn Beers	University of Oslo
33	Kati Anttila	Finnish Meteorol. Inst./Finnish Geodetic Institute
34	Kati Laakso	Department of Geology, University of Helsinki
35	Kristín Björg Ólafsdóttir	Institute of Earth Sciences, University of Iceland
36	Lena Schlichting	University of Oslo
37	Line Johanne Barkved	University of Oslo
39	Magnús Már Magnússon	International Glaciological Society (IGS)
40	Magnús T. Guðmundsson	Institute of Earth Sciences, University of Iceland
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42	Martina Schäfer	Arctic Centre, Rovaniemi, Finland
43	Maxime Arséne Duguay	University of Oslo
44	Monica Sund	University Centre in Svalbard (UNIS)

45	Nora J. Schneevoigt	Dept. of Geosciences, University of Oslo
46	Oddur Sigurðsson	Icelandic Meteorological Office (IMO)
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48	Ólafur Ingólfsson	Institute of Earth Sciences, University of Iceland
49	Paweł M. Szubtarski	University of Oslo
50	Rianne Giesen	Inst. f. Marine and Atmospheric Research Utrecht
51	Robert G. T. Way	University of Oslo
52	Sabine Baumann	University of Würzburg
53	Saille Bishop-Legowski	University of Oslo
54	Sanja Forsström	Norwegian Polar Institute, Tromsø
55	Skafti Brynjólfsson	Icelandic Institute of Natural History
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61	Veijo Pohjola	University of Uppsala
62	Zoe Robinson	Keele University
63	Þorsteinn Þorsteinsson	Icelandic Meteorological Office (IMO)
64	Þorvarður Árnason	Hornafjörður University Center, Iceland
65	Øivind Thorvald Due Trier	University of Oslo

Modelling the 20th century and future evolution of Hoffellsjökull, southeast Iceland

Guðfinna Aðalgeirsdóttir[1,2]*, Helgi Björnsson[1], Sverrir Guðmundsson,[1]
Finnur Pálsson[1] and Sven Þ. Sigurðsson[3]

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ABSTRACT

During the Little Ice Age the maximum extent of glaciers in Iceland was reached about 1890 AD and during the 20th century most of the glaciers have been retreating. Radio-echo sounding measurements from Hoffellsjökull, a south-eastern outlet glacier of Vatnajökull ice cap, were performed in 2001 and surface mass balance measurements were done. The measured bedrock topography reveals that during the Little Ice Age advance, from about 1600-1900 AD, the glacier excavated about 1.6 km^3 deep trench over an area of 11 km^2. This trench is 300 m below sea level where it is the deepest and is now emerging as a lake in front of the glacier as it retreats. Maximum thickness of the glacier is measured 560 m. The area of the glacier at maximum extent was 234 km^2 it retreated to 227 km^2 by 1936, and to 212 km^2 in 2001, or 10% during the 20th century. The volume reduction during same period is about 20%. The present mass balance and climate conditions are similar to those observed during a Swedish-Icelandic expedition 1936-1938, about -0.5 m $^{-1}$.

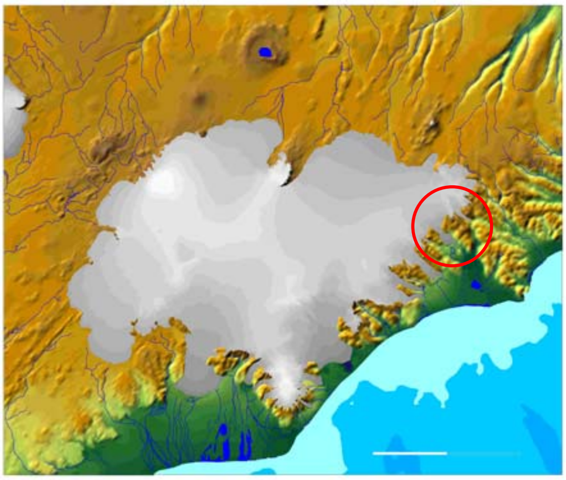

Figure 1 Surface topography of Vatnajökull ice cap on the south-east coast of Iceland. The red circle indicates the modelled area, including Hoffellsjökull and neighbouring outlet glaciers.

1. INTRODUCTION

In this study we use the measured bedrock and surface topography of Hoffellsjökull as boundary condition for a numerical ice flow model to assess the ability of a coupled ice flow and mass balance model to simulate the observed changes. A degree day mass balance model developed for glaciers in Iceland (Jóhannesson, 1997), which has been calibrated and used for climate response assessment on southern Vatnajökull (Aðalgeirsdóttir et al., 2006), is coupled with a new finite element SIA dynamic flow model, which is adopted from a code that was developed for fish migration in the Atlantic ocean. In the model computations the ice divide is kept at a fixed location and no flow allowed across the boundary. A reference climate constructed from the average measurements during the period 1980-2000 is applied as the present climate condition (Aðalgeirsdóttir et al., 2004).

The present size of Hoffellsjökull and mass balance can be simulated with the coupled flow and mass balance model forced by the reference climate (which is about 0.7°C colder than the temperature during the last decade). By lowering the reference temperature in the degree-day model by 0.3°C relative to the average 1980-2000, the maximum extent at the end of the Little Ice Age can be reconstructed. This temperature decrease lowers the ELA from 1050 m a.s. to 950 m a.s. Sensitivity study shows that a moderate change in temperature (< 1°C) can cause considerable volume changes and corresponding changes in ELA.

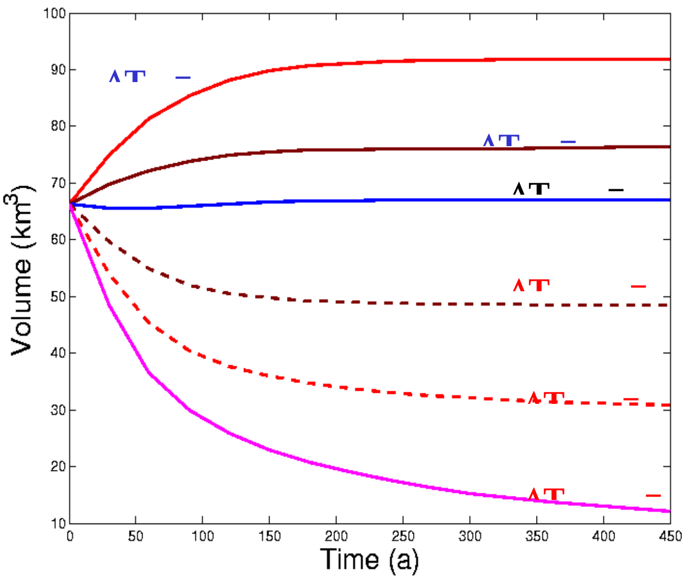

Figure 2. Sensitivity of the volume of Hoffellsjökull to changes in temperature. Step changes in temperature are applied to the mass balance model, the precipitation kept constant, and the resulting change in volume computed with the coupled mass balance-ice flow model.

Temperature and precipitation records from a number of locations around Iceland are available and the longest records go back to late 19th century. We use these records as well as measured glacier extent and corresponding glacier surface maps of Hoffellsjökull from 1904, 1936, 1945, 1988 and 2001 to assess the ability of the coupled model to simulate the 20th century glacier evolution. Model runs indicate that the 20th century evolution of the glacier is sensitive to precipitation changes that may be overestimated at the location of measurement, relative to the glacier location. The sensitivity to temperature and precipitation changes are similar to observations.

This coupled model can then be used to make projections into the near future. We use the CE climate change scenario that has been developed for the Nordic countries. This scenario projects temperature for the Icelandic highland area to increase 0.1-0.4°C per decade, with largest increase in spring and autumn. Precipitation changes are projected to be 0-1.6% per decade, larges in the autumn. Forcing the coupled model with this projection the simulated glacier evolution indicates that Hoffellsjökull will reduce in size and disappear in about 150 years.

2. CONCLUSIONS

This model study shows that the present state, the maximum LIA extent and the 20th century evolution of Hoffellsjökull can be simulated with the coupled ice flow and mass balance model. The modelled evolution is sensitive to precipitation changes that are not measured at the glacier but rather at a weather station close to the glacier. It is therefore necessary to make assumptions about the changes at the glacier location. The future evolution of Hoffellsjökull is subject to uncertainties in the applied scenario, assuming the CE scenario this model predicts that the glacier will retreat and likely disappear within the next 200 years. It should, however, be kept in mind that the model assumes a fixed ice divide location and therefore does not take into account if ice from other parts of Vatnajökull ice cap would start to flow towards this margin due to divide migration, which may delay the retreat considerably.

REFERENCES

G. Aðalgeirsdóttir, T. Jóhannesson, H. Björnsson, F. Pálsson, O. Sigurðsson. 2006. Response of Hofsjökull and southern Vatnajökull, Iceland, to climate change. *J. Geophys. Res.*, **111**, F03001, doi:10.1029/2005JF000388.

Guðfinna Aðalgeirsdóttir, Helgi Björnsson, Tómas Jóhannesson. 2004. Vatnajökull ice cap, results of computations with a dynamical model coupled with a degree-day mass-balance model. RH-11-2004, Science Institute, University of Iceland, Reykjavík.

Tómas Jóhannesson. 1997. The response of two Icelandic glaciers to climatic warming computed with a degree-day glacier mass balance model coupled to a dynamic glacier model. *Journal of Glaciology,* **43**, 143, 321-327.

Recent change of glaciers in NE Asia from the second half of 20th century until present by LANDSAT imagery

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ABSTRACT

Northern Siberia (subarctic zone of Eurasia) is a very poorly studied region in terms of glacier state (change). Measurements of the glaciers there were conducted during the IGY in 1957-59, but since then no regular observations have been made. The Siberian region is anomalous in regard to the climate warming that started at the end of 20th century and has led to general glacier retreat .

Comparison of the glacier areas obtained by *Landsat* imagery and the USSR Glacier Inventory (1960-80s) allowed assessing glacier retreat for the period of current warming. The estimate was done for glacier groups with the same morphological type and aspect.

Glacier systems analyzed in this paper represent a wide spectrum of morphology and regime types – from small cirque glaciers of Byrranga Mountains to large dendritic glaciers of the Chersky Range.

General and applied analysis techniques of multi-zonal imagery for mapping modern mountain glaciation were used to initiate the creation of a glacier data base for West (Taimyr Peninsula) and North-East Siberia, which is a poorly explored region in terms of glacier states from the LGM to present time. Up to now we identified lengths and areas of glaciers for the Suntar-Khayata Mountains, Chersky Range and Byrranga Mountains in 2002-2003 (data of Landsat surveys). Using the data about areas of the same glaciers from Inventory of the USSR Glaciers, we can assess area loss (ΔS) for the time between the glacier exploration given in the Inventory (S) and 2000s. We calculated absolute area reduction, the mean for each group ΔS (km^2), and relative decrease of area ΔS/S, (%).

As for Suntar-Khayta, the portion of the lost area of small corrie, corrie-valley, and corrie-hanging glaciers (between 10 and 80%) is higher than that of larger valley and compound-valley glaciers. Mostly these are glaciers which face north; south-oriented glaciers lost less in % expression (0.2-40%) which possibly can be explained by enlarged accumulation on these glaciers due to higher precipitation from the Okhotsk sea basin.

The scale of area loss in the Cherskiy Range is consistent with glacier size and intensity of the warming over the last 35 years. The prevailing aspect of glaciers is northern and north-western. In absolute value the valley and complicated-valley glaciers of these aspects lost maximum area – from 0.84 to almost 2 km^2. The largest ΔS is fixed among those corrie glaciers, which face NW and NE (0.7-0.8 km^2), in accordance with more intensive warming in this region.

In the Byrranga Mountains the heaviest losses in absolute values since 1967are attributed to valley and transaction types, basically of the northern aspect as the largest ones (2-4.5 km^2,

1967). On average these glaciers reduced in size from 0.1 to 0 7 km^2. Corrie, corrie-valley, corry-hanging, near-slope glaciers reduced their area by as much as 0.01 – 0.1 km^2, (the initial areas are 0.1 till 1.0 km^2 (data of 1967). In relative values (%) the biggest loss ΔS refers to corrie, valley and couloirs glaciers, of middle and small size.

The total reduction of glacier areas in the three mountain ranges in percentage as compared with the USSR Glacier inventory is: For Suntar-Khayta: – 19% (since 1945), Chersky Range: – 28% (since 1970) and for the Byrranga Mountains: –17% (since 1967).

The shrinkage of the glaciers of Koryak Upland (Northern Far East) is the largest, more than 50% since the inventory in 1950.

SNORTEX 2009 Terrestrial Laser Scanning and Related Ground Measurements

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ABSTRACT

SNORTEX (Snow Reflectance Transition Experiment) is a 3-year investigation (starting in 2008) piloted by Météo-France and FMI (Roujean et al.). The key objectives of SNORTEX are to improve the characterization of snow-melting patterns in boreal regions using a multiscale approach supported by multi-angular and multi-spectral remote sensing information, and to build an integrated database for snow variables (albedo, fraction, water equivalence) in a forested environment for the validation of the SAF (Satellite Application Facilities) snow-related products. SNORTEX is a part of the SAF Land, Climate and Hydrology activities supported by EUMETSAT and meteorological institutes.

In 2009 the campaign concentrated in the melting season. The field work was scheduled to include different snow/weather conditions and to include a time period with fractional snow cover. There will be one more field measurement period in spring 2010.

The field survey took place at in Sodankylä in Finnish Lapland. The existing facilities provided by FMI-ARC (67.4 °N 26.6 °E) were used. The area has several advantages considering the snow measurements. The studied area is located far from the coasts, which makes the climate more settled and the area has a long and cold winter period when adequate snow cover is present. Therefore the snow cover consists of layers from a long period of time. Although the area is located north of the Arctic Circle there are still forests in the area so it is possible to study the impact of forests on snow and albedo. Also the snow cover is different in forested and open areas. Therefore it is possible to compare different types of snow cover. The topography of the area is plain enough so that the satellite data from the area are not shadowed by mountains. This is important because the results and conclusions of the ground measurements will be used to SAF product validations and to support the aerial data collected during the campaign.

During the campaign several TLS (terrestrial laser scanner) measurements were made in several different locations with a LeicaHDS600 scanner. These measurements were georeferenced and normalized so that they could be compared. The results were used to estimate the usability of the point cloud and intensity data of the scanner in measuring different snow properties. Preliminary results show that TLS data is applicable in profiling seasonal snow conditions and the intensity data helps the classifying of the snow cover. The

laser backscatter from snow surface is not directly related to any of the snow cover properties measured during the campaign but the snow structure has a clear effect on the TLS intensity.

Roujean, Jean-Louis et al. SNORTEX (Snow Reflectance Transition Experiment): Remote Sensing Measurement of the Dynamic Properties of the Boreal Snow-Forest inSupport to Climate and Weather Forecast: Report of IOP-2008. Proceedings of IGARSS 2009 (in press).

Past and future investigations on present-day glacio-isostatic rebound near Vatnajökull, Iceland, from InSAR and GPS data

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ABSTRACT
Numerous studies on the glacio-isostatic rebound near Vatnajökull give important constraints on the rheology of the Earth in this area. Data that have been collected show an uplift rate up to 25-30 mm/yr. Model calculations to explain the deformation data indicate a low viscosity lower crust and mantle. Other studies have quantified the influence of the uplift on magma generation at the rift zone. We propose future observations and modelling of the glacio-isostatic rebound using an extensive data set of InSAR images collected around Vatnajökull since 1992. Moreover, international collaboration aims at collecting new GPS data on nunataks within the ice cap, and extending GPS time series of deformation around the ice cap. Implications of this uplift for the rheological properties of the crust/mantle as well as magma generation at volcanic centres will be investigated through three-dimensional modelling.

1. INTRODUCTION AND PREVIOUS STUDIES

Iceland was covered by an extensive ice sheet during the Last Glacial Maximum (LGM) 18,000 years ago. Its melting induced post-glacial rebound that was finished around 1000 years after the final disappearance of that ice sheet. Similarly, retreating ice caps in Iceland due to warmer climate are presently inducing a response of the solid Earth. Numerous observations based on GPS measurements, gravity data and also lake levelling show an uplift of the ground close to its edges (e.g. Pagli *et al*., 2007 observed an uplift of the ground at GPS stations close to Vatnajökull, from 1996 to 2004, ranging from 9 to 25 mm/year for the vertical velocities and from 3 to 4 mm/yr for the horizontal ones). Various models have been evaluated to try to best reproduce the observed data. Some use the finite element method to model the retreat of an ice cap on top of an elastic plate lying on a viscoelastic half-space. Most of the models assume horizontal layering of the lithosphere and the mantle. Different thicknesses for the elastic plate have been applied and the one that best fits the data ranges from 10 km (e.g. Sigmundsson, 1991; Pagli *et al*., 2007) to 30 km (e.g. Sjöberg *et al.*, 2000; Fleming *et al.*, 2007). Árnadóttir *et al.* (2009) found that an 80-km-thick elastic layer could fit their data, but have a preferred model with a thickness of only 10 km. The viscosity of the lower crust and upper mantle has also been inferred from the observations. The viscosity ranges mostly from 1-2 x 10^{18} Pa s (Fleming *et al.*, 2007) and 4-10 x 10^{18} Pa s (Pagli *et al.*, 2007) to 5 x 10^{19} Pa s (Sigmundsson and Einarsson, 1992). Árnadóttir *et al.* (2009) used a more complex model implying a viscoelastic layer in between the elastic layer (on top) and the viscoelastic half-space (at the bottom). Their estimated mantle viscosity ranges from 6 to 15 x 10^{18} Pa s. These low values are in agreement with the rapid glacial rebound that occurred following the LGM. The differences in the viscosity estimates arise from the different data used, the model chosen, the various parameters and the assumptions that are made, such as the ice loss estimate for Vatnajökull since 1890 (182 km^3 between 1980 and 1973 for Sigmundsson and Einarsson, 1992, and 435 km^3 between 1890 and 2003 for Pagli *et al.*, 2007). This last value is a revised estimate, taking more into account the effect of climate warming in the last few decades.

Previous studies also show peaks in the eruption rate during the postglacial rebound which occurred after the end of the LGM. Modelling has been carried out to evaluate how the retreat of an ice cap can enhance magma production in the crust. Jull and McKenzie (1996) found that the removal of 2-km-thick ice sheet lying on top of a wedge-shaped melting region could increase by a factor of 30 the normal melt production rate in the period following the LGM. Pagli and Sigmundsson (2008) modelled similarly the present-day retreat of the Vatnajökull ice cap in order to constrain the amount of magma it could overproduce. They found an increase in magma production of 0.014 km^3/yr, occurring only within the rift zone. This is equivalent to a 10% increase of the average melting rate under Iceland.

2. FUTURE STUDIES

Numerous InSAR images from the ERS and ENVISAT synthetic aperture radar satellites are available for the whole Vatnajökull area. Equally, GPS data from past surveys and new measurements on nunataks within the Vatnajökull ice cap will be used. They will help to improve the times series of uplift rates around the ice cap. Both InSAR and GPS data will be analysed to better constrain the response of the crust to ice unloading. As Vatnajökull lies on top of crusts of different age (from young age at the rift zone in the West to about 15 Ma in the East), one could expect lateral variations of the crustal response. Modelling using a more complex structure of the oceanic lithosphere (lateral variations of the viscosity of the crust and of the thickness of the elastic plate) is then necessary. This would imply three-dimensional modelling of the area using e.g. finite element methods. Árnadóttir *et al.* (2009) showed that the data are better modelled if one takes into account not only the retreat of Vatnajökull but also the retreat and implied uplift occurring at glaciers close to it (mainly Hofsjökull and Myrdalsjökull). Modelling will also be used to quantify the response of magma generation to load changes.

Other considerations can be taken into account in this study such as, for example, the influence of pressure changes or variable flow rate in a mantle plume under Iceland, which could be an alternative idea to explain at least part of the uplift. Also, deformation due to volcanic eruptions (e.g. Grímsvötn in 1998 and 2004, Sturkell *et al.*, 2003) and glacier surges (e.g. Dyngjujökull in 1998-2000, Björnsson *et al.*, 2003, and Siðujökull in 1994, Sigmundsson *et al.*, 2006) will be considered. Finally, we will evaluate if it is possible to use the observed deformation to constrain past ice mass variations.

3. CONCLUSIONS

In the past few years, numerous GPS data and InSAR images have been collected around Vatnajökull. These data, supplemented by new data, will help us to have a better comprehension on both the rheology of the crust beneath and around Vatnajökull and the implications for magma generation within the rift zone. Realistic three-dimensional models are needed to improve the observations.

ACKNOWLEDGEMENT
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Parameterization of glacier inventory data from Jötunheimen, Norway, in comparison to the European Alps and the Southern Alps of New Zealand

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ABSTRACT
Based on the glacier inventories of LIA maximum, the 1980s and 2003 of Jötunheimen, South-Norway, a simple parameterization (scheme by Haeberli and Hoelzle, 1995) was performed to estimate unmeasured glacier parameters, as e.g. surface velocity or mean net mass balance. Input data were glacier area, minimum and maximum elevation, and glacier length. Some additional assumptions had to be made in advance (e.g. value of mass balance gradient, bed geometry). Minimum glacier size was 0.2 km² related to the area of the 1980s. Therefore, 125 glaciers (57.3%) of the 1980s with a total area of 182.5 km² (87.8%) remained. For adjusting the parameterisation, measured data of all glaciers in Jötunheimen with mass balance measurements (Stor-, Hellstugu-, and Gråsubreen) were used. This resulted in a separation of the area in a more maritime Western and a more continental Eastern part. The parameterization was applied to the glacier inventory data of Jötunheimen.

The results of the parameterization were compared with the results of a former parameterization performed in the European Alps (Haeberli and Hoelzle, 1995) and in the Southern Alps of New Zealand (Hoelzle and others, 2007). The comparison was performed for the LIA maximum and the 1970s/80s. The relative volume change in this time period is highest in the Southern Alps of New Zealand (-61%). The relative loss in the European Alps and Jötunheimen is quite similar (~ -45%). The mean specific net mass balance for this time period was calculated as -0.33 m w.e./a for the European Alps. In New Zealand, the values varied between -0.67 m w.e./a in the most maritime area and -0.57 in the most continental area. In Jötunheimen, a mean value of -0.05 m w.e./a for the more maritime part was calculated, and -0.02 m w.e./a for the Eastern part. The parameterization shows a clear difference in the glaciological regime of the European Alps, Southern Alps of New Zealand, and Jötunheimen. A difference between the Eastern and the Western part of Jötunheimen was also visible in the parameterization results.

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Dating of Holtedahlfonna ice cap based on ice chemistry and comparison with other deep Svalbard ice cores

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ABSTRACT

Svalbard glaciers are sensitive to climatic changes due to both atmospheric and oceanic circulation patterns (1). Several ice cores have been recently collected and have undergone multi-proxy analysis in order to reconstruct the Barents region paleoclimate for the last millennium and understand the behaviour of the main Svalbard ice caps under warming conditions.

In 2005, a 125m deep ice core has been drilled on Holtedahlfonna (13˚27'E, 79˚14' N, 1150 m a.s.l.) to improve our understanding of the spatial variability of Svalbard climate. The preliminary analyses suggest that this ice core spans the last 400 years, its precise dating remains however problematic since the depth to the bedrock at the drill site is not well determined. Counting the seasonally varying parameters in annual layers was not sufficient to achieve the dating. Thus, the idea we use to date the core is that there should be similarities between Holtedahlfonna and the well-dated Lomonosovfonna core (with a dating accuracy better than decadal accuracy) drilled in 1997 (2). The way we look at the similarities is with wavelet coherence between the different ions in Lomonosovfonna and Holtedahlfonna so that we can see signals at all periods from biannual up to hundred years in a single plot and check that they are in-phase (3) (Figure 1).

The comparison of wavelet analysis with a different input for the bottom depth of the glacier lead us to establish that the depth to the bedrock is at least 275m. From the chemical point of view, we found that the sea salt ions and Ca are more coherent than SO_4 and especially NH_4 NO_3. The SO_4 differences probably reflect different budgets for sources between Lomonosovfonna and Holtedahlfonna while NH_4 and NO_3 incoherencies are perhaps related to the Arctic Haze phenomenon observed at Holtedahlfonna but not at Lomonosovfonna. Once we established the depth to the bedrock, we used the sulphate residual program described in Moore et al., 2006 to find volcanic markers in the Lomonosovfonna core by trying to fit as much of the sulphate data as possible to a multiple regression of the other ions (Figure 2).

With the statistical use of the chemistry data to date Holtedahlfonna ice, our poster also presents the first results of a comparative study of the chemical records from the latest deep and shallow ice cores drilled on Svalbard ice caps.

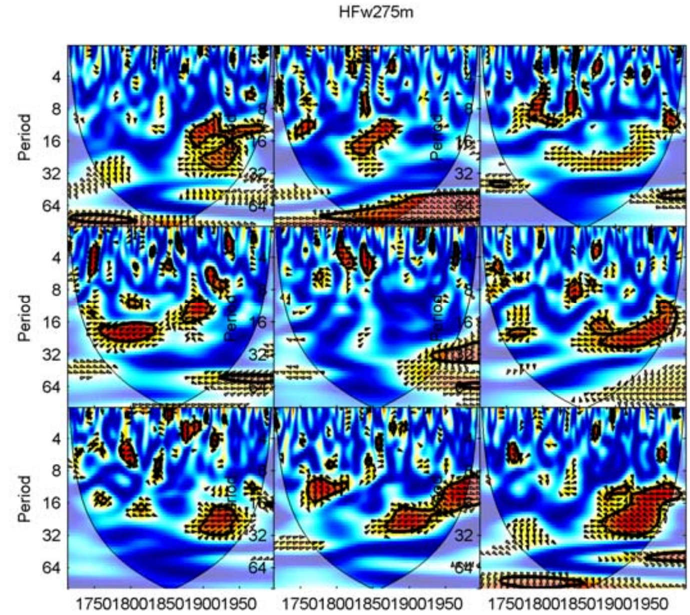

Figure 1. Wavelet coherence between the different ions in Lomonosovfonna and Holtedahlfonna. The top row are from left to right for Cl, NO_3, SO_4 middle row, MSA, NH_4 K, bottom row Ca, Mg, Na. The arrows pointing to the right indicate in-phase relationships between the 2 sites.

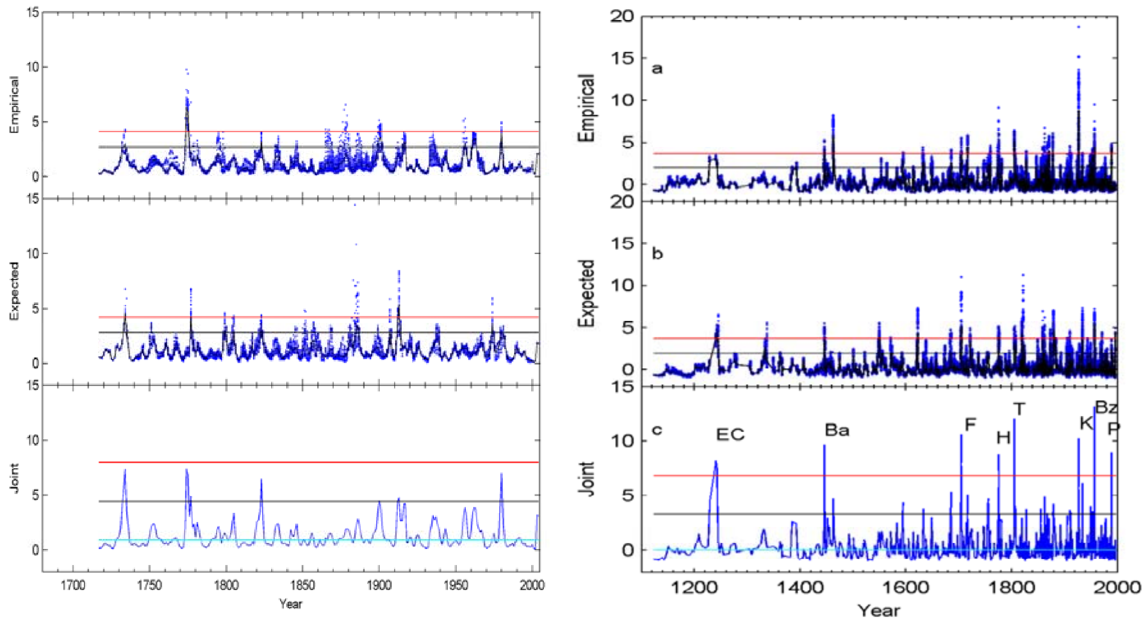

Figure 2 Residual plots (left: Holtedahlfonna, right: Lomonosovfonna) from 2 regression models (Empirical, Expected) when the chemistry data are interpolated to yearly values. The dots in the upper two plots are each of the 50 models that run for each sample. The upper and lower lines are 95% and 99% significance levels. The Holtedahlfonna plot has good similarities with known major eruptions spikes on Lomonosovfonna.

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The 1890 surge end moraines of Eyjabakkajökull: architecture and structural evolution

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ABSTRACT

This study reveals the glaciotectonic architecture and structural evolution of the Eyjabakkajökull 1890 surge end moraines in Iceland. Based on morphological, geological and geophysical data from terrain cross-profiles, cross-sections and ground penetrating radar profiles, we demonstrate that three different conceptual models are required to explain the genesis of the Eyjabakkajökull moraines. Firstly, a narrow, single crested moraine ridge at the distal end of a marginal sediment wedge formed in response to decoupling of the subglacial sediment from the bedrock and associated down-glacier sediment transport. Secondly, large lobate end-moraine ridges with multiple, closely spaced, narrow asymmetric crests formed by proglacial piggy-back thrusting. Thirdly, a new model shows that moraine ridges with different morphologies may reflect different members of an end-moraine continuum. This is true for the eastern and western parts of the Eyjabakkajökull moraines as they show similar morphological and structural styles which developed to different degrees. The former represents an intermediate member with décollement at 4-5 m depth and 27-33% shortening through multiple open anticlines that are reflected as moderately spaced symmetric crests on the surface. The latter represents an end member with décollement at about 27 m depth and 39% horizontal shortening through multiple high amplitude, overturned and overthrusted anticlines, appearing as broadly spaced symmetric crests. We propose that the opposite end member would be a moraine of multiple symmetric, wide open anticlinal crests of low amplitude. Our data suggest that the glacier coupled to the foreland to initiate the end-moraine formation when it had surged to within 70-190 m of its terminal position. This indicates a time frame of 2-6 days for the formation of the end moraines.

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The Múlajökull project: findings of the first field season

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ABSTRACT
The aim of the project is to investigate the glacial history and surge dynamics of Múlajökull, a southern surge-type piedmont outlet of the Hofsjökull ice cap in central Iceland. Múlajökull descends through a 2 km wide trough and spreads out on the Þjórsárver plain with a 12 km long margin. Its surge history is known back to 1924 with surges occurring on average every 10 years, the last surge being in 1992. At present, the glacier has a steep gradient (10-12°) in the marginal ~1 km but levels out above (1-3°). The forefield is characterized by a number of end-moraine ridges, drumlins, crevasse-fill ridges, lakes and small outwash fans. The drumlins are juxtaposed across the forefield forming a drumlin field on which the other landforms are superimposed. Annual moraines were observed in front of the present margin in the NE and SW part of the forefield.

The first field season took place in the summer 2009 with two weeks of fieldwork in the forefield of Múlajökull. Five main tasks were set for the first season: 1) To establish a net of ground control points with a DGPS in order to orthorectify a series of aerial photogaphs from 1945-2000 and produce digital elevation models that will be used for quantifying sediment transport, dead-ice melting and other changes related to the Múlajökll surges; 2) to investigate the stratigraphy of the forefield in order to identify surge-related sedimentary units and to gain insight into the surge history; 3) to examine the geometry and sedimentary composition of the drumlins; 4) to investigate the internal architecture of the end moraines; and 5) to document the situation and ongoing processes at the glacier margin.

The stratigraphy in the forefield is dominated by till layers which are differentiated on the basis of their sedimentary properties, such as grain size, matrix composition, clast content, and deformation structures. Stratigraphical investigations revealed 4 different tills where each till is thought to represent one surge. This is especially clear on either side of the 1992 end moraine where an extra till was found at the surface proximal to the moraine.

The drumlin field is formed by juxtaposed drumlins across the entire forefield. The drumlins are 5-10 m high separated by glacial lakes, streams or outwash fans. Investigation of the interior of the drumlins showed that they are made of at least 4-5 till units, indicating that the drumlins are formed by till deposition during repeated surges. Drumlin fields are commonly described from Pleistocene ice sheets (e.g. the New York drumlin field of the Laurentide ice sheet) but have rarely been reported from modern glaciers. Therefore, the drumlin field at Múlajökull provides an ideal opportunity to study the origin of drumlin fields, and thereby serves as an analogue to Pleistocene drumlin fields.

The outermost end moraine, known as Arnarfellsmúlar, is 5-10 m high and ~100 m wide. It usually has a steep proximal slope and a gently sloping foreslope. The moraine consists of a sequence of loess, peat and tephra that is draped by, and interfingered with, basal till on the proximal slope. The end-moraine architecture is dominated by multiple narrow and

overturned anticlines and shear zones in the proximal and central parts, but inclined and open anticlines in the distal part. This indicates high ice-marginal stresses during the formation of the moraine and is compatible with other surge moraines in Iceland.

Observations at the present ice margin revealed a prominent and newly developed end moraine and a series of annual moraines. The end moraine was ~5 m high with the toe of the glacier standing on its crest in some places, but at the foot of the proximal slope in other places due to the summer melting. Although mainly single-crested, the moraine had several minor asymmetric ridges on the crest and the foreslope, indicating thrusting as the principal style of deformation. Thus, the moraine is thought to represent a recent advance of Múlajökull, possibly a small surge. The annual moraines were observed within ~200 m from the ice margin in the NE and SW parts of the forefield. Counting of these moraines on the ground, from terrain-cross profiles and oblique aerial photographs showed 10-12 moraines with 5-20 m spacing, indicating small winter re-advances during an overall retreat of the margin in the past 10-12 years. Annual moraines are very unusual at surge-type glaciers as movement in the marginal zone tends to be negligible after a surge. Thus, the question arises whether for 10-12 years ago the glacier switched from being a surge-type glacier with negligible motion between surges to be a non-surging glacier with steady annual flow and winter re-advances. Further investigation of past years' behaviour is needed for answering that question.

Future work at Múlajökull will be directed towards: a) further documentation of the general stratigraphy in the area; b) mapping of the drumlin field, drumlin geometry and sedimentary composition; c) quantifying the sediment volumes re-distributed by the previous surges and; d) sediment coring in lakes and peat bogs on the Þjórsárver plain in order to document the environmental history of the area.

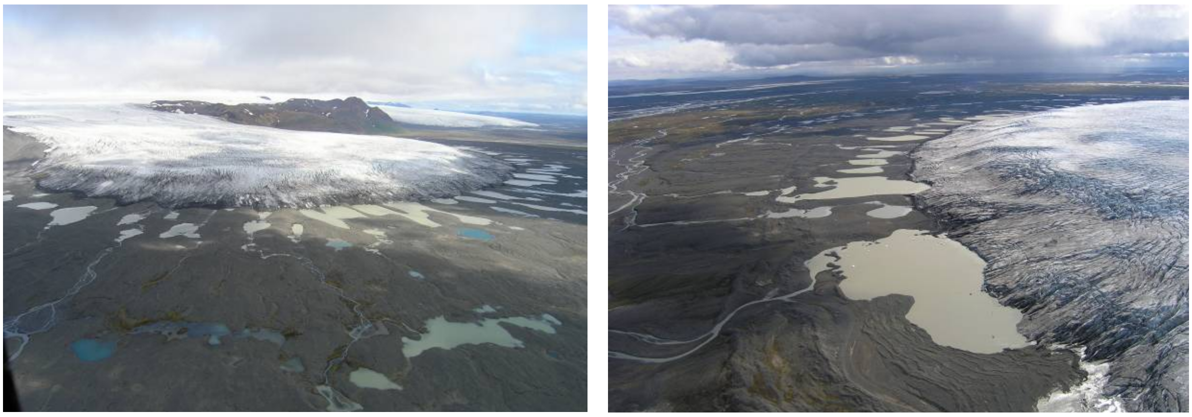

Figure 1 Left: The Múlajökull piedmont lobe viewed from the south. Note the drumlin field with lakes between the drumlins. Right: View from the NE across the Múlajökull forefield. Note the profile of the glacier front, the annual moraines and 1992 surge moraines at the bottom of the photo. Dark linear feature along the margin is the newly formed moraine.

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Low contribution of Alaskan glaciers to sea level rise derived from satellite imagery

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ABSTRACT
Over the last 50 years, retreating glaciers and ice caps (GIC) contributed 0.5 mm/yr to SLR, and one third is believed to originate from ice masses bordering the Gulf of Alaska. However, these estimates of ice wastage in Alaska are based on methods that directly measure a limited number of glaciers and extrapolate the results to estimate ice loss for the many thousands of others. Here, using a comprehensive glacier inventory with elevation changes derived from sequential digital elevation models (DEMs), we found that, between 1962 and 2006, Alaskan glaciers lost 41.9 ± 8.6 km^3/yr water equivalent (w.e.) and contributed 0.12 ± 0.02 mm/yr to SLR. Our estimate of the ice loss is 34% lower than previous estimates. Reasons for our lower values include the higher spatial resolution of the glacier inventory used in our study and the complex pattern of ice elevation changes at the scale of individual glaciers and mountain ranges which was not resolved in earlier work. Estimates of mass loss from GIC in other mountain regions could be subject to similar revisions.

Character of surge activity in small cirque glaciers at Tröllaskagi, Northern Iceland

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ABSTRACT

Systematic studies of surging glaciers in Iceland and elsewhere over the past decades have greatly increased our understanding of surging glacier behaviour. Most studies have focussed on surging behaviour of large outlet glaciers, whereas comprehensive studies of small cirque glaciers have been lacking. In consequence, small surging cirque glaciers in Iceland have hitherto not been thoroughly studied. The three surging cirque glaciers known in Iceland are situated at Tröllaskagi peninsula, a high mountainous area in Northern Iceland. Two of the glaciers, Búrfellsjökull and Teigarjökull, are located in cirques located 800–1100m a.s.l., which are surrounded by 1200–1300m high shading mountains.

Monitoring of the 2001 – 2004 surge in Búrfellsjökull generated some new data that can improve the understanding of small surging cirque glacier behaviour in Iceland. Data that includes photographs, observations on surface and frontal changes as well as measurements of the frontal advance were collected during the surge. The geographical software ArcGis was used to compare GPS measurements of the glacier surface with DEM (digital elevation model) and areal photographs to identify ice volume and mass transition of the surge.

Even though we were first aware that the surge had started in late winter of 2000-2001, we can not exclude that it started up to a year earlier. During the winter 2000-2001 a remarkable formation of crevasses in the glacier was noticed. In addition it was noticed late in the summer of 2001 that a major bergschrund was forming along the mountain slopes near the head of the glacier. Until the summer of 2003 numerous new crevasses formed and the surface morphology of the glacier became rough and broken. During the late summer 2003 the glacier was impassable because of its heavily crevassed surface. At that time the surge bulge was pressing to the glacier front and the margin had started to advance. The main advance occurred between late summer 2003 and the summer of 2004, when the glacial front flattened out as it advanced 150 – 250 m. A glacial melt water outburst marked the termination of the surge, as the ice front only moved 10 - 30 meters in the weeks following the flood.

Remote sensing and observation data on the surge of Búrfellsjökull 2001-2004 have increased our understanding of surging cirque glacier behaviour. Small cirque glaciers (0,5 km^2 - 2 km^2) show behaviour that is comparable to surge behaviour of the large surge glaciers in Iceland (which can be 10’s to 100’s of km^2). The melt water outburst that marked the termination of the surge suggests that a relatively large volume of water was stored under the glacier, and it was squeezed out when the surge stopped and the glacier settled down. An active surge phase lasting at least four years is very interesting compared to the much shorter surging phase of the large Vatnajökull surging glaciers. This difference is considered to be a consequence of a

combination of relatively cold climate in the high (>1000 m) mountains of Tröllaskagi and the thin and small cirque glaciers occurring on the peninsula. This can suggest an intermediate class of surging glaciers, between the polythermal surging glaciers in Svalbard (with a surge phase of 4 – 10 years) and temperate glaciers of Iceland (with a surge phase lasting 1 – 2 years).

Figure 1 Small surging cirque glaciers at Tröllaskagi peninsula, Teigarjökull to left and Búrfellsjökull to right.

Figure 2 Early in the surge phase of Búrfellsjökull numerous crevasses were forming near the head of the glacier, especially along the mountain slopes.

A new landsystem model for small surging cirque glaciers at Tröllaskagi, North Iceland

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ABSTRACT
Surging glaciers leave specific landforms and sediment accumulations that generate particular geomorphological settings. Characteristics of surging glacier environments have been described by a process-form landsystem model, based primarily on the surge morphology and sediments at Brúarjökull, Iceland. The surging glacier landsystem model works well for the large outlet glaciers of Vatnajökull, but does not readily explain patterns of erosion, sedimentation and morphology at surging cirque glaciers. Three surging cirque glaciers are known at the Tröllaskagi peninsula in North Iceland. By mapping the geomorphological and sedimentological environment of two surging glaciers at Tröllaskagi, Búrfellsjökull and Teigarjökull, we aimed to develop a new landsystem model for small surging cirque glaciers.

The area was mapped during two summer fieldwork periods. Sediments, moraines and other landforms in front of the glaciers were described and interpreted. The non-surging Deildarjökull glacier in Svarfaðardalur, at Tröllaskagi peninsula, was also studied for comparing geomorphological environments of surging and non-surging cirque glaciers. The geographical software ArcGis was used for mapping and remote sensing.

High grade of frost weathering and rock fall on the glaciers from the mountains make coarse and angular sediments prominent around the glaciers. Finer material (clay, silt and sand) is limited in the area. GPS measurements show a very slow ice-flow velocity during the quiescent phase, only few meters in a year. Consequently, rock-fall debris accumulates in the accumulation area of the glaciers during the quiescent phase. When the glaciers surge, this material is transported englacially and supraglacially to the marginal (ablation) zone where it forms a debris cover over a melting stagnant ice and subglacially deposited sediments. Occurrences of course-grained hummocky moraines and terminal moraines in front of the surging cirque glaciers are results of the accumulation of rock-fall sediments during the quiescent phase and short transport distance during the surge phase. In general, landforms such as flutes and crevasse ridges are considered to be typical for surging glaciers. However, they are rare in the Tröllaskagi surging glacier landsystem. Likewise, concertina eskers, typical for the large surging glacier environments, are lacking in front of the Tröllaskagi surging cirque glaciers.
A new landsystem model was developed for the small surging cirque glaciers at Tröllaskagi, to highlight and explain the uniqueness of their geomorphological environment. The model is based on the surging glacier landsystem model of Evans and Rea (2003), but modified in accordance with field observations from Búrfellsjökull and Teigarjökull. The model will be tested in a near-future survey of the more than 150 cirque and valley glaciers at Tröllaskagi peninsula.

The initiation and development of jökulhlaups from the subglacial lakes beneath the Skaftá cauldrons in the Vatnajökull ice cap, Iceland

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ABSTRACT

Results from investigations of jökulhlaups from the subglacial lakes beneath the Skaftá cauldrons in the Vatnajökull ice cap are reported. Several different parameters were monitored for two jökulhlaups from the western Skaftá cauldron in September 2006 and in August 2008, and for a jökulhlaup from the eastern cauldron in October 2008. Data interpretation for the jökulhlaup in September 2006 shows: that the flood path was mainly formed by ice deformation and lifting but not melting, that the travel time of the flood front under the glacier was in the range 0.2–0.4 ms^{-1} and that the temperature of the jökulhlaup water at the glacier snout was close to zero. Floodwater temperatures during the 2008 jökulhlaups were within 0.02°C from freezing point.

1. INTRODUCTION

The Skaftár cauldrons are two circular depressions, 1-2 km in diameter and up to 150 m in depth, located in the northwestern part of Vatnajökull. They are formed by steady subglacial melting due to the presence of powerful geothermal areas beneath each cauldron (Björnsson, 2002). The melting sustains 100 m deep subglacial lakes beneath 300 m thick ice cover (Jóhannesson et al., 2007). Jökulhlaups regularly flow into the river Skaftá when the meltwater escapes from the cauldrons. The period between jökulhlaups from each cauldron is 2-3 years and 45 events have been recorded since 1955. The total volume discharged in a single jökulhlaup averages 0.1 km^3 from the western cauldron and 0.25 km^3 from the eastern cauldron.

These jökulhlaups are of the rapidly rising type, normally reaching maximum discharge in 1-3 days and then receding in 1-2 weeks (Björnsson, 2002). This type of jökulhlaup behaviour stands in contrast to the typical, slowly rising outburst floods from the Grímsvötn subglacial lake, which have been explained by the classic Nye theory of jökulhlaups (Nye, 1976). The Nye theory fails to simulate the rapidly rising jökulhlaups from Skaftárkatlar (Björnsson, 1992).

An extensive campaign involving measurements within the Skaftá cauldrons, in the subglacial lakes and of the jökulhlaups originating in them, was initiated in 2006. A measurement set was acquired for a jökulhlaup from the western cauldron in September 2006. Further measurements have been made on jökulhlaups emerging from the western cauldron in August 2008 and from the eastern cauldron in October 2008. For the jökulhlaup in September 2006 results will be presented on: jökulhlaup discharge, flood water storage under the glacier, temperature in the subglacial lake and temperature of the jökulhlaup water close to the glacier snout. For the two jökulhlaups in 2008 GPS measurements over the flood path and temperature measurements at the glacier snout will be presented. Furthermore efforts to model the discharge of the jökulhlaup in September 2006 with a coupled conduit-sheet model are briefly discussed.

2. METHODS

The 300 m thick ice shelf covering the western cauldron was penetrated with a hot water drill in June 2006 (Thorsteinsson et al., 2007; Jóhannesson et al., 2007). Temperature profiles in the lake were measured and a water sample was taken for geochemical and microbiological studies. A pressure and temperature sensor was deployed at the bottom of the lake and connected with a cable to a continuously recording datalogger at the ice shelf surface. A continuously recording differential GPS instrument was placed at the centre of the ice shelf and a water temperature logger was placed in the Skaftá river some distance downstream from the port where the river emerges from beneath the ice. The discharge in the jökulhlaup from the Western Skaftá cauldron in the autumn 2006 was measured at the hydrological station at Sveinstindur (25 km down river from the glacier margin), as for other recent jökulhlaups from the Skaftá cauldrons. The discharge at the outlet of Skaftá at the glacier snout was back-calculated using flood routing with the HEC-RAS hydraulic model.

Furthermore, the outflow from the cauldron during the jökulhlaup was calculated from GPS measurements of the elevation of the ice shelf and a volume-elevation curve for the subglacial lake. Data from the pressure transducer at the bottom could unfortunately not be used for this task as the cable connecting it to the datalogger broke eight days before the jökulhlaup. The relationship between the volume of the subglacial lake and the elevation of the overlying ice shelf was derived from information about the shape of the cauldron when the lake is empty. This made it possible to convert the lowering of the ice shelf to outflow of flood water from the lake. The glacier bottom is expected to be reasonably smooth and the lake assumes the form of a half dome extending upwards from the glacier bed into the ice. Prior to a jökulhlaup, the water is kept sealed in the lake by a minimum in the water potential due to the surface depression formed by melting at the base (Björnsson, 2002). The cauldron will thus take the shape of an inverted lake when the lake is emptied.

In 2006 the temperature of the jökulhlaup water was measured continuously at a location 3 km from the glacier snout. A Starmon mini temperature recorder with accuracy of ±0.05°C was used. For the jökulhlaups in August and October 2008 a trip was made, when the discharge was near its maximum, to the place where the jökulhlaup emerges at glacier snout and the temperature of the outflow water was measured with a precision thermometer from RBR (accuracy of ±0,002°C).

3. RESULTS AND DISCUSSION

3.1 The 2006 jökulhlaup from the western cauldron

The maximum outflow from the lake during the jökulhlaup is estimated as 123 m^3s^{-1} while the maximum discharge of jökulhlaup water at the glacier terminus is estimated as 97 m^3s^{-1} (Fig. 1). This jökulhlaup was a fast-rising jökulhlaup as other jökulhlaups in Skaftá and cannot be described by the traditional Nye-theory of jökulhlaups. The average propagation speed of the subglacial jökulhlaup flood front was found to be in the range 0.2–0.4 ms^{-1}. The total volume of flood water was estimated as 53 Gl. The volume of storage in the subglacial flood path, reached a maximum of 35 Gl which corresponds to two-thirds of the total flood volume (Fig. 2). The volume of subglacial storage was an order of magnitude larger than could have been melted with the initial heat of the lake water and heat formed by friction in the flow along the flood path. The largest part of the space for subglacial storage was therefore formed by ice lifting and deformation induced by subglacial water pressures higher than ice overburden pressure.

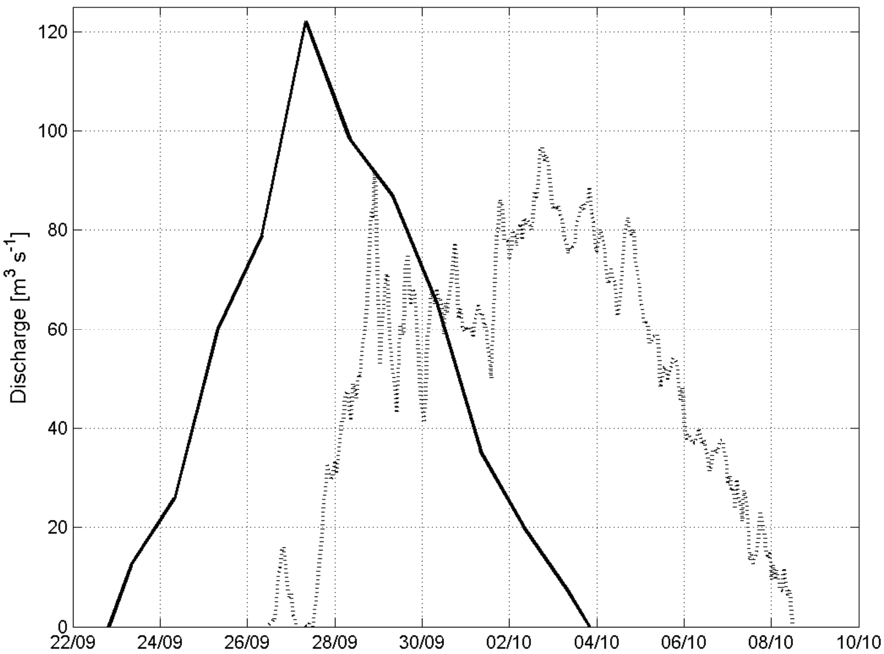

Figure 1 Discharge of jökulhlaup water at the glacier terminus, calculated by backtracking shown as dotted curve, and discharge out of the subglacial lake calculated from the subsidence of the cauldron, shown as solid curve, during the September 2006 jökulhlaup.

The discharge data and the derived size of the subglacial flood path, as indicated by the volume of water stored subglacially, indicates a development towards more efficient subglacial flow over the course of the jökulhlaup. Thus, a discharge in the range 80–90 m^3s^{-1} was flushed through the flood path near the end of the flood with only one-third of the flood path volume that transported a similar discharge a day or two after outflow started at the terminus. This may be interpreted as a development towards conduit flow and/or initial storage in subglacial reservoirs that do not contribute much to the transportation of flood water.

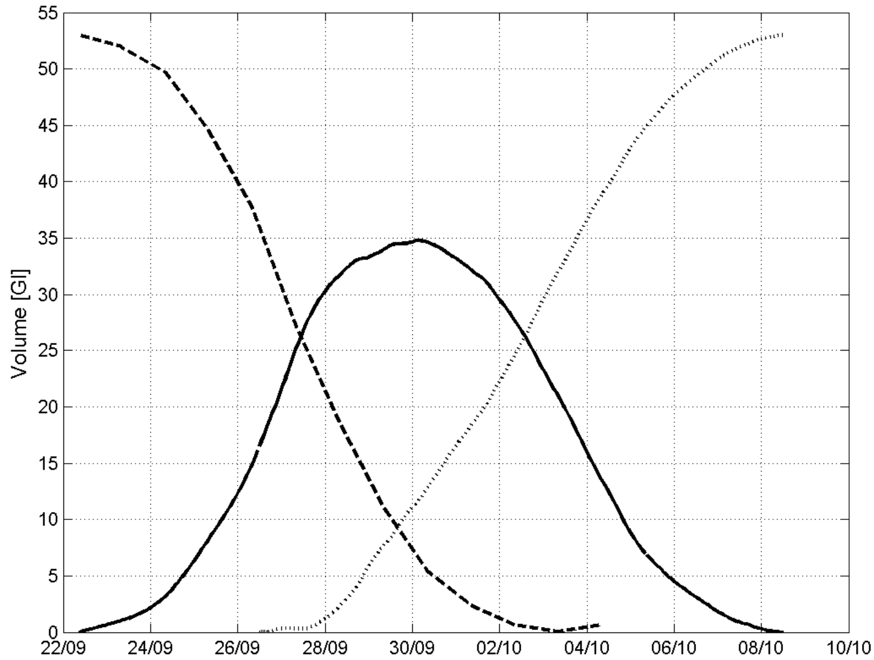

Figure 2 Volume of floodwater during the September 2006 jökulhlaup. Water volume in the subglacial lake is shown as a broken curve, cumulative volume at the glacier terminus as a dotted curve and volume stored subglacially as a solid curve.

3.2 Modelling of fast rising jökulhlaup with coupled sheet conduit model

Flowers et al. (2004) presented a coupled sheet–conduit model for the extreme November 1996 jökulhlaup from Grímsvötn. By connecting subglacial flow in a sheet to flow in conduits they managed to capture the fast rise of the jökulhlaup. The September 2006 jökulhlaup from the western cauldron was simulated with this same model in order to see whether it explains a fast-rising jökulhlaup, two orders of magnitude smaller in discharge and volume than the November 1996 jökulhlaup from Grímsvötn.

The model was forced with the estimated outflow from the subglacial lake. The simulations were not successful as a realistic subglacial pressure field could not be obtained for a reasonable fit of the jökulhlaup discharge at the glacier terminus. This failure can be traced to the simplistic description of the interplay between subglacial water pressure and sheet thickness in the model. As ice deformation seems to be a substantial process in the formation of the subglacial flood path, a detailed treatment of the response of the glacier to the water input into the subglacial hydraulic system appears to be needed in order to simulate the fast-rising jökulhlaups in Skaftá successfully.

3.3 Temperature of jökulhlaup water near the glacier margin and in the subglacial lake

At the location 3 km from the glacier snout, the temperature of the jökulhlaup water in September 2006 was between 0.0°C and 0.5°C. The air temperature recorded at a nearby weather station varied between –1°C and 10°C during the jökulhlaup, but was between 2°C and 6°C most of the time. Hence, some warming of the outburst water may be assumed to take place on the 3 km long distance between glacier snout and the measuring point. During times of air temperature close to zero when warming was minimal water temperatures were close to zero. This indicates that that the outburst water was at or very close to the freezing point as it emerged from beneath the ice cap. The temperature of the jökulhlaup water was also found to be very close to the freezing point as it emerged from the glacier in both of the jökulhlaups in 2008 or 0.013 ± 0.002 °C for the one in August and -0.012 ± 0.002 °C for the one in October. In both of the two events in 2008 no visual signs of frazil ice were seen on the surface of the flood waters. A water sample was collected into a bucket in both events. The rise of the temperature of the water in the bucket with time as it was brought out of the jökulhlaup into air with temperatures few degree warmer than 0°C was measured. The temperature rose steadily straight from the beginning in both cases indicating that there was no frazil ice or ice needles in the water.

The temperature of the water in the cauldron was measured over a three month period before the jökulhlaup in september 2006 and found to be near 4°C (Jóhannesson et al., 2007). As the water is close to freezing point at the glacier snout, almost all the thermal energy in the lake water and potential energy released on the way down the subglacial water course was used for melting of ice indicating a very efficient transfer of heat from the flood water to the surrounding glacier ice.

3.4 **GPS measurements over the flood path**

Ice movement during the 2008 floods was measured via a network of five continuously recording GPS stations, positioned both within the cauldrons and above the flood route. Recordings were made at 15 s intervals and the data were processed kinematically relative to a fixed station near the ice edge. The passage of both jökulhlaup was associated with enhanced down-glacier movement of the ice surface, followed by sudden vertical uplift. For instance, within 5 km of the ice edge, the arrival of the October jökulhlaup generated 0.8 m of temporary uplift within 35 minutes. We interpret these signals as heightened basal sliding accompanied by basal uplift due to increasing water pressure. In the same region, the jökulhlaup breached the ice surface along extensive fractures, where brittle-type seismicity was also registered by Iceland's seismic network.

4. CONCLUSIONS

All of the three jökulhlaups mentioned above are fast-rising jökulhlaups and cannot be explained by the classic Nye theory of jökulhlaups which assumes that the flood path is formed by melting of the surrounding ice. Ice deformation and lifting seems to be a substantial process in the formation of the subglacial flood path in fast-rising jökulhlaups and spatial variations in subglacial water pressure, channel cross section and discharge seem to be important aspects of fast-rising jökulhlaups

ACKNOWLEDGEMENT

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Meteorological Office and the Iceland Glaciological Society. Special thanks go to Gwenn E. Flowers at the Simon Fraser University in Vancouver for providing her Matlab code for the coupled sheet–conduit model, for her comments and assistance with model calibration and discussions of model results. We thank Finnur Pálsson and Helgi Björnsson at the Institute of Earth Sciences at the University of Iceland for providing profiles of the subglacial flood paths and data about the subglacial bedrock-topography below the western cauldron.

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Elemental Carbon Distribution in Svalbard Snow

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ABSTRACT

Carbonaceous particles, resulting from fossil fuel and biomass burning (soot), absorb solar radiation effectively. The global radiative balance of the atmosphere is thus altered via several processes in the atmosphere and at the surface via a lowering of the albedo of snow covered areas. Although most of the human-induced global warming is due to the greenhouse gases with long atmospheric lifetimes, the part caused by the short-lived pollutants, especially carbonaceous aerosol particles, has caught a lot of attention lately.

The modern climate models include carbonaceous particles in the snow pack. The model parameterizations are based on very little or no data as the previous soot measurements in the Arctic snow pack are few and mainly from the 1980s. The objective of this work (partly published in Forsström et al., 2009) was to study the present-day carbonaceous aerosol particle distribution in snow in Svalbard, and compare these findings to concentrations measured in the air. Further, the atmospheric transport of soot to Svalbard was studied by connecting the atmospheric soot measurements to back-trajectory calculations.

The apparent elemental carbon (EC, carbonaceous particle proxy based on a thermal-optical method) content in snow samples collected in Svalbard (European Arctic), during spring 2007 and 2008, was measured. The median EC-concentration of total 181 samples was 4.9 $\mu g/l$ (for 2007) and 6.6 $\mu g/l$ (for 2008) and the values ranged from 0 to 80.8 $\mu g/l$ of melt water. The median concentration is nearly an order of magnitude lower than the previously published data of equivalent black carbon (BC, based on an optical method), obtained from Svalbard snow in the 1980s by Clarke and Noone (1985).

A systematic regional difference was evident, both 2007 and 2008: EC-concentrations were higher in East-Svalbard compared to West-Svalbard. The observations of snow EC cover spatial scales up to several hundred kilometers, which is comparable to the resolution of many climate models. Figure 1 shows the snow EC concentrations measured 2007.

Measurements of atmospheric carbonaceous aerosol (2002-2008) at Zeppelin station in Ny-Ålesund, Svalbard, were divided to air mass sectors based on calculated HYSPLIT (Draxler and Rolph, 2003) back-trajectories (Figure 2). The results show that air originating from the eastern sector contains more than two and half times higher levels of soot than air arriving from South-West. This result is in agreement with the findings by Eleftheriadis et al. 2009.

The observed East-West gradient of EC-concentrations in snow may be due to a combination of the atmospheric concentration gradient, the orographic effect of the archipelago, and the

efficient scavenging of the carbonaceous particles through precipitation. Regional differences in the amount of precipitation may also influence.

In addition to the gradient in regional scale, a large small scale variability within samples collected at one sampling site (typically within a meter horizontal distance) was discovered. This high variability might be connected to post-depositional processes like wind redistribution and evaporation.

Figure 1 Medians of apparent elemental carbon (EC) in $\mu g/l$ at seven sampling locations in spring 2007.

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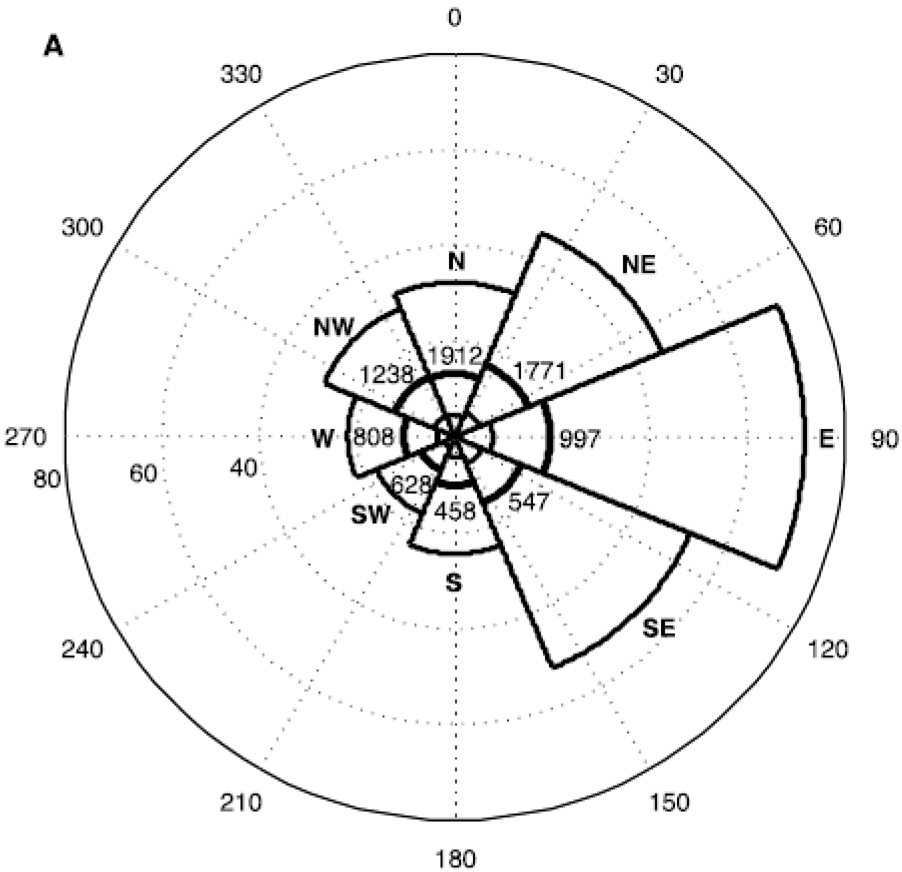

Figure 2 Sector plot showing the connection between the measured air [BC] and the direction of the flow to Zeppelin station according to the back-trajectory runs. The number of trajectories falling into each sector is indicated by the number. The thick arc shows the median of the six-hours mean air [BC] on when the mean vector of the corresponding back-trajectory falls into the sector. The innermost arc indicates the 25^{th} percentile and the outermost arc the 75^{th} percentile of the concentration. The axis unit is ng/m^3 .

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Sólheimajökull – From the Little Ice Age to the present

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ABSTRACT
Sólheimajökull is an outlet glacier draining the Mýrdalsjökull ice cap, southern Iceland. The glacier is 15 km long, 1-2 km wide and covers 44 km². It descends from 1000 m a.s.l to 100 m a.s.l. The base of the glacier reaches about 50 m below present sea-level, about 2 km inside the present margin.

Mýrdalsjökull covers the Katla central volcano, one of the most active volcanoes in Iceland. Subglacial eruptions of Katla have led to jökulhlaups at Sólheimajökull, which have had a huge impact on the proglacial landscape. The marginal fluctuations of Sólheimajökull correspond well to changes in the climate. In 2008, it had retreated 1130 meters since ice front measurements were initiated in 1931, despite a period of significant advance from 1969-1995. The objectives of this study are firstly to (i) map and interpret landforms and sediments exposed in the forefield since 1995: (ii) map and interpret changes in the size and extent of the glacier during the Little Ice Age (14^{th} – 19^{th} century): (iii) confine the extent of the glacier during the Mid-Holocene.

ArcMap and ArcSCENE have been used in the work of reconstructing the extent of Sólheimajökull through time. This has been done by analyzing a series of aerial photographs from 1945 to present and a topographical map from 1904. Fieldwork conducted during the summer of 2009 offered the possibility to check the quality of the mapping work as well as to do stratigraphical work in the glacier forefield. Preliminary results confine the end moraines in front of Sólheimajökull to the period after AD 1573, which is important to reconstruct the extent of the Little Ice Age glacier advances. Furthermore, a preliminary geomorphological map shows a number of recently exposed landforms that allow investigation of the processes operating during these advances.

Glaciers terminating in closed water bodies: reassessing the behavior of glaciers that terminate in lakes based on multibeam bathymetric surveys

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ABSTRACT

We provide observations from an outlet glacier that calved into a proglacial lake to reassess the behavior of glaciers terminating in closed water bodies. Langjökull, one of Iceland's ice caps, feeds two outlet glaciers, Suðurjökull and Norðurjökull. Both glaciers terminated in glacial lake Hvítárvatn (422 m asl; 12 x 3 km; maximum water depth 85 m) during the Little Ice Age (LIA). Suðurjökull remained in the lake until the mid 20th Century; Norðurjökull still calves into the lake. The distribution of ice-rafted detritus (grains ≥2 mm) in sediment cores recovered from Hvítárvatn indicates that following regional deglaciation 10 ka ago, glaciers calved in the lake only during the LIA. Lateral moraines preserved along both outlet glacier valley margins define LIA terminal positions on land.

Patterns revealed by high-resolution multibeam imagery allow derivation of a unique explanation for the genesis of landforms in Hvítárvatn. A striking set of radiating furrows found in front of Suðurjökull were formed during the LIA by narrow fingers of ice intact with the main ice flow during multiple advances/still stands of two different catchments within Suðurjökull. As the advancing ice entered deep water it thinned and its velocity increased in an extensional flow regime. Eventually, the terminus broke up into a series of ice fingers, that carved the furrows.

Maintaining narrow fingers of ice, <200 m wide and >1000 m long, in water depths of 50 to 60 m as demonstrated by the multibeam images, requires buttressing. We suggest that the most likely scenario is that during the coldest summers of the LIA iceberg production exceeded the rate of iceberg melt, resulting in the lake becoming so tightly packed with icebergs that there was effectively no surface iceberg motion.With an outlet depth <3 m, Hvítárvatn retains all but the smallest icebergs. A lake-full iceberg scenario is consistent with our observation of rimmed iceberg pits, indicative of persistent iceberg stability with only slight motion.

The Hvítárvatn sediments are characterized by varves producing an annually resolved record of late Holocene ice-sheet activity in Iceland. It has been demonstrated that the varve record reflects sediment flux to lake, which is broadly controlled by the activity of Langjökull and the two outlet glaciers that drain into the lake. Current research is focused on coring each of the furrows and use the varve records in each furrow to reconstruct a precise chronology for the dramatic fluctuations of Suðurjökull during the LIA.

The ice cap Hardangerjøkulen, southern Norway, in the 21st century

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ABSTRACT
Glacier mass balance changes lead to geometry changes and vice versa. To include this interdependence in the response of glaciers to climate change, models should include an interactive scheme coupling mass balance and ice dynamics. We present a spatially distributed mass balance model coupled to a two-dimensional ice-flow model and apply this model to the ice cap Hardangerjøkulen in southern Norway. The available glacio-meteorological records, mass balance and glacier length change measurements were utilized for model calibration and validation. Driven with meteorological data from nearby synoptic weather stations, the coupled model realistically simulated the observed mass balance and glacier length changes during the 20th century. The mean climate for the period 1961-1990, computed from local meteorological data, was used as a basis to prescribe climate projections for the 21st century at Hardangerjøkulen. For a projected temperature increase of 3^{o}C from 1961-1990 to 2071-2100, the modelled net mass balance soon becomes negative at all altitudes and Hardangerjøkulen disappears around the year 2100. The projected changes in the other meteorological variables could at most partly compensate for the effect of the projected warming.

Volume changes of ice caps in Iceland, deduced from elevation data and in-situ mass balance observations

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ABSTRACT
Icelandic glaciers, covering about 11% of Iceland, are located in the North Atlantic Area, at the confluence of air/water masses from the mid latitudes and from the arctic. These glaciers are temperate with high annual mass turnover and are highly sensitive to climate fluctuations. Annual mass balance observations on the three largest ice caps in Iceland over the last decades (on Langjökull ~900 km^2, Hofsjökull ~890 km^2 and Vatnajökull ~8100 km^2), show a declining specific mass balance from ~0 m yr^{-1} w. eq. on average from 1980 to 1994 to -1 to -1.5 m yr^{-1} w. eq. on average after 1995. This is consistent with the warming in Iceland that took place after 1994. To obtain a comprehensive view of glacier changes in Iceland, we estimate volume and mass balance changes by comparing multi-temporal elevation maps, obtained by using i) dense *in-situ* GPS and airborne radar altimetry profiles, ii) high resolution elevation maps from both satellite and airborne remote sensors (optical and radar). Volume changes deduced from elevation maps show a good agreement with the *in-situ* mass balance observations at stakes on Langjökull. The mass balance on Mýrdalsjökull ice cap (~570 km^2), deduced from elevation maps, is consistent with the observed mass balance on both Hofsjökull and Vatnajökull. Much faster retreat rate is however observed on a few small ice caps (15-80 km^2) that comprise a present day AAR of only 0-25%.

Response of glacier mass balance to regional warming, deduced by remote sensing on three glaciers in S-Iceland

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ABSTRACT

We assess the mass balance and volume changes of three ice caps in South Iceland, for two periods, 1980 to 1998 and 1998 to 2004, by comparing digital elevation models (DEMs). The ice caps are Eyjafjallajökull (~81 km^2), Tindfjallajökull (~15 km^2) and Torfajökull (~14 km^2) with satellite derived present day accumulation area ratio (AAR) of only ~25%, ~5% and 0%, respectively. The DEMs were compiled using aerial photographs from 1979 to 1984, airborne EMISAR radar images obtained in 1998 and two image pairs from the SPOT 5 high-resolution stereoscopic (HRS) instrument acquired in 2004. The ice-free part of the EMISAR-DEM (5x5 m spatial resolution with accuracy <2 m in elevation) was used as a reference map for co-registering and offset-correction of the HRS-DEMs (40x40 m) and the DMA-DEMs (40x40 m interpolated from 20 m contour lines). The average specific mass balance was estimated as the mean elevation difference between glaciated areas of the DEMs. The glacier mass balance declined significantly between the two periods: from -0.2 to 0.2 m yr-1 w. eq. during first period 1979/1984-1998 to -1.8 to -1.5 m yr-1 w. eq. for the period 1998 to 2004. This declining mass balance reflects the average regional summer temperature increase of ~1 °C from the first to the second period (1980-1998 to 1998-2004). The low mass balance and AAR of those ice caps indicate that they will disappear if the present day climate condition continues.

Surface flow of meltwater in volcanic eruptions within glaciers

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ABSTRACT
Volcanic eruptions under glaciers are common in Iceland and they occur in some other parts of the world, notably in Antarctica and Alaska. During glacial periods many volcanic regions have been covered by ice sheets and volcano-ice interaction has had a major effect on the style of volcanism and the types of landforms formed in eruptions. A volcanic eruption underneath a glacier is essentially a major thermal event, where the thermal energy of the eruption is dissipated by ice melting. In a warm-based glacier, the meltwater generated will migrate along the bed towards the margin of the glacier resulting in a jökulhlaup. In major eruptions these can be very large with peak discharges of order 10^5 m^3/s. A volcanic eruption may melt its way through the glacier. Geological evidence from Iceland, Canada and Antarctica shows that sustained eruptions lead to the formation of distinct volcanic landforms, the tuyas, characterized by steep slopes and flat tops. Surrounding the central crater, lava-fed deltas form, made of a subaqueous part (hyaloclastite breccias) and overlying subaerial part made of lavas. The boundary between the two parts, the passage zone, is very distinct and easily recognizable.

Essentially identical landforms are created in sustained eruptions in lakes or the ocean, with the island of Surtsey, formed off the south coast of Iceland in 1963-1967, being a good example. Observed eruptions within glaciers have not built tuyas. These eruptions were relatively short-lived and did not make the necessary transformation from the phreatomagmatic (explosive) phase to the lava forming (effusive) phase. A striking feature of many tuyas is an apparently stable level of the englacial meltwater lake that surrounds the evolving volcano, as witnessed by the semi-constant elevation of the passage zone. From the perspective of glacial hydrology this is enigmatic, since ice dammed lakes that are drained subglacially in jökulhlaups are characterized by a variable lake level. It has been suggested that supraglacial drainage of lakes surrounding erupting volcanoes is a possible explanation for a semi-stable lake level for long periods (Smellie, 2006). However, the mechanism by which supraglacial drainage may be established and remain stable needs to be explained.

Most basaltic eruptions start off with an initial high-discharge phase. A subglacial eruption of this kind will in its early phases melt large volumes of ice with the meltwater draining away subglacially. If the eruption continues for an extended period of time, magma discharge is likely to drop. Considering the thermal regime within the growing tuya, and that the subglacial meltwater tunnel may close, even if only temporarily, a supraglacial drainage path may form along the depression in the ice surface overlying the initial subglacial drainage path. Evidence suggests this occurred only weeks after the end of the 13 day long Gjálp eruption in Iceland in 1996.

If supraglacial drainage can explain stable lake levels, conditions must exist where the rate of incision of the supraglacial channel into the ice is small enough during the lifetime of an

eruption (possibly decades) to be insignificant. The rate of incision is controlled by the energy flux from the water to the ice at the bottom of the channel and the temperature of the ice. The energy flux in turn is dependent on ice surface slope, lake size, meltwater flux and temperature (Raymond and Nolan, 2000). It turns out that the rate of incision is largely determined by water flow rate and temperature while ice temperature is of minor importance. Evidence from Hawaii and Surtsey suggests that magma flow rates are probably quite low (a few m^3/s) in delta-forming eruptions. Meltwater flow rates are therefore unlikely to be more than a few tens of m^3/s. The stability of such a lake turns out to be critically dependent on the lake temperature. For a convecting lake (temperature above 4°C) the incision rate in the surface ice channel will be of order 1 m/day and conditions for a stable lake level will not be met. However, if the lake temperature drops below 4°C, convection will stop, the lake surface will cool fast and freeze. Under such conditions the incision rate of the cold surface water flowing down the channel will be of order 10 m/year. Compressive ice flow from the sides will act to lift the bottom of the channel, partly offsetting the down-cutting by the water. Thus, it seems that surface drainage of meltwater may be a viable mechanism for a semi-stable ice dammed lake surrounding an erupting volcano, but only if the magma flow rate (and hence heat available for ice melting) is small and lake surface temperature is effectively zero.

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GLACIODYN – The dynamic response of Arctic glaciers to global warming

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ABSTRACT

The aim of GLACIODYN is to reduce the uncertainties in Arctic Glaciers and Ice Cap (GIC) contribution to sea level changes. This involves to include calving in mass budget calculations, improve process understanding of calving and basal sliding and include dynamics in modeling of future glacier response.

Selected target GICs have been studied in the Arctic. In this presentation we will show examples from activities on Svalbard GICs with main focus on the Austfonna ice cap (8200 km^2). Studies have been focused on 1) Surface mass balance 2) Elevation changes (volume changes) by satellite data, airborne laser profiles and ground-based GPS 3) Dynamics; surge and calving.

For the Austfonna ice cap net surface mass balance shows slightly negative results (-0.1 m water eq. y^{-1}), The calving is important (2.5 km^3) and stands for 30-40 % of the ablation. However, the elevation change measurements on Austfonna show a thickening in the interior of c. 0.5 my^{-1}, and an increasing thinning closer to the coast of 1-2 my^{-1}, indicating a large dynamic instability.

The general picture from Svalbard glaciers is retreating glacier fronts with thinning in lower elevation and a thickening in higher elevations. However, the frequent surge-type dynamics of Svalbard glaciers must be considered in geometry change studies. Flux calculations show the importance of the dynamics for many different glaciers.

The current overall Arctic data indicates that the Arctic (Canada, Svalbard, Russian Arctic), glaciers and ice caps, which contain about 1/3 of all ice in the world's GICs, display an increasingly negative mass balance. The net mass balance is: $B_n = -38 \pm 7$ km^3 yr^{-1} or $b_n = -0.15 \pm 0.03$ m yr^{-1} which is in SLE = 0.11 ± 0.02 mm yr^{-1}. Thus they contribute less than 15 % of the ice input to global sea level but have a large potential for a higher contribution.

Evolution of three outlet glaciers of southeast Vatnajökull, Iceland: observed changes and modelling

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ABSTRACT

The small non-surging outlet glaciers of southeast Vatnajökull are located in the warmest and wettest area of Iceland. Skálafellsjökull, Heinabergsjökull and Fláajökull emerge down from an ice divide around 1400 m, and calve into frontal lakes. Detailed data on 20th century glacier changes, bedrock and surface topography, meterological data (from 1880), documentary records of Little Ice Age (LIA) glacier variations and geomorphological evidence of previous glacial extent are used to study the connection of glacier variation and climate change. A coupled ice flow-mass balance model is used to simulate the evolution of the three glaciers over the next centuries in response to prescribed climate scenarios. The model is based on finite element analysis with shallow-ice approximation (Aðalgeirsdóttir, 2003; Aðalgeirsdóttir et al., 2006). The degree-day-mass balance model uses records from meterological stations located away from the glaciers, and is calibrated to mass balance observations at 23 stakes on southern Vatnajökull (Jóhannesson et al., 1995, 1997). Simulation of the glacier response was initialized with ice geometries of the year 2000 and using the average 1981-2000 reference climate. Preliminary results indicate continuous retreat of the glaciers for a 200 year model run, with a constant reference climate. A cooling of 0.3 °C results in advancing glaciers, but they do not come close to their maximum extent of the LIA. Heinabergsjökull is not in balance with current climate, whereas Skálafellsjökull responds differently, hence has a much larger accumulation area. Several adjustments need to be done, including modification of the mass balance model to local conditions, improvement of bedrock data for selected areas, and boundary conditions. Calving and sliding at the bed are parameters that also need to be considered.

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Collapse of an ice sheet – the last deglaciation of Iceland

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ABSTRACT

Iceland was heavily glaciated at the Last Glacial Maximum (LGM). Glaciers extended towards the shelf break around Iceland and ice thickness reached 1500±500 m. A very rapid deglaciation, starting 17.5-15.4 cal. kyr BP, was primarily controlled by rising global sea level. The marine part of the ice sheet collapsed 15.4 - 14.6 cal. kyr BP and glaciers subsequently retreated well inside the present coastline. The shelf off western Iceland was deglaciated before 14.9 cal. kyr BP and coastal areas in western Iceland became ice-free but submerged at 14.6 cal. kyr BP. This signifies the rapid glacial unloading and transgression of relative sea level in coastal areas. During Younger Dryas, 12.6 - 12.0 cal. kyr BP, the ice sheet re-advanced and terminated near the present coastline. It is argued that this re-growth of the Icelandic ice sheet was partly glaciodynamically controlled as the ice sheet reached a new balance after intense loss of volume during the preceding collapse. Partly the advance was controlled by the colder Younger Dryas climate. A step-wise recession of the ice sheet after the Younger Dryas advance is reflected in series of terminal moraines in the highlands. The outermost post-Younger Dryas moraines, the inner Búði-moraines in southern central Iceland, were formed during a short lived re-advance of the Icelandic ice sheet at about 11.2 cal. kyr BP. After 11.2 cal. kyr BP the ice sheet retreated rapidly and relative sea level fell towards and eventually below present sea level at 10.7 cal. kyr BP. At 8.7 cal. kyr BP glaciers terminated proximal to their present margins. Some of the present ice caps on Iceland may have been very small or absent during the mid-Holocene climate optimum.

Measurements of the ice surface elevation of Icelandic ice caps with LIDAR during the IPY

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ABSTRACT

As a part of the International Polar Year (IPY), an accurate DTM of Icelandic ice caps is being produced with airborne LIDAR technology. Accurate DTMs make it possible to carry out various glaciological and geophysical research. Changes in ice volume may be assessed by repeated mapping and, thereby, the contribution of Icelandic ice caps to the ongoing rise in global sea level may be computed. Accurate maps are necessary to compute subglacial water courses and delineate watersheds on glaciers. The maps are important for investigations of glacier surges and research of isostatic uplift due to reduction in ice volume and they shed light on ice dynamics and on ice flow over bottom topography. According to a preliminary comparison of new DTMs of Snæfellsjökull and Hofsjökull with available DTMs from 1999, the average lowering of the ice surface is ~13 m, which corresponds to an annual average ice loss of ~1.5 m per year in the nine-year period 1999–2008 for both ice caps. The thinning is greatest near the ice margin, up to ~30–50 m in some areas, but least near the summits of the ice caps. These preliminary comparisons confirm the rapid ongoing volume changes of the Icelandic ice caps which have been shown by mass-balance measurements since 1995/1996. It is important to obtain accurate baseline data for monitoring this development, both because of important local societal consequences related to changes in river runoff and hydro-power potential, and also due to global implications. The Icelandic ice caps are a part of the global reservoir of ice stored in glaciers and small ice caps which is likely to contribute substantially to the expected future rise in global sea level.

1. INTRODUCTION

Rapid retreat of glaciers has been observed at many locations of the Earth in recent decades. The potential of substantial *local* changes, affecting for instance the hydrology of neighbouring areas, and *global* consequences in terms of a rising sea level, make it important to monitor these changes closely and develop an ability to forecast future changes of glaciers and small ice caps worldwide (IPCC, 2007; Meier and others, 2007).

Icelandic glaciers store a total of ~3600 km^3 of ice (Björnsson and Pálsson, 2008) and are retreating and thinning rapidly at present (Fig. 1). The downwasting of the glaciers is projected to intensify during the coming decades, leading to their almost complete disappearance in the next 150–200 years (Bergström and others, 2007; Jóhannesson and others, 2007). This will have a large effect on river runoff which is simulated to increase by ~25% between 1961–1990 and 2071–2100, mainly due to increased melting of glaciers. Subglacial water courses and outlet locations of many glacial rivers are also likely to change due to the thinning of ice caps and the retreat of glacier margins. A total melting of all glaciers in Iceland will lead to ~1 cm rise in global sea level.

2. IPY DTMS OF THE ICELANDIC ICE CAPS

As a part of the International Polar Year (IPY), an accurate DTM of Icelandic ice caps is being produced with airborne LIDAR technology. It is important that the glaciers are accurately mapped now when rapid changes have started in response to warming climate. The plan is to produce DTMs of Vatnajökull, Hofsjökull, Langjökull, Mýrdalsjökull, Eyjafjallajökull and Drangajökull and some smaller ice caps. Financial support for the mapping has been provided by RANNIS (The Icelandic Centre for Research), and by institutes and companies that are affected by glacier changes or benefit from accurate knowledge of snow and ice covered areas of Iceland. The LIDAR measurements are carried out by the German mapping company TopScan GmbH. This technology is well suited for the glacier mapping because it can map crevassed areas and other glacier areas that are difficult to access on land.

Figure 2 shows a shaded relief image of a DTM of the Eiríksjökull ice cap in western Iceland measured in September 2008. The high resolution 5x5 m DTM clearly shows the smooth surface geometry of the central part of the dome-shaped ice cap, heavily crevassed areas in the upper reaches of the main outlet glaciers and various geomorphological features of glacial origin in the forefield of the glacier.

The new IPY DTMs will be a reference against which future glacier changes in Iceland may be judged. They will also increase the usefulness of other ice surface measurements because they may be compared to any other measurements, both existing measurements of past geometry and future measurements. Accurate DTMs make it possible to carry out various glaciological and geophysical research and have in addition considerable economic value. Changes in ice volume may be assessed by repeated mapping or simpler measurements on lines across the glaciers. Thereby, the contribution of Icelandic ice caps to the ongoing rise in global sea level may be computed. Accurate maps are necessary to compute subglacial water courses and delineate watersheds on glaciers. The maps are important for investigations of glacier surges and research of isostatic uplift due to reduction in ice volume and they shed light on ice dynamics and on ice flow over bottom topography.

3. PRELIMINARY ANALYSIS OF ICE SURFACE CHANGES

Figure 3 shows the thinning since 1999 for Snæfellsjökull, a small ice cap on the Snæfellsnes peninsula in western Iceland. According to a preliminary comparison of the new DTM with an available DTM of Snæfellsjökull from 1999, the average lowering of the ice surface is ~13 m, which corresponds to an annual average ice loss of ~1.5 m per year in the nine-year period 1999–2008. The thinning is greatest near the ice margin, up to ~40 m in some areas, but least near the summit of the ice cap where the surface lowering is found to be ca. 5 m on average over the nine-year period above 1200 m a.s.l.

Figure 4 shows the thinning with respect to a composite DTM from 1999, 2001 and 1983 to 2008 for most of the Hofsjökull ice cap and Figure 5 shows the thinning since 2003 for a small area in the SA part of the ice cap where an accurate DTM measured in 2003 is available. It is notable that the lowering of the ice surface in the ablation area in only nine years is well in excess of 30 m over large areas close to the ice margin. The summit area has, however, more or less maintained its altitude. The average lowering of the ice surface since

1999 according to a preliminary analysis is estimated as 12.5–13 m when first order corrections have been made to account for the different timing of the summit measurements from 2001 and the measurements in the intermediate altitude range from 1983. The new DTM was compared to an accurate DTM from 2003 of a small area in the SA part of Hofsjökull made for the national power company Landsvirkjun. Figure 5 shows that the lowering reaches more than 30 m where it is greatest near the ice margin. The average lowering of this 17.5 km^2 area was approximately 13 m over the five-year period 2003–2008.

4. MONITORING OF FUTURE CHANGES

These preliminary comparisons confirm the rapid ongoing volume changes of the Icelandic ice caps which have been shown by mass-balance measurements since 1995/1996 (Björnsson and Pálsson, 2008). Some of the smallest ice caps, such as Snæfellsjökull, are experiencing the relatively largest changes, and may loose most of their current ice volume in the next few decades. The larger ice caps in the central and south-eastern highland have greater average ice thickness and will last longer. If climate warming continues in accordance with currently adopted scenarios, the larger ice caps will continue to thin rapidly and will loose on the order of half or more of their current volumes before the end of this century. It is important to obtain accurate baseline data for monitoring this development, both because of important local societal consequences related to changes in river runoff and hydro-power potential, and also due to global implications. The Icelandic ice caps are a part of the global reservoir of ice stored in glaciers and small ice caps which is likely to contribute substantially to the expected future rise in global sea level.

ACKNOWLEDGEMENT

Financial support for LIDAR mapping of glaciers in Iceland is provided by RANNIS (The Icelandic Centre for Research), Landsvirkjun (the National Power Company of Iceland), The Icelandic Public Road Administration, Orkuveita Reykjavíkur (the Municipal Electricity, Geothermal Heating and Water Distribution Service of Reykjavík) and the National Land Survey of Iceland.

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FIGURES

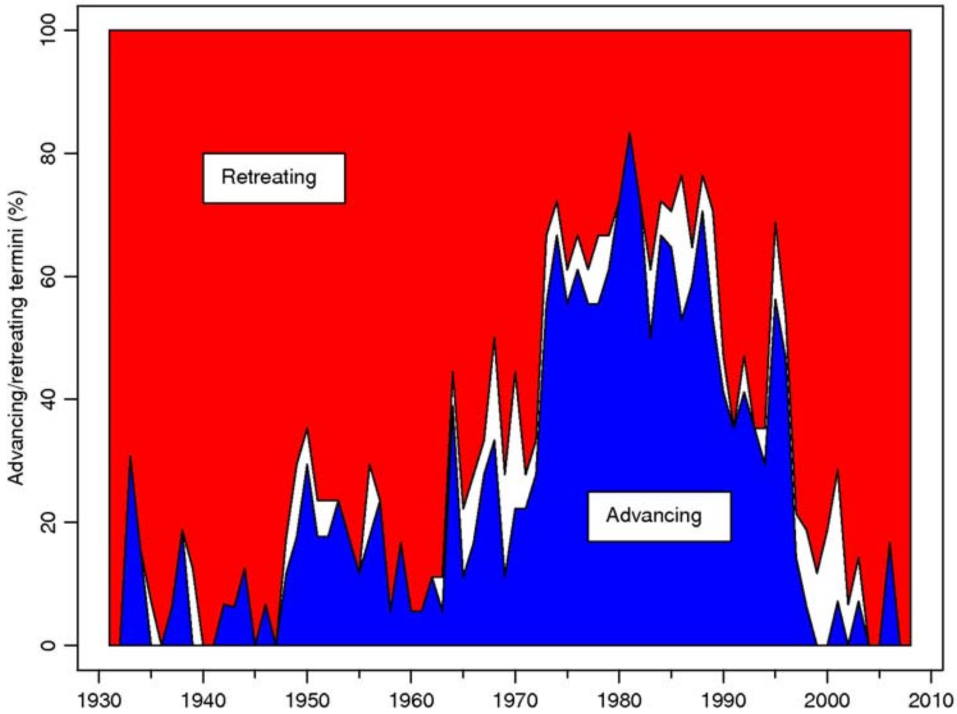

Figure 1 Percentage of advancing and retreating termini of non-surging glaciers in Iceland from 1930/1931 to 2007/2008. Over most of the time period shown, the figure is based on measurements at 11 to 19 locations (somewhat fewer termini in the years 1931 and 1932).

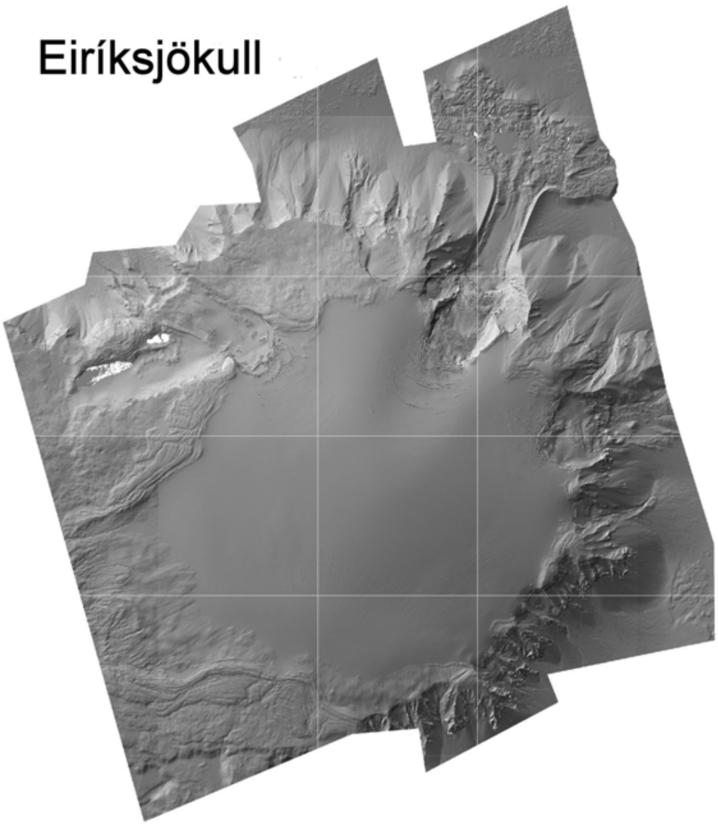

Figure 2 A shaded relief image of the 2008 DTM of the Eiríksjökull ice cap (area 22 km^2 in 2000) in western Iceland.

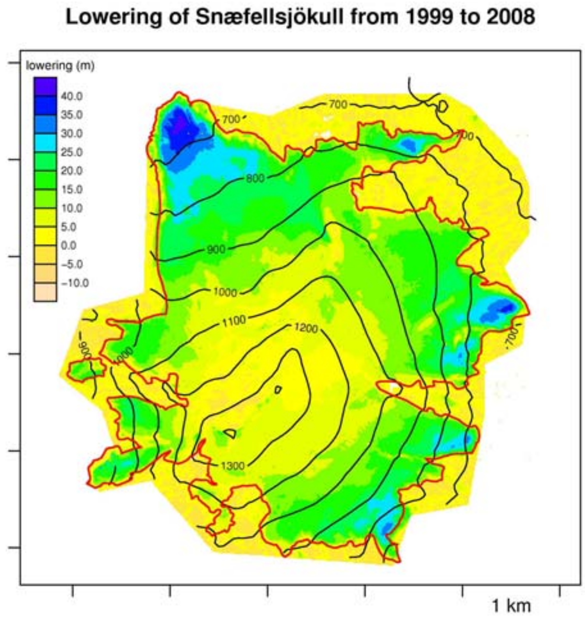

Figure 3 Lowering of the Snæfellsjökull ice cap (area 12.5 km^2 in 2000) from 1999 to 2008. The 1999 DTM that was used for comparison was made by aerial photography by Loftmyndir ehf.

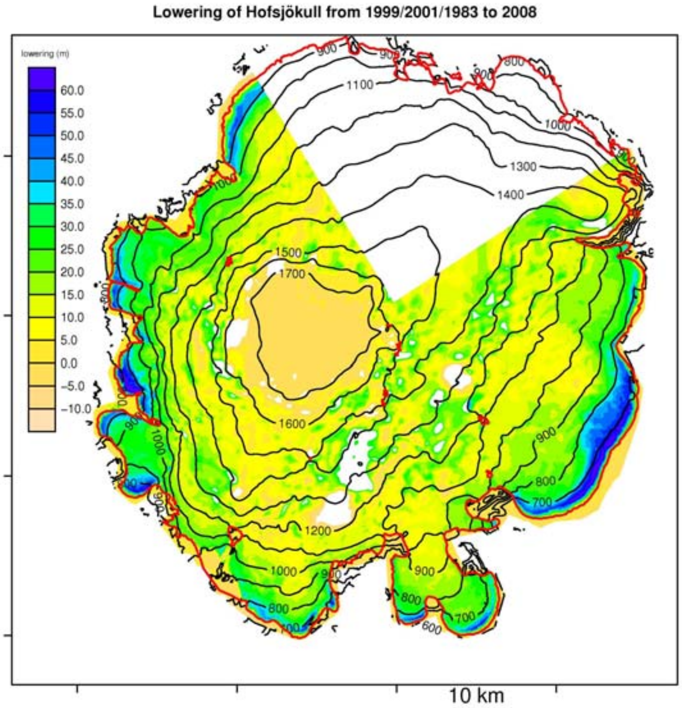

Figure 4 Lowering of the Hofsjökull ice cap (area 889 km^2 in 2000) from 1999/2001/1983 to 2008. A DTM from 1999 encompassing the ablation area and lower part of the accumulation area that was used for comparison was made by Loftmyndir ehf. The summit of the ice cap was mapped by GPS measurements in 2001. A DTM from 1983 based on precision barometric altimetry was used to fill in the gap between the ablation area and summit area DTMs from 1999 and 2001. Surface elevation changes in the period 1983 to 1999 are believed to have been rather small compared with more rapid changes during the last decade. The north-eastern part of the ice cap was not measured in 2008. Holes in the figure are due to uncertain or lacking measurements in the 1983 DTM in inaccessible areas.

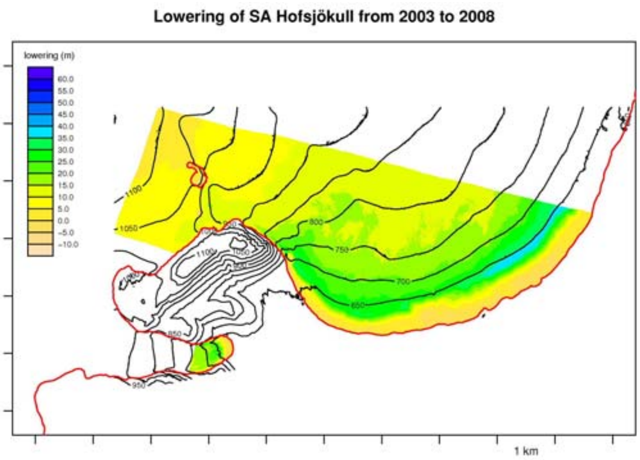

Figure 5 Lowering of a 17.5 km^2 area from SA Hofsjökull from 2003 to 2008. The 2003 DTM that was used for comparison was made aerial photography by Hnit hf.

Modelling the evolution of Vestfonna glacier, Svalbard, during the last full glacial cycle

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ABSTRACT
Svalbard (74°-81° N) lies at the northern limit of the North Atlantic Drift. This combined to the general tendency of high frequency southerly winds and advection of different air masses leads to a relatively mild but strongly fluctuating climate in Svalbard. The particular environmental setting makes the archipelago and its glaciers sensitive to subtle oceanographical and meteorological changes. Glaciers and ice caps cover 60 % of the present-day Svalbard so that the largest glaciers are located in Nordaustlandet, the north eastern island of the archipelago. Our research, *Quaternary studies in Murchisonfjorden area*, is an outcome of the IPY-Kinnvika research co-operation. Here we describe its recently started subproject, which concentrates on Vestfonna, the second largest ice cap on Nordaustlandet. The project is intended to simulate the evolution of Vestfonna during the last full glacial cycle covering a time span of 100 ka. A thermomechanical ice sheet model SICOPOLIS will be applied to Vestfonna in order to determine its extent, thickness, thermal regime and flow dynamics as a function of time. A finite element software Elmer will be used to solve computational tasks of heat transfer and ice flow with special emphasis on the last 10 ka. The input data will consist of the following major components: i) temperature and precipitation data ii) global sea level data iii) geothermal heat flux data and iv) bedrock and surface DEMs. We will validate the simulation results by comparing them to geological evidence from field observations. More specifically, the results will be compared to striae and section observations on glacial flow events and their chronology. In addition we will assess the accuracy of simulation results by comparing them to glacial isostatic adjustment calculations. The glacier model obtained from simulations will be coupled to a glacial sequence stratigraphic model of the research area in order to create new terminology for the poorly studied glacial sequence stratigraphy.

Distributed glacier mass balance for the Swiss Alps from regional climate model output: method development and the influence of bias correction

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ABSTRACT

We apply regional climate model (RCM) output to calculate glacier mass balance distribution at daily steps and 100 m spatial resolution for the entire Swiss Alps. The mass balance model is driven from daily fields of air-temperature, global radiation and precipitation which are downscaled from the RCM output at 18 km resolution by means of interpolation techniques and simple sub-grid parameterizations. In a first step, mass balance is calculated without bias correction of the RCM output. In a second step, weather stations data and a gridded precipitation climatology are used to correct RCM biases. Modelled mass balance is validated against time series of observed mass balance and observed precipitation at the equilibrium line altitude (P_{ELA}). The validation of the model output prior to the bias correction shows (i) a good agreement of modelled and observed time series, (ii) reasonable agreement of observed and modelled P_{ELA} and (iii) local over or underestimations of mass balance mainly stemming from biased precipitation. We finally show that the effect of the bias correction is primarily a new pattern of over and underestimations. We conclude that local biases in precipitation are a major challenge to be addressed and seem to be present even in gridded climatologies.

1. INTRODUCTION

We present a methodology to calculate high resolution (100 m spatial resolution, daily temporal resolution) mass balance calculation at a regional scale (i.e. entire mountain ranges). The approach uses RCM data for input and thus bears the potential to calculate high resolution future scenarios of mass balance. However, in the present study we focus on retrospective calculations (1979-2003) to explore the potential and uncertainties of the methodology. In a second model run (1985-2000) we study the potential of measurements from weather stations and of a gridded precipitation climatology derived from observations (Schwarb and others, 2001) to correct biases in the driving RCM data.

This study is based upon Machguth and others (in press) and Machguth (2008). For an in-depth description and discussion of the methodology, including additional validation techniques, reference is given to these two publications. The comparison of measured and observed P_{ELA} is a new addition to the methodology and only shown here.

1.1 Model Domain and Data

The mass balance calculation is applied to the entire Swiss Alps (approx. 25,000 km^2), being represented by the DTM25 level2 from swisstopo, a digital terrain model (DTM) from the mid-nineties. For the purpose of this study the DTM was down-sampled from 25 m to 100 m resolution (Figure 1).

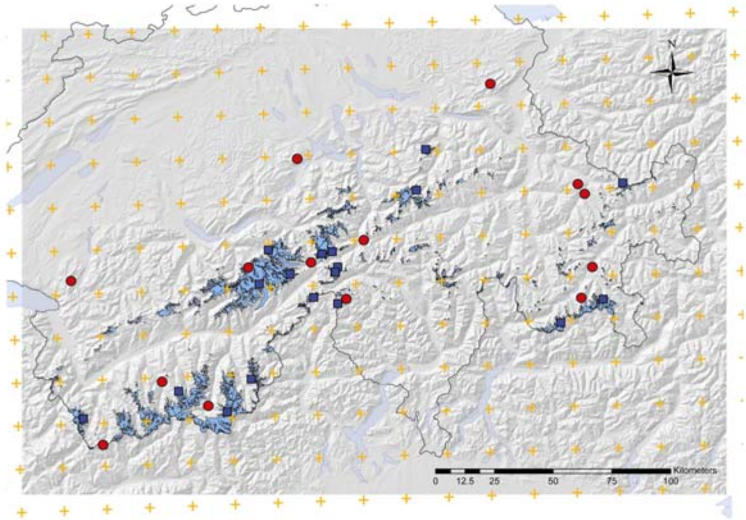

Figure 1 Model domain with the full DTM. Light blue: glaciers; Blue squares: available mass balance or stake measurements; Red dots: weather stations; Orange crosses: centres of the RCM grid cells.

We use digital glacier outlines from the Swiss Glacier Inventory from 1973 (Müller and others, 1973; Paul and others, 2007) which is the most complete data set currently available (Figure 1). At that time the glacierized area in Switzerland was 1280 km^2.

The mass balance model is driven from output of the hydrostatic RCM REMO (REgional MOdel) (e.g. Jacob and others, 2001). We use REMO output on 2 m air temperature (T_a), precipitation (P) and cloudiness (n) from a 1958-2003, 1/6° (approx. 18 km) spatial resolution run (Figure 1), driven by ERA-40 re-analysis data at the lateral boundaries.

For bias correction we acquired daily means of global radiation (S_{in}) and T_a from 14 high mountain weather stations in the Swiss Alps. To correct P we use the 2 km resolution mean annual precipitation (1971 – 1990) for the Swiss Alps from the Schwarb and others (2001) precipitation climatology.

2. METHODS

2.1 The mass balance model

The applied glacier mass balance model is a simplified version of the energy balance approach and requires T_a, S_{in} and P for meteorological input.. The model runs at daily steps, and the cumulative mass balance b_c on day t + 1 is calculated for every time-step and over each grid cell of the DTM according to Oerlemans (2001):

$$b_c(t+1) = b_c(t) + \begin{cases} \Delta t \cdot (-Q_m)/l_m + P^{solid} & if\ Q_m > 0 \\ P^{solid} & if\ Q_m \le 0 \end{cases}$$

Where t is the discrete time variable, Δt is the time step, l_m is the latent heat of fusion of ice (334kJ kg^{-1}) and P_{solid} is solid precipitation in meter water equivalent (m w.e.). The energy available for melt (Q_m) is calculated as follows:

$$Q_m = (1-\alpha)S_{in} + C_0 + C_1 T_a$$

Where α is the albedo for the surface (three fixed albedo values are applied: snow = 0.72, firn = 0.45 and ice = 0.27), T_a is in °C and $C_0 + C_1 T_a$ is the sum of the longwave radiation balance and the turbulent exchange (Oerlemans, 2001). C_1 is set to 10 $Wm^{-2}K^{-1}$ (Oerlemans, 2001) and C_0 is tuned to -45 Wm^{-2}. Accumulation equals P_{solid}, redistribution of snow is not taken into account and any melt water is considered as runoff. A threshold range of 1 to 2°C is used to distinguish snowfall and rain.

2.2 Downscaling of the RCM data

Downscaling of T_a and P includes the following two steps, both being performed every time step (daily) during the model run: (1) REMO output at approx. 18 km resolution is interpolated to 100 m resolution. (2) Vertical gradients of T_a (lapse rate) or P are applied to account for variability on a sub-grid scale. For illustration, the interpolation and downscaling scheme is applied to mean annual P (Figure 2).

A direct retrieval of S_{in} from the RCM-output would cause severe problems due to the large influence of topography (e.g. shading) at 100 m spatial resolution. Instead, we calculate clear-sky global radiation beforehand according to Corripio (2003). During the model run daily cloudiness (n) is obtained from the RCM, interpolated to 100 m resolution and is then used to derive attenuation of pre-calculated clear-sky global radiation from clouds according to Greuell and others (1997).

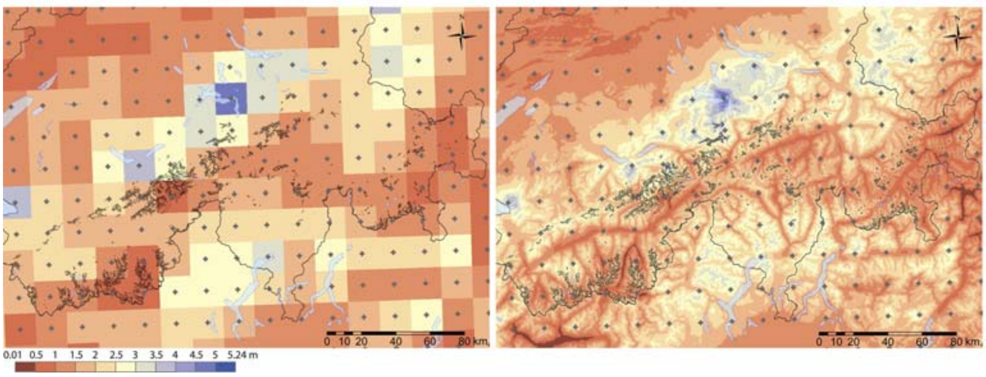

Figure 1 Left: Mean annual P (1979-2003) at the native REMO resolution. Right: Mean annual P (1979-2003) after downscaling. Switzerland's border is shown in black, glacier outlines are in grey and lakes in light blue.

2.3 Bias correction

Biases have a temporal (bias varies with time) and a spatial component (bias varies in space). Comparing the downscaled RCM fields to measurements at the 14 high mountain weather stations shows that for T_a and S_{in} the temporal component is important while for P the spatial component dominates.

To correct the temporal bias of T_a we calculate daily offset of measurement and downscaled REMO field at each weather station and for the entire calculation period. The offset-values are averaged over all stations and all years of the calculation period to obtain the 365 correction values for each day of the year. S_{in} is corrected by adjusting n because RCM cloudiness is the main source of bias. The approach is similar to T_a but requires additional parameterizations to guarantee $0 \leq n \leq 1$.

To correct spatial bias of P a spatial correction array (P_{corr}) is calculated from the ratio of mean annual P according to REMO and according to the Schwarb and others (2001) precipitation climatology. We then multiply daily precipitation arrays from REMO with P_{corr}. This approach ensures that in a long term mean the spatial distribution of P is identical to Schwarb and others (2001) whereas temporal variability comes from the RCM. The scaling results in the same (spatially variable) precipitation gradients as being derived from a large number of observations by Schwarb and others (2001) and the precipitation gradient (Section 2.2.) becomes obsolete.

3. RESULTS AND DISCUSSION

In a first step no bias correction of the RCM data is performed and mass balance distribution is calculated for the time span 1979-2003 and for all glaciers. Two sections from the resulting mean annual mass balance distribution are shown in Figure 3. A visual assessment reveals a reasonable picture but certain glaciers have accumulation areas which are either too small or too large. Looking at all glaciers (not shown here) one can see that these over or underestimations are not evenly distributed in space but vary among the regions.

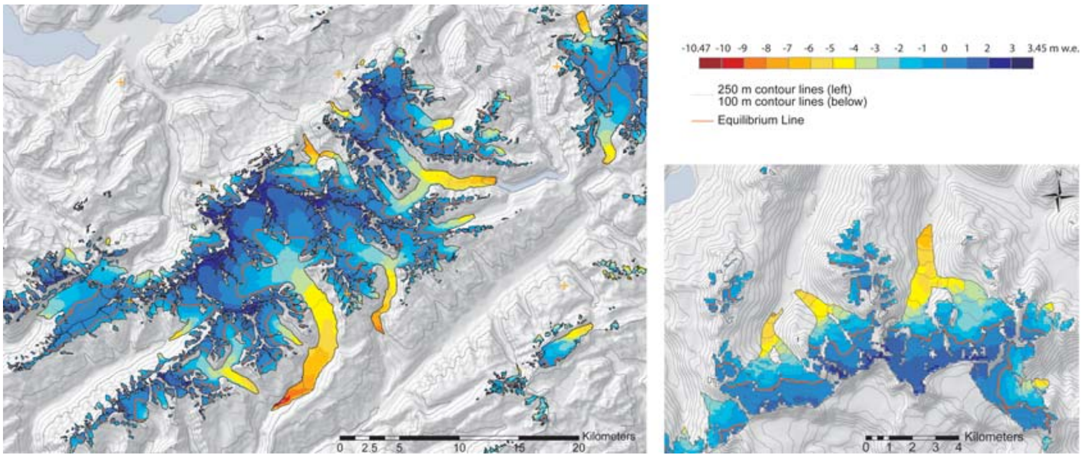

Figure 2 Mean modelled annual mass balance distribution (1979-2003, no bias correction) for the region around Grosser Aletschgletscher (left) and Morteratschgletscher (right). Note the difference in scale.

Due to limitations in the mass balance model (e.g. glaciers are regarded as debris free), 94 glaciers are selected where reasonable results are expected (cf. Machguth and others, in press) and further validation is performed for them. Temporal variability of mass balance agrees well with data from WGMS (2007) and Huss and others (2008) (Figure 4a). The values averaged over a small sample size (the four glaciers studied by Huss and others, 2008) show a systematic shift which is averaged out in the mean of all selected glaciers. This observation indicates local over or underestimations of mass balance which are mainly related to areas with strong biases in RCM precipitation (cf. Machguth and others, in press).

The relationship of summer (June, July August) air temperature at the ELA ($T_{summer\text{-}ELA}$) to P_{ELA} as derived from the model output is in good agreement with observations reported in Ohmura and others (1992) (Figure 4b). Except for one outlier who is considered an erroneous value, modelled accumulation and melt rates at the ELA seem to be realistic.

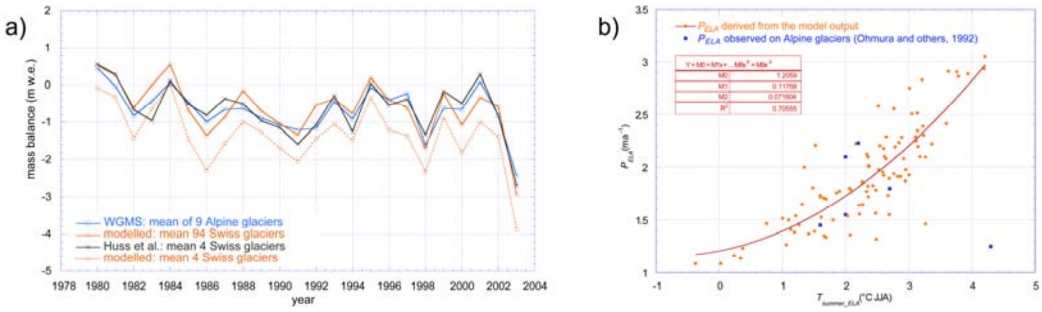

Figure 1 Two examples of model validation (input not bias corrected): a) Modelled annual mean mass balances for 94 selected glaciers compared to WGMS (2007) and Huss and others (2008). b) Scatterplot of $T_{ELA\text{-}summer}$ and P_{ELA}, showing also observed values for the Alps from Ohmura and others, (1992)

Finally a model run including the bias correction is performed for 1985-2000. Mass balance calculated for each of the 94 selected glaciers (B_{mod}) is compared to mass balance (1985-2000) as derived by Paul and Haeberli (2008) by means of DTM subtraction (B_{meas}). The resulting differences $B_{mod} - B_{meas} = \Delta B$ are shown in Figure 5. The pattern of the ΔB is somewhat systematic with negative ΔB to the east and positive ΔB in the Aletsch area.

Can we assume that ΔB indicates regional biases at high mountain elevations in the precipitation climatology? One should be careful because our modelling chain includes numerous sources of uncertainty (e.g. the mass balance model, the RCM, B_{meas}). Nevertheless, findings from other studies using the same precipitation climatology for glacier modelling (Zemp and others, 2006; Huss and others, 2008, 2009) or a comparison to Skoda and Lorenz (2003) indicate similar regional biases.

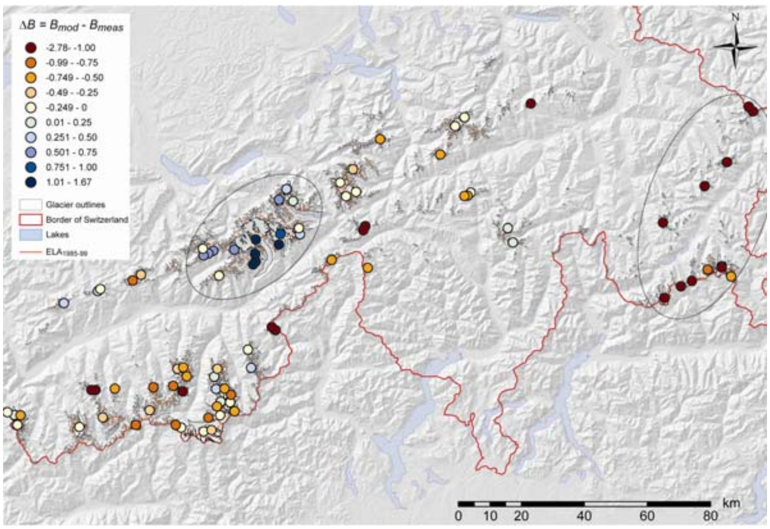

Figure 2 ΔB of mean annual mass balances for 1985-2000 (input bias corrected). The two regions with uniformly positive or negative ΔB are highlighted.

We demonstrated a regional scale mass balance model driven from downscaled RCM fields. Whereas the gap in spatial resolution is not considered a major drawback, biases in the RCM data are a critical source of errors and have to be reduced. It must be stressed that such a bias correction is not trivial for High Mountain or remote areas where glaciers are mostly located and where only few meteorological data is available. Even the applied high resolution precipitation climatology, being based on a very large number of observations, seems to be regionally biased at the elevation of glaciers.

ACKNOWLEDGEMENT
We acknowledge M. Huss for detailed mass balance data and MeteoSwiss for meteorological data. Figures 1, 2, 3 and 5 show the DHM25Level2 from swisstopo (BA081414).

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Glacier sliding reduced by persistent drainage from a subglacial lake

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ABSTRACT

We present velocity observations of a glacier outlet in Vatnajökull, Iceland, deduced from interferometric synthetic aperture radar (InSAR) data obtained during the ERS1/2 tandem mission in 1995-2000. More than 50% decrease in glacier motion was observed subsequent to a large jökulhlaup from the subglacial lake Grímsvötn in November 1996 and it had not reached its former flow rate at the end of our study period. The jökulhlaup damaged the lake ice-dam causing persistent drainage from Grímsvötn. InSAR observations of water accumulation within the lake suggest that a leakage of >3 m^3 s^{-1} prevailed throughout our study period. Our interpretation of the observed reduction in glacier motion is that the water drained underneath the whole length of the glacier outlet through tunnels at low water pressure. Further, the tunnel flow drained water from its surroundings lowering the water pressure of a linked cavity system, underneath the upper and centre part of the glacier, which prior to the jökulhlaup sustained basal sliding.

Recent elevation changes of Arctic glaciers derived from repeat track ICESat altimetry

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ABSTRACT

The Arctic region is believed to be more affected by recent climate change than the lower latitudes. Glaciers and ice caps are sensitive indicators of climate change, and there is a high demand for more accurate quantifications of recent glacier changes in the Arctic. ICESat laser altimetry has been successfully used to assess 2003-2008 elevation changes in Greenland. Other high Arctic glaciers have an equally dense coverage of ICESat data, but the quantity and quality of elevation comparisons are degraded due to smaller glacier sizes and steeper slopes. We have tested two different methods for comparing ICESat repeat tracks over Svalbard glaciers. The first method uses an external DEM to correct for the cross track slope between repeated tracks, while the other method uses all available ICESat data in a joint analysis where slope, aspect and elevation change are estimated for homogeneous planes that are fitted to the data along each track. The two methods yield similar results and compare well to more accurate elevation change calculations at crossover points between ascending and descending tracks. The good performance of the plane method implies that it can also be used in other regions of similar characteristics where accurate DEMs are typically not available. Some preliminary results of 2003-2008 elevation changes will be presented for the Norwegian Arctic (Svalbard), the Canadian Arctic and the Russian Arctic. We also show a few examples where unstable glacier dynamics can be inferred from elevation changes along ICESat tracks.

Deglaciation of Fljótsdalshérað and Fljótsdalur, a prelude to the earliest formation of Lake Lögurinn, East Iceland

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ABSTRACT
During the rapid post-LGM deglaciation of the shelf around Iceland, coastal areas became ice-free and inundated by the sea as early as 12.6 ka BP. In Central East Iceland both Fljótsdalshérað and Fljótsdalur were deglaciated at that time and probably submerged in the sea before relative sea-level, due to rapid glacio-isostatic uplift, regressed to altitudes below the Lagarfoss bedrock threshold in outer parts of the area. Subsequently, in Younger Dryas and Preboreal times glaciers in East Iceland advanced and relative sea-level transgressed before the area was finally deglaciated and relative sea-level regressed to an altitude well below present sea-level in early Holocene times.

Figure 1 Kame-terraces and raised lake shorelines at Hengifossá in Fljótsdalur.

Lateral terraces, kames and pitted sandur show that a northwardly flowing outlet glacier in Fljótsdalur terminated in the area between Tjarnarland and Eiðar in Fljótsdalshérað when a pro-glacial sandur, now reaching about 30 m a.s.l., was aggraded and controlled by rising relative sea-level culminating close to 30 m above sea level. The location of the Tjarnarland-Eiðar marginal zone and thus the extent of the Fljótsdalur outlet glacier was controlled by climatic deterioration but also by bedrock topography at the northern end of the Lake Lögurinn basin, which constitutes an overdeepened bedrock basin reaching at least 90 m below present sea-level. After a slow thinning and retreat of the margin of the Fljótsdalur outlet glacier the Lake Lögurinn basin rapidly became ice-free when the glacier retreated to a higher ground south of the basin.

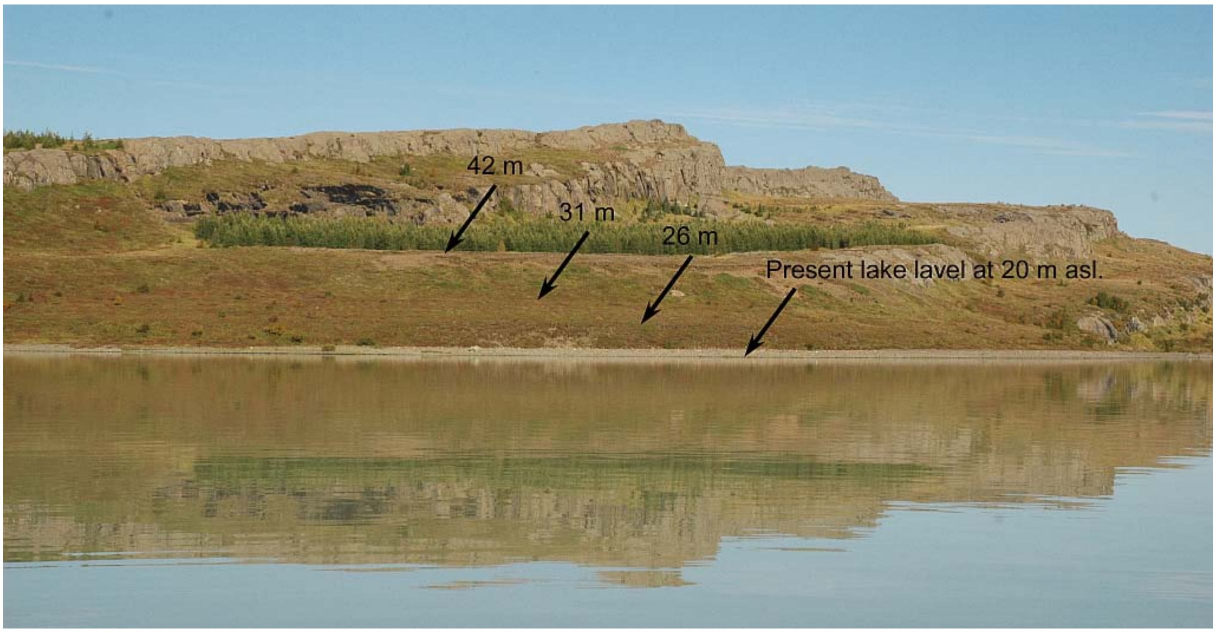

Figure 2 A flight of raised lake shorelines at 42, 31, and 26 m asl. at Freysnes opposite Egilsstaðir.

From Tjarnarland-Eiðar and along both sides of Fljótsdalur scattered remnants of shoreline features are found at altitudes from 32 m a.s.l. around Tjarnarland in the north, and from there at increasingly higher altitudes reaching up to 63 m a.s.l. at the southern end of the present Lake Lögurinn. The southwardly increasing altitude of these shoreline features reflect an ongoing differential glacio-isostatic uplift of the area, and also that the surface altitudes of Lake Lögurinn was in fact at the same time controlled by the Lagarfoss bedrock threshold. The maximum apparent gradient of the oldest Lake Lögurinn palaeo-shorelines is about 0.7 m/km and reach about 0.0 m/km about 10 m above the surface of the present lake. Lowering of the Lake Lögurinn from about 30 a.s.l. to its present altitude close to 20.0 m a.s.l. thus occurred after the glacio-isostatic uplift was depleted and the lowering is reflecting erosion and lowering of the bedrock threshold at Lagarfoss.

Marine shells found at about 15 m a.s.l. in fine grained sediments that are related to relative sea-level close to the 30 m level have yielded a radiocarbon age of about 9.4 ka BP, an age that is interpreted as a minimum age for the Tjarnarland-Eiðar marginal zone. Glacio-isostatic uplift in Iceland seems to have been depleted in the coastal areas at about 9.0 ka BP, a date that might be related to the age of the earliest non-tilted Lake Lögurinn shoreline. At about 7.8 ka BP the Icelandic ice sheet had been diminished to such an extent that lava could be erupted from volcanoes in the centre of Iceland. That date could mark the the time when Lake Lögurinn was for the first time transformed from a glacio-lacustrine to a lacustrine lake.

Periodicities in varve thickness of Hvítárvatn sediments, Iceland

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ABSTRACT

A 3000 year long varve thickness record from Hvítárvatn (HVT), a glacial lake in central Iceland, is used to reconstruct activity of Langjökull and the two outlet glaciers that drain into the lake. During extended periods of cold summers the ice cap expands and consequent erosion delivers more sediment to the basin. The first-order trend of the varve thickness record is increased erosion through the Late Holocene, reaching a peak during the Little Ice Age (LIA). Superimposed on this trend are large inter-annual to decadal fluctuations in varve thickness that we suggest may reflect precipitation variability that influences the proportion of newly eroded sediment delivered to the lake each year.

In order to analyse if there is some regular high-frequency cyclicity in the last 3 ka of the varve thickness record from Hvítárvatn, spectral analysis was applied. Prior to the spectral analysis the non-linear long-term trend describing the change from relatively low sedimentation rate to higher and more variable sedimentation rates during the LIA, was filtered out. Singular Spectrum Analysis and the Multi-Taper Method were used to calculate a power spectrum. The results show that dominant variations in the varve thickness record are 90-120, 30, 11-13 and 2-4 year cycles. Some of these cycles show similar variability to that of the North Atlantic Oscillation (NAO) and the North Atlantic Multidecadal Oscillation (NAMO). Wavelet Analysis was used to test whether the dominant frequencies of these cycles evolved through the 3ka record. However, in order to get more confident results the record was split into two parts, separating the high variance LIA portion from the more uniform older record. The dominant cycles are virtually continuous through the last 3ka, both before and during the Little Ice Age (1250-1900 AD) with only minor changes in the length of the cycles, although some of the cycles become stronger and more dominant during the LIA portion of the record. This suggests the mechanism controlling the high frequency variations is permanent through the time in study.

A correlation is found between the HVT varve thickness record and precipitation over the instrumental period. Icelandic precipitation is significantly correlated with the NAO (Hanna et al, 2004). Therefore cross-spectral analysis was used to compare the HVT record with a ~140 yr long NAO index and a ~150 yr long precipitation record from Iceland. Common periodicities found in all three records support a link between short term variability in HVT varve thickness, precipitation, and the NAO. We conclude that NAO driven fluctuations in year-to-year precipitation are influencing the higher frequency cycles in the varve thickness record from the Hvítárvatn.

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The impact of volcanic and geothermal activity on the mass balance of Vatnajökull

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1. INTRODUCTION

About 60 % of glaciers in Iceland are underlain by an active volcanic zone (Fig. 1). Ice is continuously melted at a few subglacial geothermal areas (Fig. 2) and occasionally during short-lived eruptions. In about 4 % of the area of Vatnajökull ice cap (8100 km^2) geothermal activity eternally affects the ice flow and basal drainage of meltwater. During the period 1992 to 2005, more than 90% of the ablation within these areas was basal melting while less than 10% of the melting took place during two volcanic eruptions (1996 and 1998). Volcanic eruptions in the entire volcanic zone have permanently amplified the glacier surface ablation through the dispersal of tephra over the glaciers, maintaining albedo as low as 0.1 in the ablation areas; rarely they insulate the glacier and prevent melting. Increased net short-wave radiation considerably increased the summer melting after the two most recent eruptions in Vatnajökull (in 1997 and 1999). Looking at the entire Vatnajökull ice cap over the period 1992 to 2005 basal melting comprised only 3% of the total ablation.

2. MELTING AT SUBGLACIAL GEOTHERMAL AREAS

Ice is continuously melted at the glacier bed creating permanent depressions in the glacier surface that reveal hydrothermal activity (Fig. 2; Björnsson, 1988). The surface depressions tend to be gradually reduced by inflow of ice. The meltwater may be trapped in a lake at the bed due to relatively low basal fluid potential under the depression. High overburden pressure at the rim around the depression seals the lake.

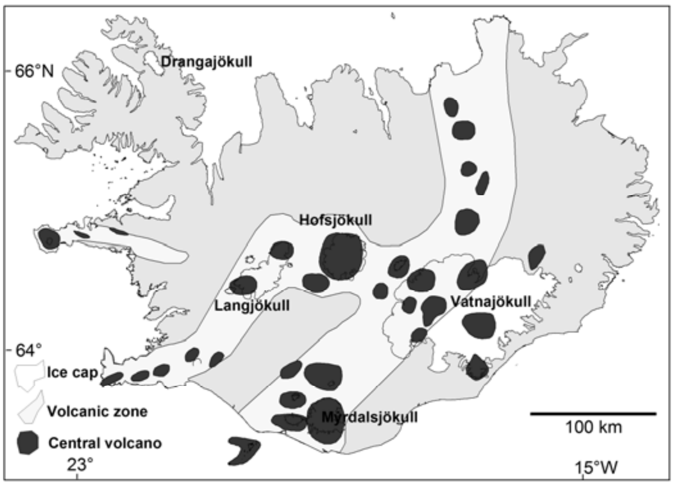

Figure 1 Map of Iceland.

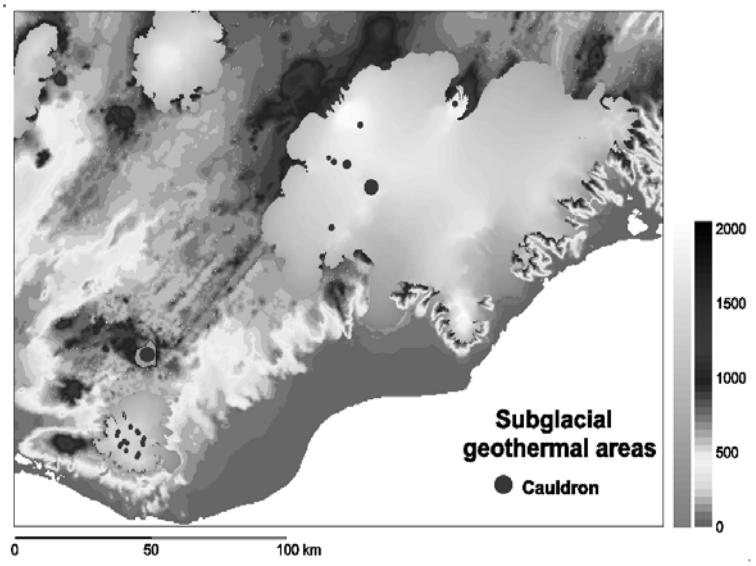

Figure 2 Subglacial geothermal areas.

3. MELTING IN SUBGLACIAL ERUPTIONS

There are several active volcanic systems beneath Vatnajökull ice cap (Fig. 3). Research of the tephra layers cropping out of the ice in the glacier ablation zone yields a minimum of 86 eruptions the past 800 years (Larsen *et al*., 1998). The Grímsvötn caldera and vicinity is the most active eruption site, and has erupted 8 times the past 100 years. In 1938 and 1996 eruption´s in Gjálp north of Grímsvötn melted 3-4 km^3, but recent eruptions within the Grímsvötn caldera have melted about 0.1 km^3 or less (Björnsson, 1988; Björnsson *et al*., 1993; Guðmundsson *et al*., 2004). Small subglacial eruptions may not melt through the ice, and are therefore not seen in the tephrochronical record. On average we estimate eruptions melting 0.05 km^3a^{-1}.

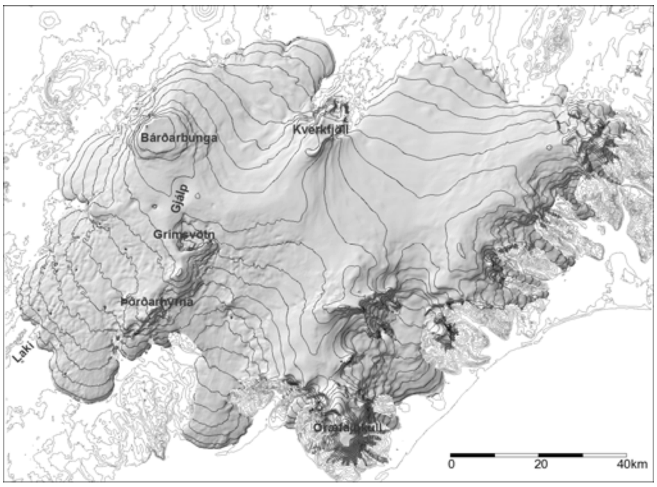

Figure 3 Location of subglacial volcanoes.

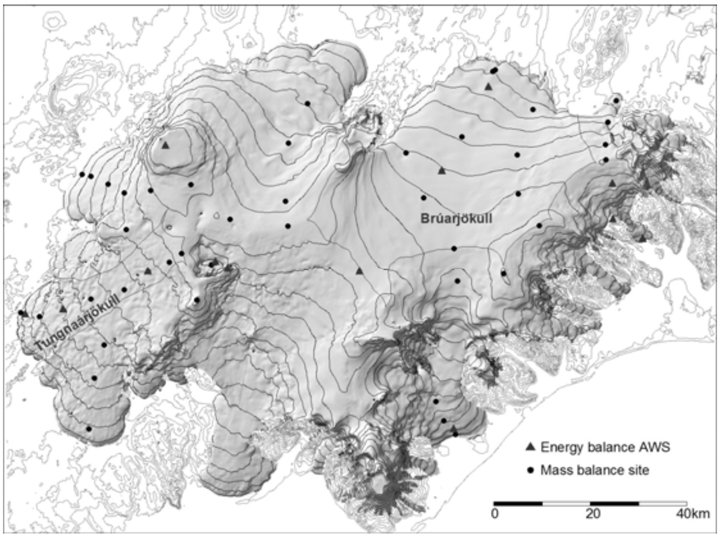

Figure 4. Mass and energy balance observation sites.

4. ENHANCED MELTING DUE TO VOLCANIC TEPHRA AND DUST

Volcanic ash is spread aerially over large areas. Depending on wind direction during eruption, Vatnajökull may be partially or totally covered with volcanic ash from eruptions within or outside the glacier. In the ablation zone most of the particles will wash off in the next melting season. In the accumulation area the tephra cover gets buried and turns up again few hundredyears later in the ablation zone. Mass balance for the outlets of Vatnajökull has been monitored since 1991-92 (Björnsson *et al*., 1998; 2003) and automatic weather station (AWS) been operated since 1996 for surface full energy balance estimation (Fig. 4; Guðmundsson *et al*., 2006). Surface conditions have also been observed with optical ASTER and SPOT5 remote sensing images. The AWS-, mass balance- and remote sensing data have been used for spatial modelling of the surface energy balance and melting. The energy contribution from short wave radiation is on average about 70-80%, long wave radiation contribution is small and turbulent heat fluxes contribute about 20-30%.

Volcanic debris cropping out in the ablation zone lowers the albedo considerably. Values as low as 0.1 are measured, whereas typical values of albedo for pure ice are about 0.4. For evaluating the inpact of low albedo we run spatial energy balance models for the outlet glaciers Brúarjökull and Tungnaárjökull (Fig. 4; Guðmundsson *et al*., 2006) for different assumed minimum values of albedo (Figs. 5 and 6). Changing the dirty ablation zone to pure ice results in about 13% less total ablation (upto about 20-25% in the ablation zone). The low albedo in the ablation zone highly affects the long term mass balance of Vatnajökull (Fig. 6). Clean ice would result in Brúarjökull being in a long term mass equilibrium instead of fast shrinkage.

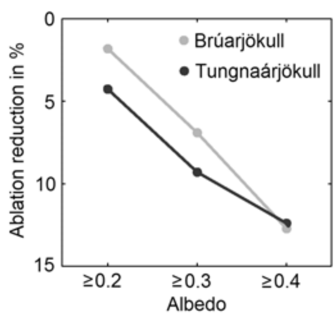

Figure 5. Ablation reduction with increased albedo for ice,relative to observed.

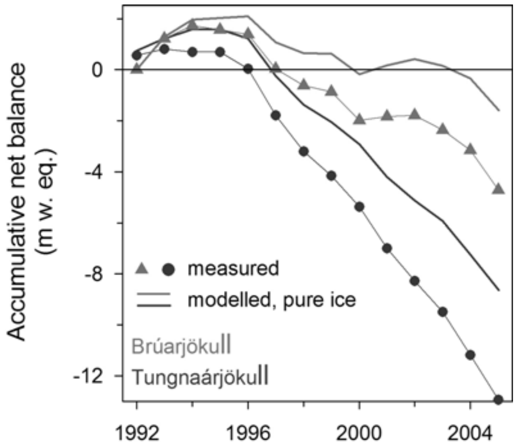

Figure 6. Measured mass balance, compared to that resulting from surface energy

5. CONCLUDING DISCUSSION

The short term effect of volcanic activity on the mass balance of glaciers are direct melting in subglacial eruptions, melting during cooling of a volcanic edifice and one or a few seasons of increased melt due to exposed volcanic ash. This may control the mass balance in close vicinity of the volcano for a few years, but has little effect on the long term mass balance of the ice cap (Table 1).

The long term effects are basal melting in geothermal areas, and enhanced melting in the ablation zone where volcanic ash layers crop out of the ice and increase absorption of short wave radiation. In drainage basins presently containing geothermal areas 90% of the ablation is due to basal melting. The enhanced melting due to volcanic ash is in the order of 10% of the total melting (Table 1) and has significant impact on the mass balance of the ice cap.

Despite geothermal and volcanic influence on Vatnajökull the mass balance reflects meteorological conditions (Table 1), and the ice cap can be used as a laboratory for study of climate variations.

Table 1. Melting rates of Vatnajökull late 20th century.

	Surface ablation $km^3\ a^{-1}$	**Geothermal systems $km^3\ a^{-1}$**	**Volcanic eruptions $km^3\ a^{-1}$**
Vatnajökull 8200 km^2 3100 km^3	20 (3)*	0.5	0.05
Geothermal areas 200 km^2	0.05	0.5	0.05

ACKNOWLEDGEMENT

We acknowledge the support of the National Power Company of Iceland, The road authority of Iceland, European Union (Framework V, projects TEMBA, ICE-MASS and SPICE), the Public Roads Administration, Rannís, Iceland University Research Fund and Iceland Glaciological Society for help in field work. SPOT5 images were made available through the two OASIS projects number 36 and 94.

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Application of airborne imaging goniometer and on ground measurements for snow remote sensing research

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ABSTRACT
A research facility to measure the reflectance and polarisation of land surfaces using unmanned aerial vehicle based measurement system and on ground instruments has been created. The system has been applied to snow remote sensing research. The Finnish Geodetic Institute Field Goniospectropolarimeter system FIGIFIGO consists of ASD Field Spec Pro FR spectroradiometer, broad band linear polariser, moving arm that can tilt the sensor optics ±90◦ around the target, Spectralon reference plate, all sky camera, pyranometer, and several other support sensors and components. It can measure the bidirectional reflectance factor (BRF) of a target in 10 minutes, with polarisation in 20–30 minutes.

Figure 1 Left: FIGIFIGO measuring snow in Sodankylä. Foreoptics are located in the arm, ASD and electronics are inside the box. Spectralon reference panel can be seen right of the box, and sun pyranometer behind. Right: Microdrone flying in Sodankylä.

The first prototype for the airborne imaging goniometer consists of a Microdrone md4-200 quadrocopter type unmanned aerial vehicle (UAV), Ricoh GR II digital camera, and on ground reference plate. The Microdrone can fly automatically preprogrammed path, taking pictures in selected points. The camera is calibrated in laboratory for flat field and geometry. The BRF of the reference plate has been measured in laboratory. The brightness of the selected target area is read from camera data, and normalised by reference panel brightness in the same image. Flat field and reference plate BRF corrections are applied.

The reflectance and polarisation of several snow types have been measured. Snow types differ by anisotropic properties somewhat, but using this for inversion is difficult. By polarisation, some wet and dry snow types can be distinguished. The spectrum reveals a lot of information about grain size, wetness and purity. From the results hemispherical albedos have been derived. They show varying dependence on solar zenith angle, depending on the snow type. The bidirectional reflectance factor of snow was also observed using airborne imaging goniometer in three colours. The results agree very well with on ground measurements.

The measurements have increased the understanding of snow reflectance properties significantly, allowing design of more optimal sensors and analysis techniques. The new research tools, especially small UAV based measurement systems, show huge potentials for new applications.

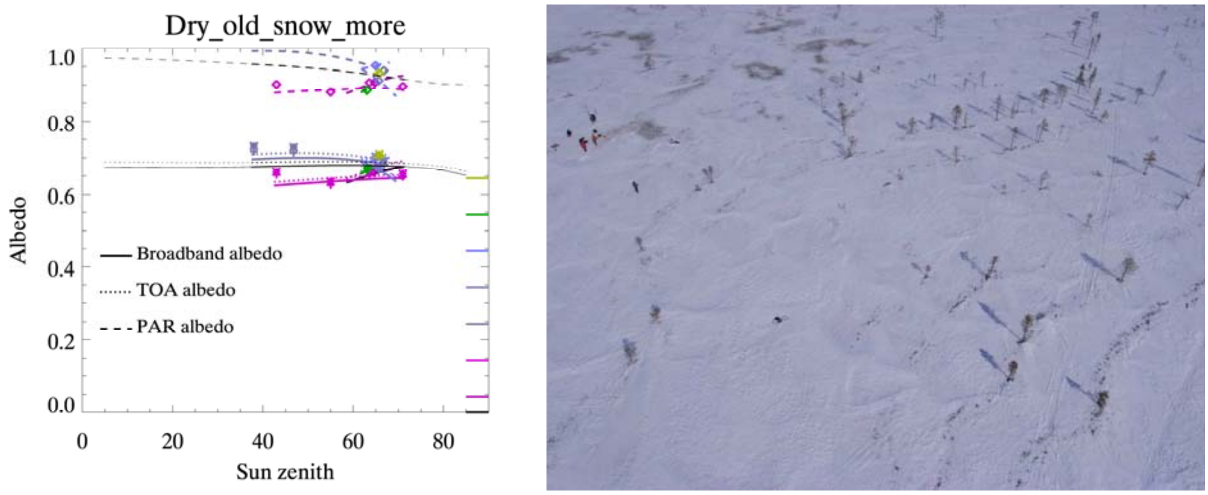

Figure 2 Left: hemispherical albedo of several dry snow samples as a function of solar zenith angle. Right: an aerial photo taken by Microdrone over the research area. Left top corner several ground measurements going on. Two reference plates can be seen left from middle foreground.

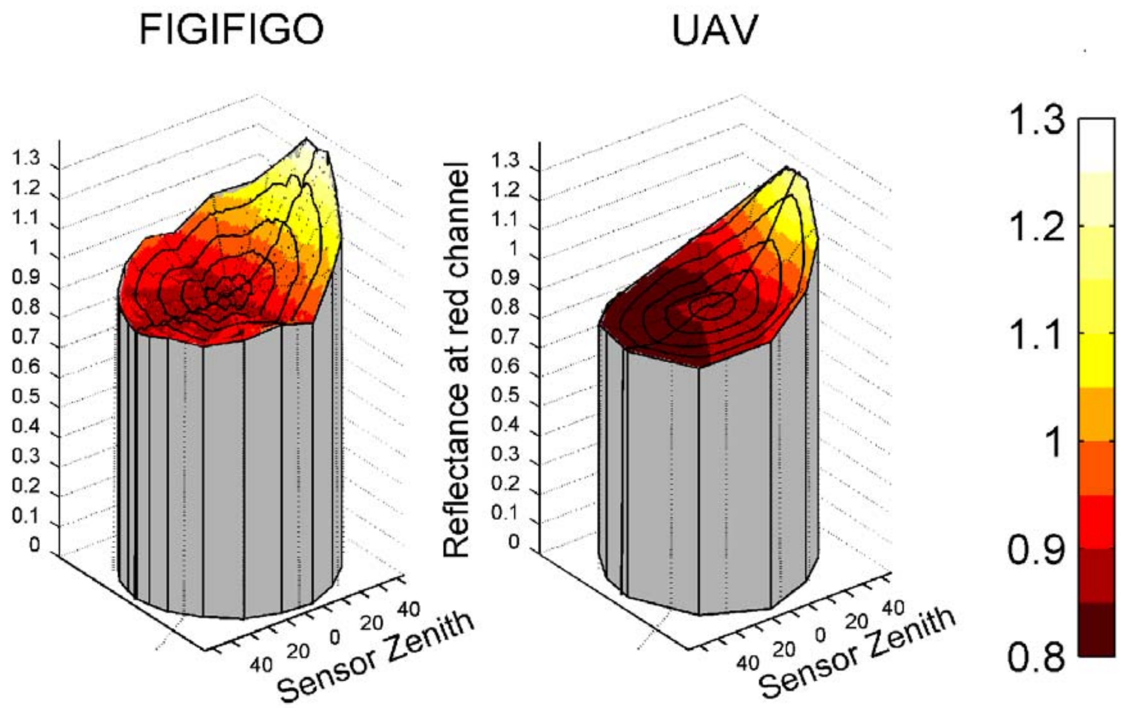

Figure 3 The bidirectional reflectance factor of melting snow in Sodankylä March 2009 measured using FIGIFIGO and airborne imaging goniometer.

Recent elevation change of Vestfonna, Svalbard Archipelago, comparing surface DGPS campaigns with ICESat and NASA altimetry

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ABSTRACT
During IPY4 (2007-2009) DGPS ground elevation profiles were accomplished by snow-mobile traverses across the 2,500 km^2 sized Ice Cap Vestfonna situated in the northeast of the Svalbard Archipelago (80° N, 19° W). The repeated campaigns show local spatial and temporal changes of the ice cap elevation, most likely caused by changes in the wind patterns over the ice cap. Our ground profiles were aimed to follow ICESat profiles (2003-2008) and airborne NASA altimetry profiles (1996, 2002) that criss-cross the ice cap. Comparisons between ground DGPS altimetry and ICESat altimetry during near-in-time campaigns for both platforms in 2008 show good agreement between both series. Analysis of all the available elevation time-series suggests only local changes, but indicates no coherent trend in elevation change for the whole ice cap. Thus it seems that Vestfonna is anomalous compared to other glaciers in Svalbard and in the Arctic by not displaying significant mass changes during the last decades.

3D discrete numerical modelling of ridge keel punch through tests

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ABSTRACT

Ridge keel punch through tests were simulated in 3D. In simulations unconsolidated ridge keel was modelled as a rubble pile of loose ice blocks. Combined finite-discrete element method (FEM-DEM) with rigid discrete elements representing ice blocks was used. Simulations were run in full scale. In total 47 simulations were run with various friction coefficients and keel depths. The failure process of simulated rubble piles was analysed and the shear strength of the rubble pile was derived from results. The effect of rubble porosity, keel depth and friction on shear strength of the pile was also analysed. The simulation results were compared to laboratory and full-scale punch through tests of unconsolidated ice rubble. Shear strength values achieved from simulations were in range for experimental results. Failure process was observed to be similar to laboratory experiments.

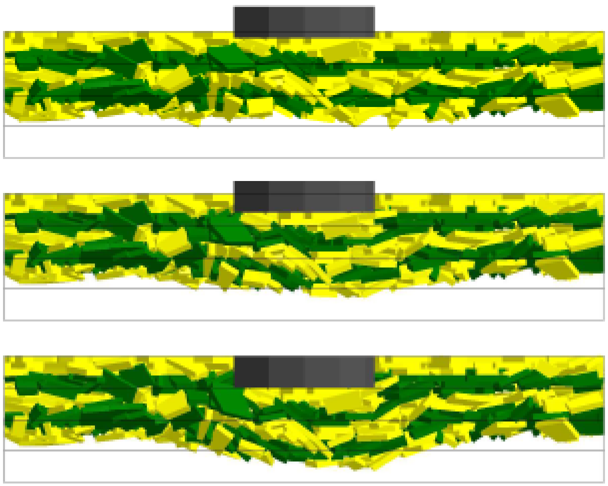

Figure 1 An illustrative example of a simulation run.

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10 years of hydrogeological investigations at Skeiðarársandur, SE Iceland

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ABSTRACT

Hydrogeology in glacial environments has been referred as a ‘no-man’s land,’ reflected by the paucity of research in this field. However, the hydrogeology of glacial environments has important implications to the ecological functioning of proglacial environments, proglacial geomorphology, glacier dynamics, and surface water systems. Glacially-influenced groundwater systems respond to changes in glacier geometry and hydrological routing of meltwater rivers, itself a function of changes in the glacial system. Hence consideration of hydrogeological processes in glacial environments is imperative in light of the aim of understanding and predicting the effects of climate-driven glacial retreat on hydrological systems. Currently there is a paucity of systematic baseline, and particularly long-term, monitoring data in these areas, necessary for the development of hydrogeological models in glacial environments.

Hydrogeological investigations on shallow groundwater systems at Skeiðarársandur have been carried out since 1998 on a number of different aspects of the hydrogeological system. (1) Investigation of inter- and intra-annual variations in groundwater level has highlighted the spatially-variable response of the shallow groundwater system to seasonal and shorter-term recharge dynamics in addition to overall lowering of the water table in response to larger system changes in hydrological routing and glacier extent. (2) Investigation of spatial and temporal variations in recharge has identified two principal and isotopically-distinct sources of groundwater recharge (glacier melt and local precipitation) with a predictable spatial trend of increasingly isotopically heavy signatures with decreasing depth and increasing distance from the glacier margin, a pattern which is modified by groundwater flow paths and vertical mixing processes, and recharge from meltwater rivers. (3) Investigation of weathering reactions, solute sources and solute fluxes, with particular emphasis on sources of sulphur, has shown that the hydrogeochemistry of the hydrogeological system is spatially variable reflecting flow paths and spatial variability in solute sources and processes. The system is dominated by the carbonation of both silicates and carbonates, with evidence for sulphide oxidation coupled to both carbonate and silicate dissolution, and additional solute inputs from geothermal systems. Distinct $\delta^{34}S_{-SO4}$ compositions within lakes formed in the kettle holes generated during the November 1996 jökulhlaup suggest high proportions of sulphide oxidation derived sulphate and/or bacterially-mediated sulphide oxidation occurring in these environments. (4) Investigation of the evolution of groundwater-surface water interactions particularly related to the evolution of November 1996 jökulhlaup-generated kettle holes, has highlighted the importance of these environments as transient ecological niches.

This presentation summarises the results of 10 years of hydrogeological investigations at Skeiðarársandur drawing on both high spatial and temporal resolution water table measurements and geochemical and stable isotope analyses ($\delta^{18}O$, δD, $\delta^{34}S$), and subsequent spot measurements looking at longer-term changes within the hydrogeological system. This baseline information highlights the need for: continued monitoring of these dynamic systems, the integration of ecological investigations to investigate the impacts of hydrogeological changes on the ecological functioning of the proglacial zone, and the development of integrated hydrogeological models in glacial environments.

Multivariate analysis of Japanese ice core data from several Svalbard sites: an exploratory study

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ABSTRACT

Despite its remoteness from major anthropogenic polluting sources as compared with most Arctic glaciated areas, environmental scientists have shown increasing interest in Svalbard in the last decades. One of the main reasons for this interest is that Svalbard is located at the crossroads of major oceanic and atmospheric currents from the Arctic, and is thereby affected by long-range transport of contaminants from industrial areas, including Eastern and Western Europe and Canada. Another reason, of particular interest to glaciologists, is that Svalbard ice caps are affected by seasonal melt, which has long been thought to irreversibly disturb the enclosed climate proxies.

Recently published Japanese ice core data from various sites in Svalbard have been analyzed here from a statistical point of view in order to investigate the potential for differential trends in environmental proxies and solute relocation. It is shown that, by reducing the original data sets to simpler variables, and by estimating their interdependence, multivariate analysis methods can provide useful tools in this regard. In this work, the original data sets from various ice coring sites were first recompiled to take account of their variable sampling resolution and variable sets of analyzed proxies. Thanks to radioactivity measurements, local accumulation rates could be calculated and dating models built. Despite the low vertical analytical resolution of the cores, multivariate analysis methods allowed us to identify interesting trends, which can be considered for further ice core/snow pit studies. Various hypotheses will be discussed to explain these trends, keeping emphasis on nitrate dynamics (which are still poorly known but paramount for the study of the oxidation chain of atmospheric reactive nitrogen).

This work is part of the interdisciplinary NSINK Marie Curie program, the scope of which is to unravel the enrichment of Arctic terrestrial and aquatic ecosystems by reactive atmospheric nitrogen from low latitude emission centres.

Scharffenbergbotnen blue ice area, East-Antarctica

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ABSTRACT

Antarctic paleoclimatic data are available not only from deep ice cores but also from the surface of Antarctic blue ice areas (BIAs). BIAs are bare ice fields which are kept clean of snow by the wind. They are characterized by an exposed ice surface due to a negative surface mass balance. Sublimation is the dominant ablation mechanism. Many of these BIAs are known to have very old ice at the surface (e.g. Bintanja, 1999). If an ice core from such a place has remained well below the melting point throughout its history, it should preserve a chemical signature of the past climate.

The paleoclimate has been earlier studied from the few deep ice cores drilled in Greenland and Antarctica. Drilling deep cores is an expensive method and often involves logistical problems. Contrarily, sampling ice from the surface of the blue ice areas relatively inexpensive and a simple way of collecting ancient ice for paleoclimatic studies. The temporal resolution of the paleoclimatic record obtained from the surface blue ice can also be much higher than in deep cores (Sinisalo and others, 2007).

Scharffenbergbotnen (Heimefrontfjella, 74°S, 11°W) is one of the best-studied blue ice areas in Antarctica from a glaciological point of view. Bedrock and surface DEMs are available (Herzfeld and Holmlund, 1990 and respectively Sinisalo and others, 2003) as well as measured surface velocity data and mass balance data from stake observations (Sinisalo and others, 2003). ^{14}C data are available from van Roijen (1996).

The principal problem in paleoclimatic interpretation of blue ice samples has been dating the ice, as it is much more problematic than that of deep cores. This problem can be solved with geophysical measurements, ice flow modeling and comparison of the chemical data with other data sets obtained from deep ice cores. However, no glacier model employing the full Stokes equations has been run in a free time-evolving prognostic simulation. Either time-stepping ice sheet models employing a reduced set of terms, or steady-state snap-shop diagnostic pictures of glaciers have been the only choices. Grinsted and others (2003) developed for example a volume conserving flow line model assuming steady state flow.

In the project outlined on this poster, we are applying a full three-dimensional thermo-mechanically coupled Stokes solver model to the Scharffenbergbotnen BIA. The software package used is Elmer, an open-source finite element package developed at the CSC in Finland (Zwinger and others 2007). A full-Stokes model is needed because of the deep but narrow valley geometry and because horizontal and vertical velocities are of same order of magnitude.

As a first step we are currently working on a diagnostic, present day simulation. This present-day steady-state solution will be used to explore how close to steady state the glacier really is. It'll be of course compared with surface velocity measurements as well as mass balance measurements.

Later, prognostic runs with changing climate variables and different scenarios regarding the coupling with the surrounding ice-sheet are foreseen. Finally, a 100m long ice core recovered in 2003 (Sinisalo and others, 2007) will be dated.

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InSAR glacier observation near Ny Ålesund - first results

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ABSTRACT

Field research in glacial and periglacial zones provides important insights, but encounters limitations in terms of accessibility, expenses and repeatability. Remote sensing techniques hence represent a valuable additional dimension for glacier monitoring: they allow for operating at global scales with uniform data sets and measuring methods, thus providing continuous and comparable series of measurements. Synthetic aperture radar (SAR) imagery delivers a wide range of information beyond the mere visible, also at night and through cloud cover. For example, inferences on and even below the glacier surface are possible, concerning roughness and melting conditions amongst others. In this study, scenes from spring 1996 by the tandem mission of the European Remote Sensing satellites ERS 1 and ERS 2 are used for SAR interferometry (InSAR). InSAR takes advantage of the coherence between the phases of two or more satellite passes flying on the same orbit for deriving information on elevation and movements. Glacier velocities can be derived from the fringe structures in an interferogram. This allows to look into the past of for example Comfortlessbreen, a currently surging glacier, to infer 1996 velocities for comparison with present day values. Flow dynamics of other glaciers near Ny Ålesund are also evidenced with respect to their possible surge type character.

Permafrost in vegetated scree slopes below the timberline – thermal properties and permafrost conditions characterized by geophysical measurements and geoelectrical monitoring

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ABSTRACT

Discontinuous alpine permafrost is expected to exist at altitudes above 2400m a.s.l. at mean annual air temperatures (MAAT) of less than -1°C. Below timberline only a few sites are known, where sporadic permafrost exists in vegetated talus slopes with positive MAAT. Aim of the study is to characterize permafrost-humus interaction, the thermal regime and its influence on temporal and spatial permafrost variability.

Results of geophysical measurements from three talus slopes, located in the Swiss Alps (Engadin, Appenzell) at elevations between 1200 and 1800m a.s.l. with MAAT between 2,8°C and 5,5°C are presented. Parent rock-material of the slopes are granite (Bever Valley, Engadin) and dolomite (Susauna Valley, Engadin; Brüeltobel, Appenzell).

Joint application of electrical resistivity tomography (ERT) and refraction seismic tomography (RST) is used to detect and characterize permafrost. Year-around geoelectrical monitoring is used to observe temporal variability of ice content and characteristics. A number of temperature data loggers were installed in different depth of the humus layer and in different positions of the slope.

Isolated permafrost has been detected by the combination of ERT and RST in the lower parts of the investigated talus slopes. Results from geophysical measurements and monitoring indicate a high spatial and temporal variability in ice content and ice characteristics (temperature, density, content of unfrozen water) for all sites. A distinct rise of resistivities between November and December indicates a decrease of unfrozen water content, caused by a pronounced cooling in the lower parts of the slope. Decreasing ice content and extent of the permafrost lenses can be observed in decreasing seismic velocities from 2600m/sec in spring to only 1500m/sec in October. Ice characteristics, ice content and extent of permafrost lenses in the investigated talus slopes depend on the thermal regime, induced by characteristics of surface (humus, vegetation) and subsurface (parental rock material) material as well as thermal effects inside the talus slopes, with an inversive air flow inside the talus slope of cold air inflow in winter in the lower parts of the slope and cold air outflow in summer through the same vents (chimney effect). While the dolomitic talus slopes are relatively homogenous concerning surface and subsurface material, showing a consistent thick humus cover, the granitic site shows a small-scale heterogeneity of different humus forms and thicknesses as well as size of granitic boulders, influencing the thermal regime. Temperatures in the humus profile are very constant for the dolomitic sites, reflecting the insulation capability of the humus cover, with temperatures in August around 3°C at 30cm depth (mean air temperature in August 12°C). Humus temperatures (30cm depth) in the Bever Valley vary strongly

between areas with consistent humus cover (1-2°C in August) and areas with coarse, uncovered boulders, where temperatures show a stronger coupling to air temperatures.

Bottom temperatures of the snow cover (BTS) are very low (-9°C) in the lower parts of the investigated talus slopes, reflecting high influence of air temperatures on the thermal regime. BTS temperatures in permafrost-free areas of the slopes fluctuate around -2°C.

The ground thermal regime and the existence of permafrost below the timberline is determined by topography (northern exposure), distribution and duration of the snow cover as well as surface (organic layer) and subsurface factors (talus material). A low income of solar radiation is of minor importance, as the permafrost occurrences are mostly situated in the sunniest parts of the investigated talus slopes. The low insulation capability of the snow cover in winter enables a pronounced cooling of the talus slopes. As the chimney effect seems to have strong influence on the ground thermal regime of the dolomitic sites, where vents are visible, both, in the lower and upper parts of the talus slope, the theory has to be expanded for some parts of the granitic slope of the Bever Valley towards a continuous air exchange with the atmosphere along large parts of the talus slope.

Tephra from subglacial Vatnajökull volcanoes records variable mantle plume melting

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ABSTRACT
The subglacial Vatnajökull volcanoes, Grímsvötn, Bárdarbunga and Kverkfjöll are characterised by explosive basaltic eruptions forming tephra of tholeiitic composition. Compositional variability of the tephra reflects magmatic evolution beneath the volcanoes revealed by in-situ major and trace element analyses of tephra layers covering the last ~7.6 ka. The tephra provenance can be inferred from major and trace element compositional constraints. Each tephra unit is assigned an age using soil accumulation rate between tephra marker layers of known age, previously dated by the ^{14}C method. This allows establishing compositional time-series for the three volcanoes over approximately the last eight millennia.

The subtle compositional variations with time are used to infer the structure of the magma plumbing system at depth. Magmatic evolution is controlled by crystal fractionation and crustal contamination. Covariations of Ba, Nb and Th concentrations show that only the least evolved basalts from Grímsvötn (termed G-I; Th <0.9 ppm) and the most primitive Bárdarbunga basalts are consistent with fractional crystallisation alone. More evolved Grímsvötn basalts (G-II; Th >0.9 ppm), Bárdarbunga and Kverkfjöll all form linear arrays which extrapolations intercept at a single value suggesting a common contaminant of evolved basaltic composition with Th and Ba concentrations close to 2.5 ppm and 130 ppm, respectively. Close inspection of variations of highly compatible versus the most incompatible element concentrations, together with incompatible element ratios, and multi-element spectra, suggest similar source mineralogy beneath the three volcanoes. Lower La/Yb with increasing La concentration thus reflect augmenting magma source melting at depth: Bárdarbunga above the assumed centre of the Iceland mantle plume produces basalts formed by highest degree of melting whereas the smallest melting is recorded in the Kverkfjöll basalts erupted at the periphery of the assumed plume centre, which volcano also has the lowest eruption frequency during the Holocene.

Climate oscillations and Holocene surge-history of Eyjabakkajökull inferred from varved lake sediments on eastern Iceland

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We have studied the properties of varved sediments from Lake Lögurinn on eastern Iceland (Fig. 1) and their link to climate and glacial processes of Eyjabakkajökull, which is a surging outlet glacier of the Vatnajökull ice cap. A varve chronology covering the time period AD 1262-2005 was constructed from visual observations, high-resolution images, X-ray density and geochemical properties determined from XRF scanning. Independent dating by ^{137}Cs analysis and eight historical tephras verify the varve chronology. The thickness of dark-coloured seasonal laminae, mainly formed by coarser suspended matter from the non-glacial river Grímsá, is positively correlated to winter precipitation and our 743 year long varve series indicate that precipitation was highest and most variable during the 17th to 19th century.

The thickness of the light-coloured laminae is mainly controlled by the amount of glacial rock flour transported from the glacier. During the 1972 surge of Eyjabakkajökull the amount of suspended matter in Jökulsá í Fljótsdal increased significantly. The surge was followed by years of recurring drainages of Lake Háöldulón, an ice-dammed lake that was formed shortly after the surge. As a result, the amount of glacial rock flour transported to Lake Lögurinn was higher than usual as long as Lake Háöldulón continued to drain (i.e. as long as the ice front was in an advanced position enough to dam the lake). This increase in glacially derived rock flour is reflected in the sediments, as the varve that was formed in 1972 constitutes the thickest light-coloured laminae deposited during the 20th century, which is followed by the second thickest light-coloured laminae, deposited in 1973 (Fig. 2). From there on, the thicknesses of the light-coloured laminae gradually fade out. Based on these modern observations, we can conclude that the recurring cyclic pattern of light-coloured clay dominated laminae sections in the sediment sequence (Fig. 3) is related to past surges of Eyjabakkajökull, followed by drainages of Lake Háöldulón. Recurring cycles of light-coloured clay dominated laminae began to develop close to the H3 and H4 tephras, which also coincides with the time when the varves became more distinct. Further down in the sequence, which covers at least the past 10 300 years, the recurring cycles of light-coloured laminae are not found and any glacial type of varves are in general missing. Based on this and the large-scale morphology of the drainage area, we therefore propose that Eyjabakkajökull, and thus parts of, or the whole Vatnajökull ice cap, were considerably smaller or perhaps absent during the early to mid-Holocene.

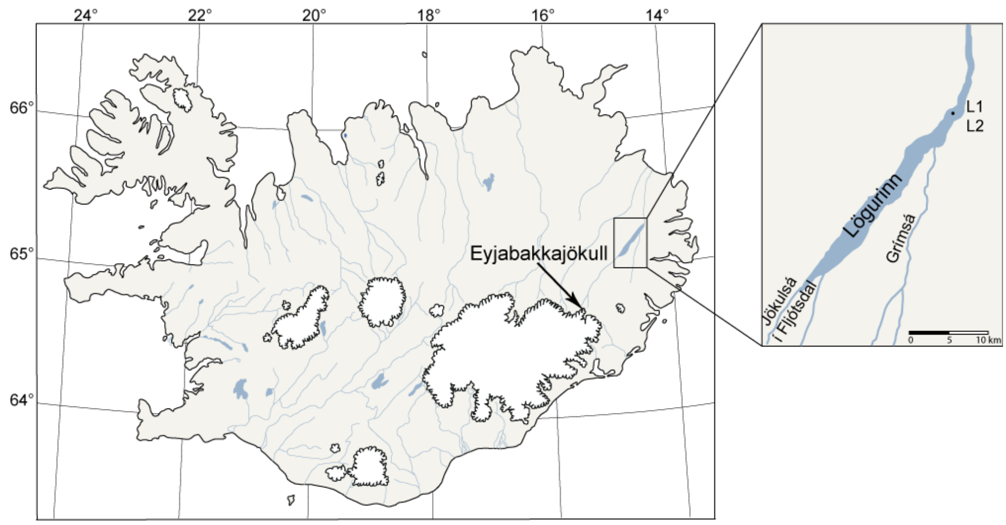

Figure 1 Location map showing the research area in eastern Iceland. Right panel shows a close up of Lake Lögurinn and the main rivers that enter the lake. The coring sites are labelled L1 and L2

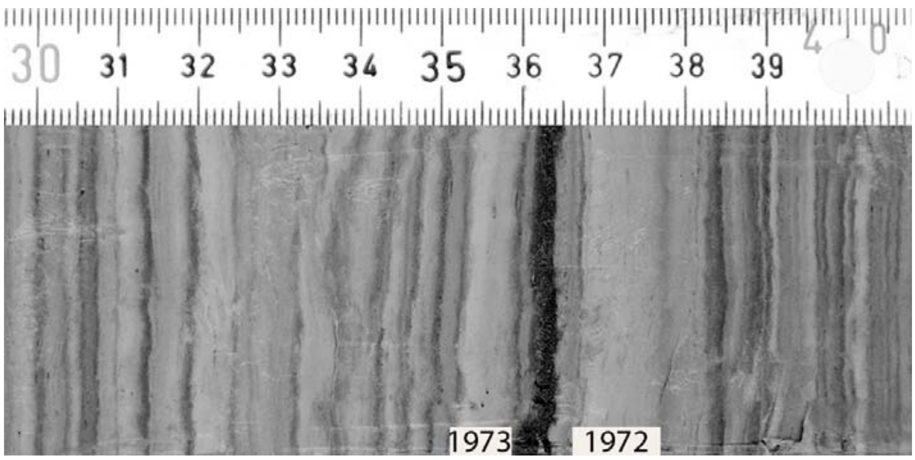

Figure 2 Close-up of the varve that was formed in 1972, which constitutes the thickest light-coloured laminae deposited during the 20th century. This is followed by the second thickest light-coloured laminae, deposited in 1973.

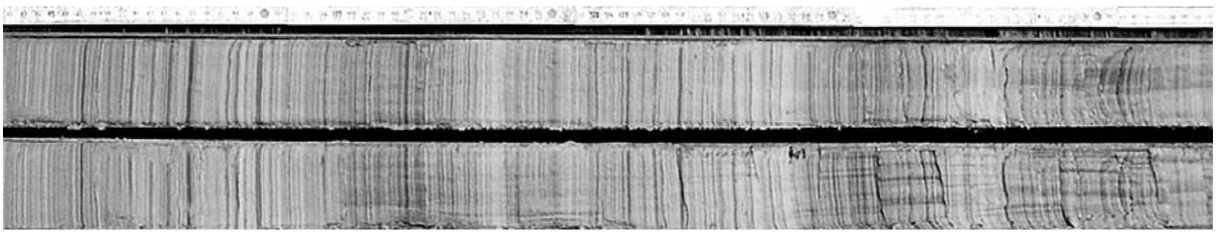

Figure 3 A 90 cm section of the sediment sequence demonstrating the recurring pattern of light-coloured clay dominated laminae sections related to past surges of Eyjabakkajökull, followed by drainages of Lake Háöldulón.

Numerical Simulation of the Failure of Sea Ice Cover

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ABSTRACT

Determination of sea ice loads on ships or offshore structures is an important problem in ice engineering. Ice forces acting on a structure are due to relative movement between the structure and ice, and the sequential failure process of the ice feature. In other words, the ice load on an engineering offshore structure depends on the deformation and failure process of sea ice. Typical sea ice features are sheets of level ice, ridges and rubble fields. Both ridges and rubble fields are piles of ice blocks, but ridges have an elongated form. A central hypothesis in traditional solid mechanics states that a body under consideration is continuous and remains continuous under the action of external forces. However, as several ice features and ice failure processes are discontinuous in nature, the traditional continuum description may not be the most appropriate, and a discontinuum approach should be used instead. As an example, when a floating sea ice sheet is driven by winds and currents against an offshore structure or a coast line, the originally intact ice sheet breaks into a myriad of discrete ice blocks. These ice blocks accumulate into a pile and affect the failure process, as in a later stage of the process, the intact ice sheet fails against the pile and not against the structure of coast line. As another example, when an offshore structure, e.g. a lighthouse, indents an ice ridge, the load on the structure is due to rearrangement of the discrete ice blocks in the ridge, in addition to possible failure of the ice blocks. The discrete element method (DEM) is a numerical tool used to simulate a system of particles and is well suited to simulation of problems in ice mechanics. DEM is based on the concept that individual material elements are considered to be separate and, if connected, are connected along their boundaries by appropriate interaction laws. An important aspect of the discrete element method is that the particles may fracture and fragment, thus increasing the total number of bodies during a simulation. In a discrete element simulation, the interaction and behaviour of individual particles will result into emergent physical properties of the particle assembly. This paper gives a review of a group of sea ice problems and their numerical analysis with DEM by the sea ice research group at the Department of Applied Mechanics of the Helsinki University of Technology.

Solute reactions of nitrogen in firn and glacier ice

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ABSTRACT
The growth in human development and the consequently increased requirement for food and energy have caused an elevation in the amount of reactive nitrogen delivered into the natural environment. This reactive nitrogen can alter atmosphere, cryosphere, hydrosphere, and marine and terrestrial ecosystems in a way that some authors had described as a "nitrogen cascade" affecting each system in different ways. Ice core data show about twofold increase in nitrogen deposition in Greenland sites during the last 100 years and in Svalbard since mid-20th century. Nitrate is produced by nitrogen oxides (NOx) oxidation and can be used to investigate NOx variations in the past by means of nitrate ice core measurements, but this proxy has been difficult to develop since nitrate in snow has several sources and undergoes post-depositional processes. Nitrate stable isotopes, $\delta^{15}N(NO_3^-)$ and $\delta^{18}O(NO_3^-)$, will be used to understand its behavior in the snowpack, considering different post-depositional processes (e.g. diffusion, percolation, chemical interaction). Field and laboratory experiments will be set-up to estimate nitrate behavior in natural snow after irradiation of UV and IR light *in situ* and inside an environmental chamber. These results will be use to interpret nitrate concentrations in Svalbard ice cores.

1. INTRODUCTION

The increasing input of reactive nitrogen (Nr) as a consequence of agriculture, industry and the use of fossil fuels has resulted in an increase of the atmospheric Nr load. This Nr can alter atmosphere, cryosphere, hydrosphere, and marine and terrestrial ecosystems in a way that some authors had described as a "nitrogen cascade" (Galloway and others, 2003). In this frame the project "Sources, sinks and impacts of atmospheric nitrogen deposition in the Arctic" (NSINK) has been development as a part of a Marie Curie Initial Training Network (ITN). The NSINK scope is to estimate the nitrogen fluxes in the High Arctic connecting different scientific views as hydrology, biogeochemistry, aquatic and terrestrial ecology, atmospheric sciences and snow physics by research centers located in UK, Norway, Sweden, Austria and Germany. The research activities of the NSINK network are based around Ny-Ålesund, Svalbard, where the infrastructure allows local or more remote research activities within this part of the European High Arctic. The main scientific objectives of NSINK are to establish the climatology and dynamics of the input of atmospheric nitrogen to the Arctic at different temporal scales; to obtain mass balance models of the biochemical reactive nitrogen cycling in snow, ice and reservoir ecosystems; to study nitrogen dynamics and fluxes that link the storages mentioned before; to evaluate the ecosystem response to enhanced atmospheric nitrogen conditions; and to produce models capable of predicting ecosystem response to changing climate, warming and nitrogen enrichment. The NSINK group will study the tropospheric and stratospheric input and chemistry of nitrogen, the mass balance and nitrogen species accumulating in the ground surface by wet and dry deposition, and the fate of nitrogen in the snowpack following the polar sunrise and melting season.

Airborne nitrogen species can easily be transported on medium and large spatial scales (Holland and others, 1999) and the increase in the long range aerial transport of Nr from low to high latitudes has generated an accumulation in the Arctic. For its remote and relative pristine location, the Arctic has very fragile nitrogen limited ecosystems that can be altered by even small increases of dry or wet depositions of Nr. Chemical analyses of ice cores have shown a twofold increase in nitrogen deposition in Greenland sites during the last 100 years (Laj and others, 1992) and in Svalbard since the mid-20th century (Goto-Azuma and Koerner, 2001; Kekonen and others, 2002). Nitrate is one of the major ions found in snow and is the final product of nitrogen oxides (NOx) oxidation. Several authors have used ice core nitrate interpretations to investigate NOx variations in the past but this proxy has been difficult to develop since nitrate in snow has several sources and since it experiences post-depositional processes (Kekonen and others, 2002; Röthlisberger and others, 2002; Hastings and others, 2004; Hastings and others, 2009). Various studies have been made in order to trace the NOx sources and fate pathways in the Arctic atmosphere (Jarvis and others, 2008; Morin and others, 2008) and learn about the processes occurring in the snowpack involving NOx-NO_3-NO_2- transformations (Honrath and others, 2000; Beine and others 2002). To estimate NO_3^- fluxes in the snow it is necessary to obtain individual pathways budgets, which can be done using isotopic ratios of nitrogen $\delta^{15}N(NO_3^-)$ and oxygen $\delta^{18}O(NO_3^-)$ conforming the NO_3^- molecule. $\delta^{15}N(NO_3^-)$ measurements could be used to identify NOx sources, since this ratio does not change significantly during NOx oxidation (Moore, 1977); $\delta^{18}O(NO_3^-)$ determinations reflect the oxidative path to form nitrate since a strong print of O_3 is transferred to its oxidations products (Michalski and others, 2003), making it possible to determinate the seasonal variability in nitrate production, owing to the different oxidative pathways dominating between winter and summer seasons (Morin and others, 2008). In order to have a better understanding of ice core nitrate it is possible to use nitrate isotopes to infer NOx chemistry and also the implications of post-depositional processes (e.g. nitrate photolysis in the snowpack; diffusion; chemical interaction within snow and ice; percolation; and gaseous nitric acid relocation) for snowpack nitrate.

Ice core interpretation will depend on local conditions such as temperature and accumulation rate, which affect the chemical concentrations in the firn (Beine and others, 2002; Hastings and others, 2004) for this reason is convenient to compare nitrate load in different drilling sites in the Arctic.

The aims of this work are to obtain a high-resolution record of water soluble ion chemistry (major ions) from ice cores from Svalbard, that would reflect past climatic and environmental changes; to study the behavior of NO_3^- in alkaline and acid snow layers; to evaluate the effect of percolation on nitrate concentrations in the ice cores by means of field data interpretation (snowpits and shallow cores nitrate concentrations) and laboratory and field experiments; have a closer view of the reactive nitrogen cycle and the oxidative capacity of the atmosphere in the High Arctic, by the combined measurements of nitrogen and oxygen stable isotope ratios of nitrate present in firn and ice samples, constraining the relationship between ice core nitrate and atmospheric NOx; to establish the seasonal variations in $\delta^{15}N(NO_3^-)$ which would reflect the sources of NOx present in the site; and to establish the seasonal variations in $\delta^{18}O(NO_3^-)$ which would reflect variations in oxidation pathways preceding the nitrate formation.

Reanalysis of the data available (snowpits and ice cores) from different Svalbard sites (sources: Norwegian Polar Institute (NPI), Uppsala University, the National Institute of Polar Research (NIPR), Japan) will be also done. This involves statistics, correlations, and eventual trends in nitrogen concentrations. A complete analysis of the data set would be done with emphasis in the chemical and physical processes linked with nitrogen relocation (e.g. melt layers, acid and alkaline layers) and spatial distribution of chemical species in Svalbard. Statistical tools such as Principal Component Analysis (PCA) will be employed to evaluate the correlation between different ionic species and different variables as water stable isotopes, physical properties of the ice or anthropogenic input of pollutants (pre- and post-industrial conditions).

The spatial and temporal variation in nitrogen fluxes will be presented in this work using ice core data available for northern Svalbard provided by the Japanese Arctic Glaciological Expedition between 1987-1999 with collaboration from the Norwegian Polar Institute, and from the Dutch-Norwegian-British-Swedish-Finnish expedition to Lomonosovfonna, Svalbard in 1997 (Isaksson et al., 2001); also airborne nitrate concentrations from Zeppelin station available since 1976 will be compared.

2. METHODS

2.1 Study site and sampling: Sampling was done in the 2009 fieldwork in the Lomonosovfonna ice cap, Svalbard, lead by the Norwegian Polar Institute and Paul Scherrer Institut at (78˚51’53’’N, 17˚25’30’’E) and an elevation of 1250 m a.s.l. during March-April. The samples were taken in accordance with the ITASE (International Trans-Antarctic Scientific Expedition) protocol (Twicker and Whitlow, 1997). The snowpits were dug upwind of the drilling tent, with a maximum depth of 150 cm where icy layers were visually located. The samples were taken in parallel in 60 ml HD-PE. Amber bottles were used to collect the samples for nitrate stable isotopes to prevent photolysis. Snow samples from pit S1 were taken discontinuously each 10 cm down to a depth of 110 cm by pushing clean plastic bottles into the side wall of the pit. In the presence of ice layers a clean plastic scraper was used to cut the samples and those were collected in PE clean bags. Pit S2 was sampled continuously each 8.5 cm placing the bottles vertically until 85 cm deep using only white bottles without double sampling. Pit S3 and S4 were double sampled continuously each 10 cm down to a depth of 150 cm. Density measurements were made in pit S3 using metal tubes of known volume. Falling snow samples were taken in two days of precipitation. Surface snow samples were collected near to pit S4 (at 10:00, 14:00, 18:00 and 22:00 h, local time). Samples were transported and stored until analyses.

2.2 Analyses: Major ions will be measured by ion chromatography. With this method it is possible to quantify ions as K^+, Na^+, NH_4^+, Ca^{+2}, Mg^{+2}, Cl^-, NO_3^-, SO_4^{-2}, $HCOO^-$, CH_3COO^- and $CH_3SO_3^-$ (MSA-). The samples will be measured in the Sediment-Solute Systems Laboratory, Sheffield University, UK using a Dionex ion chromatograph. An isotope ratio mass spectrometer (IR-MS) located at the Institute of Geology at Tallinn Technical University, Estonia, will be employed to measure water $\delta^{18}O$ and δD. For $\delta^{15}N(NO_3^-)$ and $\delta^{18}O(NO_3^-)$ analysis the denitrifier method (Sigman and others, 2001) will be used. This technique requires an amount of about 10 nmol of nitrogen, between 10-16 ml of melt water per sample according to mean nitrate concentrations in an ice core from Lomonosovfonna (Kekonen and others, 2002). This method utilizes denitrifying bacteria that transform nitrate into nitrous oxide (N_2O), which could be measured in a IR-MS to determine $\delta^{15}N(NO_3^-)$ and $\delta^{18}O(NO_3^-)$ ratios with standard deviations of about 0.2‰ and 0.4‰, respectively (Hastings and others, 2004). Two varieties of bacteria are usually used: *Pseudomonas chlororaphis* and *Pseudomonas aureofaciens* (Casciotti and others, 2002; Hastings and others, 2004). Using *P. aureofaciens* the exchange of oxygen atoms with water during the conversion of NO_3^- to N_2O occurs at very low levels, frequently less than 3% of the oxygen atoms in the N_2O product but is significant using *P. chlororaphis* (Casciotti and others, 2002). The oxygen present in N_2O obtained using *P. aureofaciens* represents the oxygen in the nitrate sample while oxygen in N_2O produced by *P. chlororaphis* is derived from (mass-dependent) water (Casciotti and others, 2002). The samples obtained in Lomonosovfonna (ice and snow samples) will be analyzed for $\delta^{15}N(NO_3^-)$ and $\delta^{18}O(NO_3^-)$ at the NERC Isotope Geosciences Laboratory (NIGL), UK.

2.3 Laboratory and field experiments: Part of the scope of this work is design experiments to understand what happens with nitrate in the snowpack after melting events. To answer this question two types of experiments will be set-up: field experiments to estimate the effects of photolysis and snow melting *in situ* and laboratory experiments. A set of experiments on natural snow will be set-up in different sites at northern Sweden-Norway and Svalbard to evaluate the changes on nitrate contain across the day (spring-summer) and during the polar night. A set of dark experiment should be developed to separate photolysis effects from melting processes. To reach this goal, natural snow will be irradiated (during the polar night) with two types of light: UV (290-400 nm) to induce photolysis over the snowpack, and IR light to produce melting. Shallow snowpits will be dug to collect snow samples before each experiment and one section of these pits will be then irradiated and sampled. Physical and chemical properties of snow will be measured in the snowpits. Laboratory experiments consist mainly in HNO_3 uptake over natural snow. The main idea of these experiments is set-up a system in which gaseous HNO_3 saturates the atmosphere inside an environmental chamber. Different series of experiments will be set-up changing variables as light (UV, IR and dark conditions), time, p-HNO3 and melting rate of snow, to estimate the effects of nitrate photolysis and percolation in the HNO_3 present in the snowpack. Nitrate concentrations and isotopes will be measured before and after each experiment.

ACKNOWLEDGEMENT

This work is supported by the project: Sources, sinks and impacts of atmospheric nitrogen deposition in the Arctic (NSINK). We thank Elisabeth Isaksson, Mats Björkman, the Norwegian Polar Institute logistics, Margit Schwikowski from Paul Scherrer Institute, Bern and all the field participants in the Lomonosovfonna 2009 field campaign.

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The mass balance record from Hofsjökull, Central Iceland, 1988-2008

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ABSTRACT

Hofsjökull is the third largest ice cap in Iceland, located in the central highlands at altitudes between 600 m and 1790 m and delivering meltwater to several large rivers. According to latest estimates the present area of the ice cap is about 880 km^2, the mean thickness is 225 m and the total volume is 200 km^3. Mass balance studies have been carried out on Hofsjökull since 1988 and the positions of outlet glacier margins have been recorded since the 1930's. Large areas of the ice cap are inaccessible due to crevasse fields and mass balance studies have thus been confined to three transects on catchment areas that in total comprise about 40% of the ice-cap area. Fig. 1 shows the locations of mass balance measurement sites on Hofsjökull and Fig. 2 shows the specific annual mass balance for the northern Sátujökull basin in the period 1988-2008 and the retreat of the ice margin since 1984 at the location indicated by a (*) in Fig. 1.

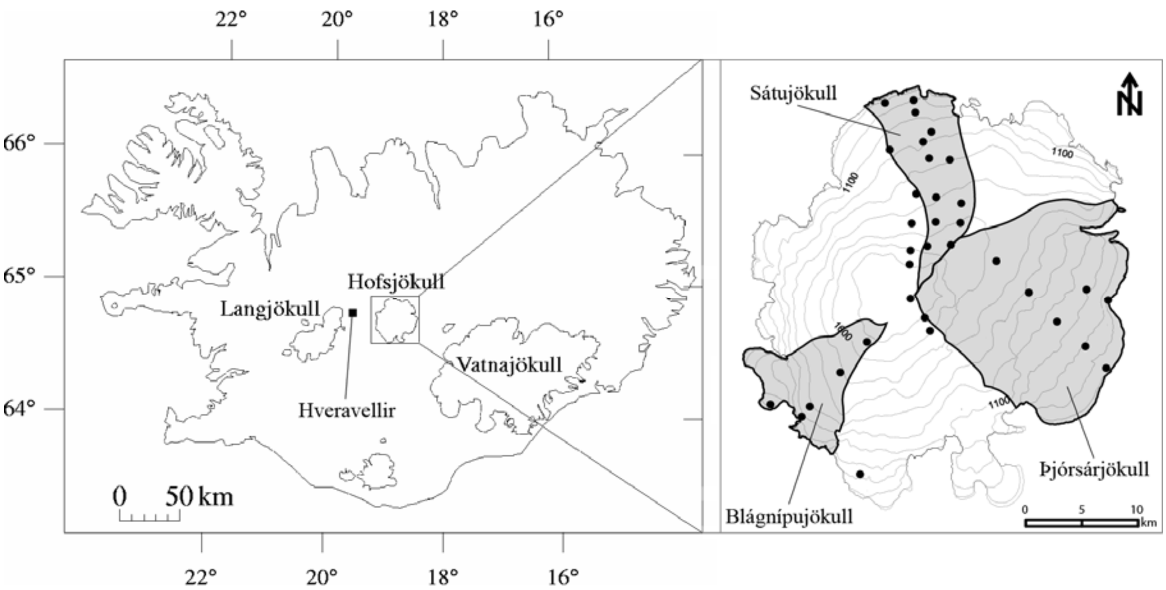


Figure 1 Location of Hofsjökull in Central Iceland (left) and a surface elevation map of the ice cap (right). The shaded areas outline the glaciers Sátujökull, Þjórsárjökull and Blágnípujökull for which mass balance data are reported. Dots mark mass balance stake locations.

As is evident from Fig. 2, the mass balance of Sátujökull has been negative every year since the start of measurements, except for the years 1989 and 1992-1994. The ice margin has receded by 670 m in the interval 1984-2008. Similar results have been obtained for the other basins and their marginal positions. Data on mean annual mass balance and volume change for the 20-year period 1989-2008 are summarized in Table 1 and Fig. 3 shows the measured mass balance data from the SE-transect, Þjórsárjökull, in the glacial year 2007/08.

The Þjórsárjökull transect spans nearly the entire elevation range of the Hofsjökull ice cap as a whole, and as seen in Fig. 3 the winter balance, now typically measured for the period Oct. 1 to April 30, was positive at all elevations during the last glacial year. The lowest measured winter balance was 0.85 m w. eq., the maximum was 3.30 m w. eq. and the precipitation gradient with elevation during this glacial year was 230 mm/100 m. The minimum summer balance was -7.4 m w. eq. but positive summer balances were recorded at the highest elevations, with a maximum of 1.1 m w. eq. at the summit (1790 m). The averaged curve for annual net balance indicates that the equilibrium line altitude was 1200 m at the end of the glacial year 2007/2008.

Fig. 4 shows the variation in the equilibrium line altitude (ELA) in the three basins. The high value in 1991, which is most prominent on Sátujökull, is due to unusually high summer melt rates caused by solar heating of volcanic ash deposited during the midwinter Hekla eruption.

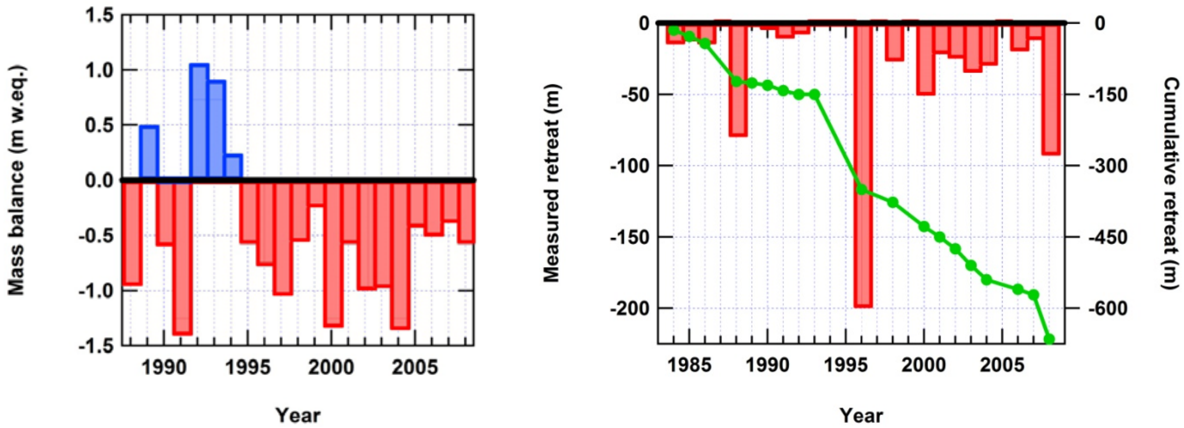


Figure 2 Left: Net annual mass balance of the 80 km^2 Sátujökull basin in the period 1987/88 to 2007/08. Right: Measured retreat of the Sátujökull margin since 1984. Note that retreat has not been measured every year, leading to larger recorded values in the subsequent year (cf. the peaks in 1988 and 1996). The green curve shows the cumulative retreat since 1984 (vertical axis on the right).

Hofsjökull basin	Net mass balance 2007-2008	Mean annual net mass balance 1989-2008*	Cumulative volume change 1989-2008*
Sátujökull (80 km^2)	– 0.58 m w. eq.	– 0.51 m w. eq.	– 0.92 km^3
Þjórsárjökull (230 km^2)	– 0.79 m w. eq.	– 0.56 m w. eq.	– 2.58 km^3
Blágnípujökull (50 km^2)	– 0.93 m w. eq.	– 0.45 m w. eq.	– 0.46 km^3

* 1988-2007 for Sátujökull

Table 1 Mass balance results for the Hofsjökull basins and cumulative mass loss from the start of measurements.

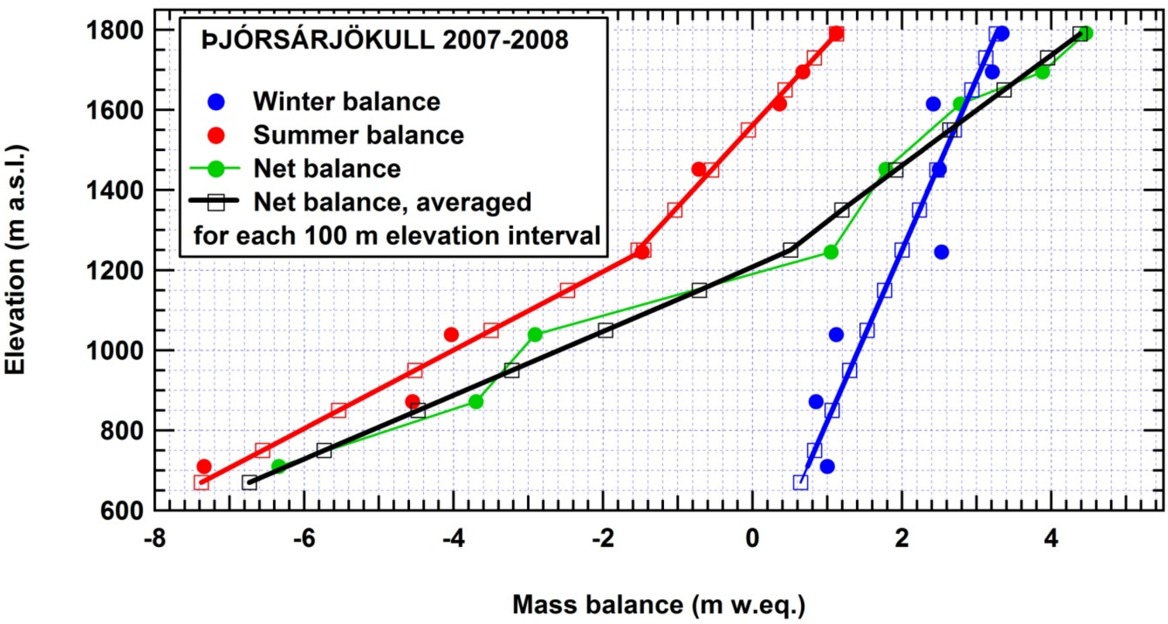
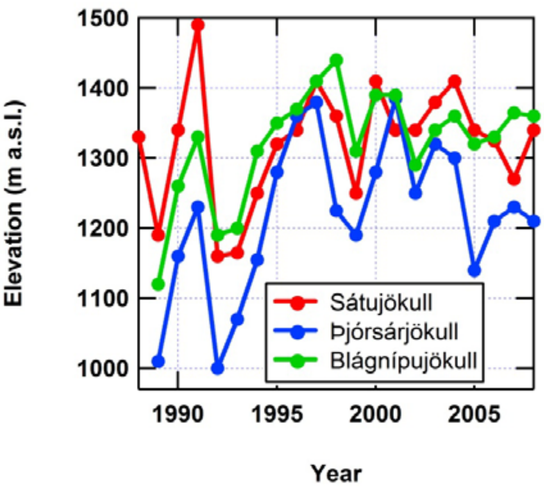


Figure 3 Winter, summer, and net annual mass balance of the 230 km^2 Þjórsárjökull basin in the glacial year 2007-2008. Shown are both results from stake-location measurements (filled circles) and averaged values for each 100 m elevation interval (open rectangles).



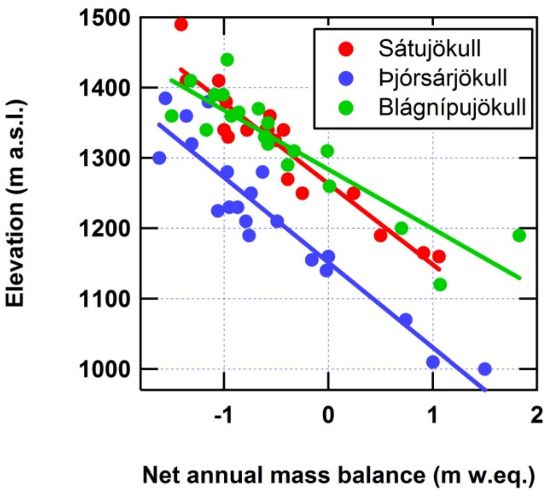


Figure 4 Left: ELA-variations on the N-, SE- and SW-transects of Hofsjökull 1989-2008 (since 1988 for Sátujökull). Right: ELA values versus net annual mass balance for each of the three basins.

Lowest ELA values are obtained for Þjórsárjökull, which probably reflects higher winter accumulation in the SE-part of the ice cap than on the N and SW-transects. Notable is a decrease in the Þjórsárjökull ELA since 2000, whereas ELA values in the other basins are more stable during this period. The variation of ELA with net annual mass balance is also shown in Fig. 4. We note that the ELA on each transect has fluctuated by 300-400 m during the period of measurements, and a net mass balance change of 1 m/yr leads to an ELA variation of 115 m for Sátujökull, 120 m for Þjórsárjökull and 85 m for Blágnípujökull. These values are lower than the average result for Vatnajökull, where a 140 m ELA change for a 1 m/yr mass balance change has been obtained.

The total mass loss from the three basins (Table 1) in the period 1989-2008 is approximately 4 km^3. Assuming that the three transects yield data representative for the ice cap as a whole, a total mass loss of roughly 10 km^3 may be estimated for Hofsjökull during this period, i.e. 5% of the volume of the ice cap.

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