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Abstracts

Migrating supraglacial lakes along the western boundary of the George VI Ice Shelf, Antarctica

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The King George VI Ice Shelf stands apart from others because it is capable of supporting large areas of supraglacial meltwater ponding without suffering the consequences of a Larsen B style disintegration. The ice shelf remains stable despite these ponds because of the unusual flow regime, directed from the peninsula transversely into a narrow fjord. Several morphological classes of supraglacial lakes are identified in time-lapse Landsat imagery, including a unique family of en echelon, pear-shaped lakes (described by early British expeditions to the area) along the strongly compressive boundary of the ice shelf with Alexander Island. This family of lakes is unique because they migrate along the boundary with time at a rate that differs from ice flow. Here, we document this migration using Landsat imagery, and present an analysis of proposed processes which control the unique morphology and migration of these lakes. This work is in progress and represents the summer research activity of an undergraduate research intern, Ms. Claire LaBarbera, and others at the University of Chicago.

Seiche band gaps in ice-filled fjords

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We compute the eigenmodes (seiches) of the barotropic and baroclinic hydrodynamic equations for an idealized fjord having length and depth scales similar to those of Ilulissat Icefjord into which Jakobshavn Isbræ (also known as *Sermeq Kujalleq*) discharges. The purpose of the computation is to determine the fjord's seiche behavior when forced by iceberg calving, capsize and mélange movement. Poorly constrained bathymetry and stratification details are an acknowledged obstacle. We are nevertheless able to make general statements about the spectrum of external and internal seiches using numerical simulations of ideal 1-dimensional channel geometry. Of particular significance in our computation is the role of weakly coupled ice mélange, which we idealize as a simple array of 20 icebergs of uniform dimensions equally spaced within the fjord. We find that the presence of these icebergs acts to both (a) slow down the propagation of both external and internal seiches, and (b) introduce band gaps where energy propagation (group velocity) vanishes. If energy is introduced into the fjord within the period range covered by a band gap, it will remain trapped as an evanescent oscillatory mode near its source, thus contributing to localized energy dissipation and ice-mélange fragmentation.

Refreezing on the Greenland ice sheet: a comparison of parameterizations

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Retention and refreezing of meltwater are acknowledged to be important processes for the mass budget of polar glaciers and ice sheets. Several parameterizations of these processes exist for use in energy and mass balance models. Due to a lack of direct observations, validation of these parameterizations is difficult. In this study we compare a set of 6 refreezing parameterizations against output of the Regional Atmospheric Climate Model (RACMO2), applied to the Greenland ice sheet. In RACMO2, refreezing is explicitly calculated in a snow model that calculates vertical profiles of temperature, density and liquid water content. For consistency, the parameterizations are forced with output of RACMO2. For the ice sheet-averaged amount of refreezing and its interannual variations, all parameterizations give similar results, especially after some tuning. However, the spatial distributions differ significantly. Results are especially sensitive to the (arbitrary) choice of the depth of thermally active layer, which determines the cold content of the snow in most parameterizations.

A spatially distributed assessment of the climatic mass balance of Vestfonna ice cap (Svalbard) in the period 2000-2009

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The ice cap Vestfonna in the northern Svalbard archipelago is one of the largest ice bodies of the European Arctic (~2400 km²), but little is known about its mass balance. We model the climatic mass balance of the ice cap for the period September 2000 to August 2009 on a daily basis. Ablation is calculated by a spatially distributed temperature-radiation-index melt model. Air temperature forcing is provided by ERA-Interim data that is downscaled using data from an automatic weather station operated on the ice cap. Spatially distributed net shortwave radiation fluxes are obtained from standard trigonometric techniques combined with MODIS based cloud cover and surface albedo information. Accumulation is derived from ERA-Interim precipitation data that are bias-corrected and spatially distributed as a function of elevation. Refreezing is incorporated using the P_{max} approach. Results indicate that mass-balance years are characterized by short ablation seasons (June to August) and correspondingly longer accumulation periods (September to May). The modeled, annual climatic mass-balance rate shows an almost balanced mean of -0.02±0.20 m w.e. a^{-1} with an associated equilibrium line altitude of 383±54 m a.s.l. (mean ± one standard deviation). The mean winter balance is +0.32±0.06 m w.e. a^{-1}, and the mean summer balance -0.35±0.17 m w.e. a^{-1}. Roughly one fourth of total surface ablation is retained by refreezing indicating that refreezing is an important component of the mass budget of Vestfonna.

Changes in maximum annual snow depths in Norway in 1961-2010

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In the mountainous Norway, approximately one third of the annual precipitation falls as snow. Consequently, good knowledge of the snow cover is an important factor in e.g. hydropower production planning and flood forecasting. In the past decades both increasing winter temperatures and precipitation has been observed in most parts of Norway. Depending on the region and elevation, this may have lead to both increase and decrease in the seasonal snow accumulation. In the present study we analyze long term trends in annual maximum snow depth in Norway for four different 30- or 50-year periods in 1961-2010 by combining annual observations of snow depth and water equivalent taken by the hydropower companies (data managed at the Norwegian Water Resources and Energy Directorate (NVE)), and daily snow depth observations from the Norwegian Meteorological institute (met.no) station network. 926 time series are analysed in our study, covering a broad elevation profile from the sea level to the higher mountain regions (>1700 masl). The analyzed dataset is the most extensive and geographically representative for the country so far, and the analysis gives an up-to-date picture of the recent development in snow accumulation. The main aims of our study are to assess recent trends in the annual maximum snow depth, to explain the geographical distribution of trends, and to project the sensitivity of further increase or decrease in snow accumulation to change in climatic characteristics.

Our results show that in regions characterized by colder winter climate long-term trends are found to be positive in general, while short-term trends shift from strongly positive in the first period to predominantly negative in the last period. Variation in snow depth is here mainly linked to variation in precipitation. In regions of warmer winter climate variation in snow depth is dominated by temperature, and long-term trends are mainly negative. Short-term trends start out weak overall in the first period but become strongly negative most places in the last period. It is likely that, although more and more regions in Norway will experience declining maximum annual snow depth in a projected wetter and warmer future climate, some inland and higher mountain regions may still accumulate more snow in the coming decades.

Local High Resolution Wind Simulation over Blue Ice Areas at Dronning Maud Land, EAAIS

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Blue ice areas (BIAs) are snow-free ablation zones mostly occurring in slow ice-flow, near coastal valleys of the Antarctic Ice Sheet (AAIS). BIAs are known to show an amazing stability with respect to the snow-ice boundary, which provides some evidence that repeating meteorological conditions have to play a role in clearing their surface. In this paper we investigate the impact of local winds on the BIA locations inside the valley of Scharffenbergbotnen (74.56 deg S, 11.05 deg W), Dronning Maud Land, East Antarctic ice sheet (EAAIS).

The model uses the newly introduced Variational Multi-Scale (VMS) method for computing the turbulent flow within our domain. The method is implemented within the Finite Element (FEM) code Elmer. The size of the problem implied the utilization of High Performance Computing (HPC) on a parallel Linux cluster.

We investigate the impact of a representative wind field obtained from averaging ECMWF ERA Interim data in the vicinity of Scharffenbergbotnen. As this dataset does not account for katabatic winds, we further introduced an additional assumed near surface wind profile that should resemble approaching katabatic wind fronts. The simulations of maximum wind speed correspond closely with the observed patterns of snow and bare ice. An inadvertent field experiment was performed when a tent full of equipment initially located near the maximum wind speed location was redistributed by an intense wind storm over the model domain. Almost all items were later recovered from the low velocity areas spread over several km. Results give clear indication that the local near surface high wind profiles are focused and accelerated towards the location of the BIAs, providing strong evidence that BIAs owe their existence partly to local wind field distributions.

A Digital Glacier Database for Svalbard

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The archipelago of Svalbard contains approximately 35,000 km^2 of glaciers, with a large number of small valley glaciers as well as large areas of contiguous ice fields and ice caps. While a first glacier inventory was compiled in 1993, there has not been a readily available digital version. Here we present a new digital glacier database, which will be available through the GLIMS project. Glacier outlines have been created for the years 1936, 1966-71, 1990, and 2007/8. For most glaciers, outlines are available from more than one of these years, a complete coverage of Svalbard, however, is not yet available for a single time epoch. Except for the 2007/8 data, glacier outlines were created using cartographic data from the original Norwegian Polar Institute topographic map series of Svalbard as basis by delineating individual glaciers and ice streams, assigning unique identification codes relating to the hydrological watersheds, digitizing center-lines, and providing a number of attributes for each glacier mask. The 2007/8 glacier outlines are derived from orthorectified satellite images acquired from the SPOT-5 and ASTER satellite-borne sensors.

We also present shortly two further glacier products under development giving glacier surface type and glacier mass balance over time.
See also http://www.cryoclim.net/cryoclim/index.php/Svalbard_glacier_products for more information

Supra-glacial lake evolution and variations on the Greenland Ice Sheet

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Supra-glacial lakes form every year in the ablation zone of the Greenland ice sheet. Inherently related to basal water conditions, surface lakes on the Greenland ice sheet provide temporary storage for meltwater that influences both the surface and basal water fluxes. Thus, to understand the effects of climate on ice sheet dynamics it is necessary to understand the surface hydrology. We have investigated the initiation, evolution, disappearance and location of these lakes on the Greenland ice sheet to obtain better understanding for the spatio-temporal variations in lake distribution.

Moderate Resolution Imaging Spectroradiometer (MODIS) images from 2007 and 2008 where used to investigate the amount of energy needed to initiate the lakes and also the processes behind the disappearance of the lakes. The lakes in each image were linked together in such a way that the lake evolution could be followed. Lakes where then divided into transient lakes (available only in one image) and sustained lakes (available in multiple images). Following from this we developed a dynamic method for supra-glacial mapping in multispectral satellite imagery. Using a multi-resolution segmentation followed by an object-oriented classification covering the melt seasons from 2002 until 2010 on roughly a 5-day interval basis. With improved knowledge of the size, presence and evolution of such lakes as well as the energy needed to initiate them we can further relate the lakes to the current climate and also make assumptions on the whereabouts of the lakes with a changing climate.

New data collection and analysis of aerosol impact on glacier albedo from five outlet glaciers of the Greenland ice sheet

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The combination of low air temperatures and nearly continuous solar radiation during the Greenland summer make the shortwave radiation balance a dominant energy flux in the surface energy budget of glacier ice surfaces. The surface albedo of melting glacier ice is affected by a number of factors among which cryoconite from precipitated aerosols is the most important on surfaces with no basal debris coverage. However, earlier results have shown that the relation between surface albedo and aerosol accumulation is not directly proportional, since post depositional processes affect the distribution pattern and hence the resulting ice albedo. This study focus on quantifying the relation between cryoconite albedo, cryoconite mass and glacier ice surface albedo based on extensive field studies.

During the summer of 2011 extensive data collection was performed along five different transects at glacier outlets from the ice sheet in the Nuuk region. The field work as well as some results will be presented at the NIGS meeting.

Dating ice cores using statistical extraction of volcanic sulfate

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Ice cores from outside the Greenland and Antarctic ice sheets are difficult to date because of seasonal melting and multiple sources (terrestrial, marine, biogenic and anthropogenic) of sulfates deposited onto the ice. Here we present a method of volcanic sulfate extraction that relies on fitting sulfate profiles to other ion species measured along the cores in moving windows in log space. We verify the method with a well dated section of an ice ore from central Eurasia. There are excellent matches to volcanoes in the pre-industrial, and clear extraction of volcanic peaks in the post 1940 period when a simple method based on calcium as a proxy for terrestrial sulfate fails due to anthropogenic sulfate deposition. We then attempt to use the same statistical scheme to locate volcanic sulfate horizons within three ice cores from Svalbard and a core from Mount Everest. Volcanic sulfate is <5% of the sulfate budget in every core, and differences in eruption signals extracted reflect the large differences in environment between western, northern and central regions of Svalbard. The Lomonosovfonna and Vestfonna cores span about the last 1000 years, with good extraction of volcanic signals, while Holtedahlfonna which extends to about AD1700 appears to lack a clear record. The Mount Everest core allows clean volcanic signal extraction and the core extends back to about AD700, slightly older than a previous flow model has suggested. The method may thus be used to extract historical volcanic records from a more diverse geographical range than hitherto.

Modelling the regional climate and isotopic composition of Svalbard precipitation using REMOiso: a comparison with available GNIP and ice core data

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The regional (approx. 50 km resolution) atmospheric circulation model REMOiso with embedded stable water isotope module is used to simulate local Svalbard climate for the period 1958-2001. The model results are compared with the two instrumental climate and four isotope series ($\delta^{18}O$) from western Svalbard. We examine the data from ice cores drilled on Svalbard ice caps in 1997 (Lomonosovfonna, 1250 m asl) and 2005 (Holtedahlfonna, 1150 m asl) and the GNIP series from Ny-Alesund and Isfjord Radio. The surface air temperature (SAT) and precipitation data from Longyearbyen and Ny-Alesund are used to assess the skill of the model in reproducing the local climate. It is found that the model successfully captures the climate variations on the daily to multidecadal times scales although it tends to systematically underestimate the winter SAT. Analysis suggests that REMOiso performs better at simulating isotope compositions of precipitation in the winter than summer. The simulated and measured Holtedahlfonna $\delta^{18}O$ series agree reasonably well, whereas no significant correlation has been observed between the modeled and measured Lomonosovfonna ice core isotopic series. It is shown that sporadic nature as well as variability in the amount inherent in precipitation process potentially limits the accuracy of the past SAT reconstruction from the ice core data. This effect in the study area is, however, diminished by the role of other factors controlling $\delta^{18}O$ in precipitation, most likely sea ice extent, which is directly related with the SAT anomalies.

Digital image analysis of snow particles and its implication for remote sensing and ground observations of snow

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Snow particle size is an important parameter when studying snowpack properties as the size of the snow particles affects the snow density and the snow pack energy balance by changing albedo and backscattering properties. In this study we present an improved method that objectively provides detailed information on the size and size distribution of snow particles. The goal of this study was to first develop an efficient field sampling method that provides a quantitatively accurate snow particle size distribution and secondly to estimate how the various snow particle size distributions affect the reflectivity and backscatter of remotely sensed imagery. Our method is based on a two step approach of (i) the rectification of digital images of snow and (ii) the object oriented segmentation and classification of the photographed snow particles. We have tested the method at different spatial and temporal scales ranging from study sites on the East Antarctic ice sheet, sites with snow on sea ice within the Ross Sea to two field sites in Northern Sweden. In addition, we have compared the method to existing methods in terms of visual analysis of snow. The advantages of our method are that it is observer-independent and that it allows the determination of both the snow particle size and shape distribution from just one snow sample. Application of our method on the East Antarctic ice sheet showed a decreasing snow grain size towards the center of Antarctica and larger grains in the coastal areas. The data demonstrate further a regional snow particle size variability from 0.63 to 0.91 mm between the plateau and the coast. The local variability ranged between 0.23-1.03 mm within 10 by 10 square meter grid at the polar plateau. A comparison of the Antarctic dataset with AMSR-E, MOA, MODIS and MERIS satellite imagery showed a strong correlation with the 89GHz AMSR-E H-pol data at r2 = 0.68-0.73. The results indicate that our method provides a quick but objective field approach to retrieve accurate ground-truth information for remote sensing products across vast spatial areas. Thus, we believe our method will help to narrow the gap between the field and remotely sensed characterization of snow particles and snow physical properties.

Basal drag pattern inferred from surface velocities for Vestfonna ice-cap (Svalbard) with a Full-Stokes model in 1995 and 2008

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Svalbard is an archipelago in the Arctic Ocean. Nordaustlandet is the second largest island and has two major ice-caps: Austfonna and Vestfonna. These ice-caps on Nordaustlandet represent one of the largest ice-covered areas in the Eurasian Arctic.

In the current project we focus on present-day and prognostic simulations in the future of the Vestfonna ice-cap. For present-day simulations Vestfonna and Austfonna can simply be treated separately since the two ice-caps are currently not connected.

To conduct present day and prognostic simulations it is crucial to gain a better understanding of the occurrence of basal sliding and possible surge areas. Even though low temperatures and low balance gradients generally result in low flow rates on the glaciers of Svalbard, the Vestfonna ice-cap is characterized by fast-flow regions (velocities over several hundreds of meters per year).

We use the full-Stokes finite element code Elmer/Ice (CSC-Finland) to model the flow of ice of the Vestfonna ice-cap. The spatial pattern of basal drag is inferred from the measured surface velocities using a Robin inverse method evaluated over two different years : 1995 (ERS-1/2 1-day InSAR velocities) and 2008 (ALOS PALSAR 46-days offset-tracking velocities).

The obtained results will be discussed with respect to existing fast flow-regions and the differences between the two periods will be opposed. The importance of this good knowledge of the basal conditions compared to a simple sliding law will be shown. First prognostic simulations with the average climatic mass balance over the last years will be presented.

In a latter step, prognostic simulations into the future are planned as well as extending our investigations to the close-by ice-cap Austfonna.

Data access was made possible by the Kinnvika IPY project consortium.

Surface energy balance and meteorology (2007–2010) in the ablation zone of Langfjordjøkelen, an ice cap in northern Norway

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Langfjordjøkelen (70_10’N, 21_45’E) is a small ice cap (7.7 km2) in the northernmost part of mainland Norway. Surface mass balance measurements have been carried out on an east-facing part (3.2 km2) since 1989, revealing a cumulative and annual mass balance of –18.2 and –0.87 m w.e./a respectively for the period 1989–2009. The mass deficit of Langfjordjøkelen is stronger than observed for any other glacier in mainland Norway. From September 2007 to August 2010, an automatic weather station (AWS) was operated in the ablation zone (650 m a.s.l.) of the glacier. Measured variables were incoming and reflected solar radiation, incoming and outgoing longwave radiation, air temperature, relative humidity, air pressure, wind speed and wind direction. In addition, surface height change was monitored. The mean air temperature over the measurement period was –1.0_C and is highly correlated (r2=0.97 for hourly values) with measurements from a second AWS, located on a rock surface above the glacier (910 m a.s.l.). Compared to this AWS, wind speeds measured by the AWS on the glacier were a factor 0.6 lower. The winter snowpack had a maximum depth of more than 3.5 m every winter and did not disappear before late July in all three summers. The majority of the surface melt takes place between May and October, but even in mid-winter, short melt periods occur during stormy conditions. The energy available for melt is largest in August, when the surface consists of ice. Surface melt is dominated by net solar radiation, over the three-year period the total ice ablation at the AWS location amounted to 6 m. Even though this AWS was located at a much higher latitude, the seasonal cycles of the meteorological variables and surface energy fluxes are not very different from results obtained from two AWSs on glaciers in southern Norway.

Tracking Synoptic Weather Event Signatures in Icefield Snowpack Structure

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A synoptic weather classification scheme is being developed to explain the climatological processes controlling mass-balance fluctuations on the Columbia Icefield in the Canadian Rockies. A detailed analysis was conducted to determine the impact of specific weather events on accumulation or ablation episodes of the 223 km2 Columbia Icefield. This simple synoptic classification system is designed to integrate the various weather-related processes that control the ice cap mass-balance. Individual weather events as observed on charts of atmospheric pressure were matched to corresponding patterns in snow stratigraphies obtained from snowpits. Reanalyses of weather maps for the time period of suspected formation of the layer were performed using Empirical Orthogonal Function methods. The snowpit data, gathered during two field seasons (April/May 2010-2011), consisted of layer thicknesses, snow density and moisture content. Measurements were collected using a dielectric probe inserted in the glacial annual snow in two-centimetre increments. The resulting data from both the field and reanalysis were combined with regional and local reference to weather station and snow profiles gathered from Jasper National Park staff. This research involves examining the large-scale weather patterns of the region as climate forcing on mass-balance and seeking layers in the glacial yearly snow that correspond to those patterns, similar to how avalanche professionals identify a surface hoar layer and matching it to the extended high pressure system that created it. As most glaciological research focuses mainly on factors affecting mass balance on a large scale and during ablation season and avalanche research focuses on internal snow pack structure, this unique research project combines both; the micro and macro scale.

Applying the WRF model at Svalbard glaciers: validation and improvements

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The SVALI project (http://ncoe-svali.org/) will study basic processes using remote sensing, airborne and in-situ measurements and carry out advanced Earth Systems Modelling (ESM) with focus on glaciers in the Arctic/N-Atlantic area and address the following questions:

1. Current ice volume changes, underlining their contribution to sea level rise,
2. Mass-balance and ice-dynamic processes to improve Earth System Models,
3. Future changes in terrestrial ice and their societal implications.

Our part in SVALI is to dynamically downscale 20 years of climate re-analysis data with a meso-scale atmospheric model (WRF) over Svalbard. Focus will be analysis of temperature, wind and precipitation in the context of mass-balance studies. The data can also serve as forcing to local mass-balance models for ice sheets. The distribution of precipitation, temperature and wind can increase the understanding of the ice dynamics in the Svalbard area. The aim is also to improve the atmosphere–cryosphere interchange process descriptions in the WRF model and to upscale our improved parameterization into ESMs within the SVALI network.

After a general qualitative analysis a first step was to verify the WRF simulations with surface observations over three Svalbard glaciers. Two set-ups of the physical process descriptions in the WRF model were tested, standard physics and polar optimized physics differing in radiation, cloud physics and atmospheric boundary layer. The model was forced by ERA-Interim reanalysis during 2007–2010 and downscaled in three steps to 2.7 km resolution.

The standard WRF simulations against observations showed cold temperature biases and too low rates of incoming and outgoing radiation. Polar optimized physics gave improved rates of incoming short- and longwave radiation. This led to decreased mean biases of the temperature. The better skills by polar optimized WRF can be explained by better simulation of high and low clouds. Wind speed however was not improved by the polar physics. The study shows the importance of correct physics descriptions suitable for Polar regions.

The future plan is also to improve the surface physics subroutine (NOAH land surface model) in the WRF model regarding albedo, snow roughness and implementation of water retention and refreezing. At present the albedo is in average to high and does not, for instance, decrease with snow age. The implementation of water retention and refreezing will be done in collaboration with other SVALI participants from Uppsala University, UNIS, DMI and GEUS.

CryoGRIDequi – a new equilibrium permafrost model applied for Norway

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The thermal regime of permafrost is likely to change significantly in response to the predicted climate change, with associated warming and degradation of permafrost. Understanding the spatial distribution and temperatures of permafrost is crucial to assess the associated geomorphological and bio-chemical consequences. Based on a spatially distributed equilibrium model (CryoGRIDequi) this presentation focuses on the effect of snow cover and organic material on the regional distribution of permafrost in Norway. In Norway, the good availability of spatially distributed data on meteorological variables, vegetation, petrophysics and sediment cover allows for an implementation of soil models with relatively high horizontal resolution, in our case 1km2. CryoGRIDequi comprises an implementation of the TTOP-model. The model determines the temperature at the top of permafrost from air temperature based on seasonal n-factors parameterizing the thermal effects of vegetation and snow cover, and the conductivity ratio between frozen and thawed states in the active layer. The model is run using operationally gridded temperature- and snow data over the period 1960-2010, provided by the Norwegian Meteorological Institute and the Norwegian Water and Energy Directorate (senorge.no). Parameterization of the model is based on data from several air/ground and snow depth stations established in various mountain sites. The modeling results are validated with 140 sites all over Norway where ground surface temperature is measured, 20 shallow boreholes equipped with temperature monitoring logger devices and maps of palsa- and rock glacier locations. The modeled permafrost distribution is in good agreement with observations. According to the model results, approximately 6% of the total mainland area in Norway is presently underlain by permafrost. Of the total permafrost area, 34% is found in till, 23% in blockfields and 17% in bedrock. The remaining areas are covered by mainly sediments and organic material. Assuming the SRES A2 scenario with an air temperature increase of on average 3°C until 2100, permafrost is modeled to disappear almost entirely in the mountains of Southern Norway, while permafrost will degrade in about 90% of the present area in Northern Norway.

A multi-method approach to the long term volume change study of Storglaciären

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Storglaciären has been monitored for volume changes since 1946 when the ongoing mass balance program on the glacier was initiated. The glacier mass balance record shows the glacier has mostly experienced mass loss for the measurements period though there have been brief but distinct periods of positive balance. The standard mass balance measurements have been augmented by decadal surveys yielding DEMs of the glacier surface. In addition, surface profiles and velocity surveys have been carried out periodically on the glacier. In 2009, the older DEMs from 1959, 1969, 1980, 1990, and 1999 of Storglaciären were re-evaluated to provide a coherent data set of DEMS for the glacier (Koblet et al. 2010; Zemp et al. 2010). Their results showed that spatially changing patterns of gain and loss could be identified.

We re-mapped the glacier surface in 2010 to produce a new decadal DEM. The mapping was accomplished using dGPS and reflectorless Total Station surveys. In this study we investigate the observed spatial changes in volume change by adding the information gathered through velocity measurements and stationary profile measurements. It is clear that particularly the ablation area of the glacier has undergone significant surface lowering but this was interrupted by a brief period of elevated surface associated with higher surface velocities in the 1990s and into first years of the new century.

The Practical Implications of Errors in Remote Sensing of Area Change of Small Glaciers

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Remote sensing platforms such as Landsat, SPOT and ASTER are used for mapping and monitoring changes in glacier area on regional scales in programmes such as GLIMS and WGMS. We have examined the accuracy of automated and manual algorithms for glacier delineation using Landsat ETM+ data from 2008 and aerial photographs as ground truthing. Errors have been assessed for their effects on small glaciers, typical of the Swedish mountains. Small glaciers are prone to the same absolute errors at their margins as larger glaciers; however, the errors are proportionally larger.

The errors for both automated and manual delineation are of a similar nature. Manual errors for an experienced user average ±6% and 25% at maximum. Both manual and automated mapping is prone to errors in areas in shadow or where moraine or water confuse the signal. Manual delineation can sometimes compensate for this using contextual evidence. The scale of the average errors is 60 to 150 m (platform dependant) and is of a similar scale to the area of the smallest glaciers. A mapping of all Swedish glaciers as of 2008 using Landsat data gave an area of 243.0 km2. Buffering this map by ±60 m alters this figure to between 179.3km2 and 313.5km2. Comparing these figures to data in the 1973 "Atlas over breer i Nord-Skandinavia: Glacier atlas of northern Scandinavia", the present area is between 55% and 97% of the 1973 value.

Daily and seasonal glacier velocity change on Kronebreen, Svalbard, as measured using FORMOSAT-2 imagery and in situ continuous GPS

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Glacier response to climate change is often heralded by changes in the velocity field. Remote sensing can be used to map changes in glacier speed. Visible satellite imagery provides high resolution products in convenient to use format, but is hampered by the presence of clouds. The high-resolution (2-m pixel nominal resolution in panchromatic mode) FORMOSAT-2 satellite has a daily revisit capability, allowing programmed acquisitions to capture occasional periods with few or no clouds. Here we use FORMOSAT-2 to derive glacier-wide velocities on the lower 10 km of Kronebreen, Svalbard's fastest-moving glacier, which has peak summer season speeds of up to 2 m d^{-1}. We present FORMOSAT-derived velocity fields for the summer melt seasons of 2007 to 2011, obtained using 4-8 images, the exact number depending on the year. We also compare the data from 2009 onward to 3-hourly measurements of speed made using a number of in situ code-phase GPS units deployed at various points on the glacier tongue. The FORMOSAT-derived data have good spatial resolution and show how velocity increases start at the front of the glacier and move upstream. The GPS data have high temporal resolution and show how the glacier reacts to meltwater inputs. The GPS data are also used to verify the spatial variability of the remote-sensing data since the receivers are located along the flow line as well as on a transect across the flow line.

Ice Is Nice

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Ever seen a snow radar driving over you? Than this might be your chance. Working on glaciers can be seen as challenging, funny or simply just breathtaking. Ice IS Nice is a 10 minutes video clip from impressions of glaciologists working on one of Europe’s largest glaciers, Austfonna. Lean back and enjoy.

A regional avalanche forecasting service for Norway

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In Norway, avalanches cause loss of life and considerable costs for the transportation sector due to closure of roads and railways each year. In 2009 NVE was appointed the national authority responsible for avalanche and landslide forecasting in Norway. In this context a research project was initiated to test and develop methods for a regional avalanche warning service covering all relevant parts of Norway. Project partners are the Norwegian Meteorological Institute, Norwegian Public Roads Administration, the Norwegian National Rail Administration and the Norwegian Geotechnical Institute. The avalanche warning service will be operational from December 2012. An integral part of the development is the extension of the existing meteorological station network. New stations will be deployed in alpine regions in Norway. Thus, being of potential interest and value to other cryospheric sciences in Scandinavia. We present briefly the current status of the project and give an outlook on the operational work.

A First Principle Crevasse and Calving Model - First Steps

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Until recently, calving models for outlet glacier systems mainly were based on heuristic methods to fit the continuous behaviour of the model to the few observations being made in nature. Only recently, Benn et al. and Nick et al. developed methods that at least introduce certain physical objectives into modeling of the calving process. A further elaboration has been introduced by Jouvet et al. by applying an ad-hoc damage model to their glacier flow model to account for transport of crevasse fields.

Nevertheless, those models all contain a certain amount of heuristic approach to the problem. The main issue for that is that material failure of ice happens at time-scales where the material cannot be treated solely as a fluid. Rather, we should account for the full (non-linear) visco-elastic aspect of the material to account for the creation of cracks that merge into crevasses. In this paper we want to present first steps towards a first principle model of the fracture of ice using Newton's equation of motion discretized on a lattice. We set up simple two-dimensional test cases to show the influence of material parameters (fracture criterion, shear and tensile stiffness, internal damping, material disorder, etc.) as well as boundary conditions (sliding, bumpy surfaces, external water column pressure).

Continuous GPS surface velocity measurements on two fast flowing outlet glaciers of Austfonna, Svalbard

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Austfonna, the largest ice cap on Svalbard, currently experiences net mass loss mainly attributed to calving and retreat of the marine ice margin, while its surface mass-balance is close to zero. A large part of the ice flux from the ice-cap interior towards the margin occurs through spatially limited flow units that may operate in a mode of steady flow or cyclic surge behavior. Previous ice-surface velocity maps rely on data acquired in the mid-1990s with limited information concerning the temporal variability.

Here, we present continuous Global Positioning System (GPS) observations along the central flowlines of two fast flowing outlet glaciers of Austfonna during 2008–2010. The data shows prominent summer speed-ups with ice-surface velocities as high as 240% of the pre-summer mean. Acceleration follows the onset of the summer melt period, indicating enhanced basal motion due to input of surface meltwater into the subglacial drainage system. In 2009, the relation between ice-surface velocities and surface melt is more complex, indicating a transition towards a hydraulically more efficient drainage system. The observed annual mean ice-surface velocities of Basin-3 triple those measured by InSAR in the mid-1990s and imply increased mass loss through calving of icebergs into the Barents Sea. Measured summer velocities up to 2md-1 are close to that of Kronebreen, often referred to as the fastest glacier on Svalbard.

Modelling variable glacier lapse rates using ERA-Interim reanalysis climatology: an evaluation at Vestari-Hagafellsjökull, Langjökull, Iceland

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In glacier-melt modeling, and regardless of whether an energy-balance or a temperature-index/degree-day approach is taken, it is typically necessary to allow for spatial variation in air temperature. This is a common issue whether upscaling from in-situ, point measurements – typically from an Automatic Weather Station, often at low elevation – or downscaling from gridded, re-analysis climatology data with spatial resolutions of 10s or 100s of km. The near-surface air temperature lapse rate is an important tool for spatially-distributing temperatures in melt models, but is difficult to parameterize, as it is not correlated in a simple way with boundary-layer meteorological variables. This contribution quantifies spring–autumn lapse-rate variability over five years at Vestari-Hagafellsjökull, a southerly outlet of Langjökull in Iceland. It is observed that summer lapse rates (0.57° C 100 m^{-1}) are lower than non-summer rates (0.70° C 100 m^{-1}), and are also lower than the Moist Adiabatic Lapse Rate (MALR). This is consistent with reduced near-surface temperature sensitivity to free-atmosphere temperature change during the occurrence of melting. However, the lack of a simple, effective method for modeling variable lapse rates has, to date, generally led to a continued dependence on the MALR for implementing the spatial distribution of temperatures for melt models. In order to evaluate the effectiveness of an alternative approach, a Variable Lapse Rate (VLR) regression model is here calibrated with standardized, 750 hPa temperature anomalies derived from ERA-Interim climatology, which is shown to be highly-significantly correlated with near-surface temperatures. The modeled VLR over-estimates cumulative June–September Positive Degree Days (PDDs) by 3% when used to extrapolate temperatures from 1100 to 500 m a.s.l. on the glacier, whereas the MALR over-estimates cumulative PDDs by 14%. Using a conservative degree-day factor, the MALR would generate 0.36 m w.e. excess melt compared to the VLR, and 0.46 m w.e. compared to the observed PDD total. ERA-Interim data therefore appear to offer a good representation of free-atmosphere temperature variability over Vestari-Hagafellsjökull, and the modelling approach offers a simple means of improving lapse-rate parameterizations in melt models. The effectiveness of the model implies a synoptic control over lapse rates, which has been suggested previously, but remains to be explained fully. Reduced monthly lapse rates over Vestari-Hagafellsjökull coincide with relatively stable, high-pressure summer conditions, suggesting a broadly inverse relationship between atmospheric pressure anomalies and lapse rate, which is consistent with lapse rates declining during melt periods in response to free-atmosphere temperature increase.

Reduced glacier speeds in large regions of the world revealed using optical satellite images

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Matching of repeat optical satellite images to derive glacier velocities is an approach that is much used within glaciology. Lately, much focus has been put into developing, improving, automating and comparing different image matching methods. This makes it now possible to investigate glacier dynamics within large regions of the world and also between regions to gain more knowledge about glacier dynamics. In this study we investigate whether the negative mass balance seen over large parts of the world has caused the glaciers to reduce their speeds. The studied regions are Pamir, Caucasus, Penny Ice Cap, Alaska Range and Patagonia. In addition we derive speed changes for Karakoram, a region known to have positive mass balance and that contains many surging glaciers. We find that the mapped glaciers in the five regions with negative mass balance have decreased their speeds over the last decades, Pamir by 43 % per decade, Caucasus by 5 % per decade, Penny Ice Cap by 16 % per decade, Alaska Range by 9 % per decade and Patagonia by 22 % per decade. Glaciers in Karakoram have generally increased their speeds, but surging glaciers and glaciers with flow instabilities are most prominent in this area.

Glacier area changes in Norway derived from time series of Landsat imagery

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Glaciers cover nearly 1% of the land area in mainland Norway. A detailed survey of the total glacier area has not been performed since the compilation of glacier inventories in the mid 1980s for southern Norway and the early 1970s for northern Norway. Within the CryoClim project we have derived glacier inventories for two periods, 1988-1997 and 1999-2006, using imagery from the complete time series of Landsat TM 4, 5 and 7 ETM +. A comparison between these two periods is performed.

One of the major challenges was to find suitable Landsat scenes as few appropriate scenes are available due to seasonal snow and cloud cover. After careful inspection 12 Landsat scenes for the period 1999-2006 were selected. In addition, 9 earlier Landsat satellite scenes were selected for the 1988-1997 period, however, the images for this earlier period do not fully cover the glacier area in Norway. A semi-automatic method was used for deriving glacier outlines with different thresholds of TM3/TM5 and an additional threshold in TM1. This method uses the spectral differences between the visible (high reflection of glacier ice) and the mid-infrared (high absorption of glacier ice) spectrum. Orthophotos were used for training and validation in test regions. Comparison with validation data show that glacier mapping with Landsat data is straightforward and accurate.

The rapid glacier area changes expected in the future will require repeated mapping. The present Landsat satellites have now passed their planned working life, and it is uncertain how long they will be operational. The availability of images from high resolution optical satellites is thus essential. Sentinel-2 and Landsat 8 will contribute to higher spatial and temporal delivery of cloud and snow-free satellite scenes over Norway in the future.

Modelling the spatial distribution of snow water equivalent taking into account changes in snow covered area

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In a previous paper the spatial probability density function (PDF) of snow water equivalent (SWE) was modelled as a sum of correlated (in time) gamma distributed variables. This methodology was constrained to estimate the PDF of SWE only for snow covered areas and was thus described as “conditional”, i.e. conditional on snow. In order to implement the model for the PDF of SWE in hydrological models, we have to take into account the change of snow coverage and thus provide the unconditional moments of the spatial PDF. The spatial variance of SWE for both an accumulation- and melting events are evaluated through the covariance matrix. For accumulation events, we have only positive elements in the covariance matrix, whereas for melting events, we have both positive and negative elements. The negative elements dictate that the correlation between melt and SWE is negative. The negative contributions become dominant only after a period into the melting season. At the onset of the melting season, the spatial variance thus continues to increase for later on to decrease. This behaviour is consistent with observations and by some authors called the “hysteretic” effect. When the model for snow distribution is implemented in a hydrological model, simulations show that the precision in predicting runoff is similar to hydrological models with classical, non-dynamic snow distribution, but the snow variables are better predicted. The parameters for the model can be estimated from observed historical rainfall data which reduces the number of parameters to be calibrated in the hydrological model by one.

River ice fluxes observed from space

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Knowledge of river ice fluxes is useful for understanding a wide range of lotic processes and systems, such as water and ice fluxes and forces, solute and sediment transport, bed and bank stability, aquatic and riparian ecology, and extreme hydrologic events. In cold regions, river-ice break up and the associated downstream transport of ice debris is often the most important hydrological event of the year, producing flood levels that commonly exceed those for the open-water period and dramatic consequences for river infrastructure and ecology. Quantification of river ice fluxes has relied mostly on very scarce in situ measurements or particle tracking in laboratory models, with few attempts to cover entire river reaches. Accurate and complete surface-velocity fields on ice-carrying rivers have rarely been produced.

In this study, we track river ice debris over a time period of about one minute, which is the typical time lapse between the two or more images that form a stereo data set in spaceborne, along-track optical-stereo mapping. Using this novel approach, we measure and visualize for the first time the almost complete two-dimensional surface velocity fields over many tens of kilometers long river reaches. We present the types of short time-delay imagery suitable for the measurements and discuss application examples on a number of North-American and Siberian rivers, using a range of high and medium resolution imagery.

The methodology and results of the novel approach will be valuable to a number of disciplines requiring detailed information about river flow and ice fluxes, such as hydraulics, hydrology, river ecology and natural-hazard management.

Pitfalls in radar diagnosis of ice-sheet bed conditions: Lessons from englacial attenuation models

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Radar power returned from ice-sheet beds has been widely accepted as an indicator of bed conditions. However, the bed returned power also depends on englacial attenuation, which is primarily a function of ice temperature. Here, using a one-dimensional attenuation model, it is demonstrated that, in most cases, variations in bed returned power are dominated by variations in englacial attenuation, rather than bed reflectivity. Both accumulation rate and geothermal flux anomalies can interfere with the interpretation. With the consequence, analytical radar algorithms that have been widely accepted likely yield false delineations of wet/dry beds. More careful consideration is needed when diagnosing bed conditions. Spatial patterns of shallow englacial radar reflectors can be used as a proxy for accumulation rates, which affect ice temperature and thus returned power. I argue that it is necessary to simultaneously interpret the returned power and englacial-reflector patterns to improve the bed diagnosis.

Bromide and ikaite measurements in Vestfonna snow show evidences of young sea ice production in winter around Nordaustlandet

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Frost flower chemical signature (with sulfate being strongly depleted relative to sodium) in Arctic snow, has been first described in 2006/07 winter snowpack from Vestfonna ice cap, Svalbard. In spring 2009, seasonal snow and a 15.5 m firn core have been collected from the same location to better assess the chemical seasonal variability and investigate the relative contribution of the open sea versus sea ice (or frost flower) source of sea-salt on Vestfonna. Because frost flowers can generate sea-salt aerosols also enriched in bromide, Br- concentration has been measured in addition to major ions routinely analyzed and to insoluble particles mass. Similarly to winter snow 2006/07, the 2008/09 winter snowpack shows a pronounce peak in fractionated sea salt species (Na+, SO4 2-) associated with a Cl-/Br- ratio of 353 indicating an enhancement of bromide over chloride by a factor of 1.8 compared to that of bulk sea water. The same signal, characteristic of a frost flower event, is detected at 3 m depth in a layer of the core relatively well preserved from percolation that we assign to winter 2006/07. In that layer, the calcium mineralogical phase analysis (Carel = [Casoluble]/[dust]) and the Ca2+/Na+ ratio greater than that of bulk sea water reveal the presence of hydrous calcium carbonate that we hypothesize to be ikaite (CaCO3.6H2O) which forms simultaneously with frost flowers at the early stage of sea ice formation. The detection of frost flowers in ice cores from maritime sites could reflect the change of surrounding sea ice production. We track layers enriched in bromide and ikaite along Vestfonna firn core and find clear chemical evidence in the layer 1994/95. The frost flower origin of sea-salt for winter 1994/95 is substantiated by the particularly low sea ice extend observed around Nordaustlandet that year and by modeled climatic parameters (geostrophic wind direction, temperature) similar to the parameters measured in situ in winter 2008/09.

A new view of the subglacial conditions in Eastern Dronning Maud Land, Antarctica

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We present results of an airborne radar survey carried out in Eastern Droning Maud Land, Antarctica, during the austral summer 2010-2011. The airborne survey was operated by the Alfred Wegener Institute and supported by the funding agency European Facility for Airborne Research (EUFAR). The Sor Rondane Mountains (SRM) are a fringing mountain system that impedes the ice flow coming from the polar plateau. Therefore, most of the ice flow is diverted around the mountains and concentrated in fast-flowing outlet glaciers. A recently published map of surface velocity in Antarctica shows that Western and Eastern Ragnhild Glaciers, east of SRM, show most distinct fast-flow features penetrating into the deep interior of the ice sheet, implying a possibility that these glaciers play a significant role to control the regional mass balance. These glaciers experience a very different flow regime: the western glacier is faster and penetrates far more upstream than the eastern glacier. The new radar data revealed that these glaciers have quite different bed topography in the midstream region and similar bed topography in the downstream region near the grounding line; the western glacier is characterized by a deep incised valley, while the eastern glacier is less steep-sided and the longitudinal profile is an upward slope in the inland direction. These features were not captured in the previous ice-thickness database. We present a reassessment of the balance velocity distribution combined with results of higher order ice sheet modeling using the new dataset.

Recent glaciological study on Werenskioldbreen (South Spitsbergen)

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Werenskioldbreen is situated in the SW part of Wedel Jarlsberg Land on the Western coast of SW Spitsbergen near Polish Polar Station in Hornsund. Werenskioldbreen is polythermal, valley glacier which is ending on the land. Studies are conducted on Werenskioldbreen with many interruptions, from the Third International Geophysical Year in 1957-1958. Werenskioldbreenhas the most large and medium scale cartographic records ever prepared by the Polish scientists. In 1957 glaciology station on firn zone was situated. In the years 1957-60, 1962, 1970 field studies were conducted on the basic of measurements madeon glacier station and tent camp placed on the glacier foreland. In 1971, on the lateral moraine of the glacier, permanent station was established by the University of Wroclaw, which serves scientists until now. In next years, during the summer studies of glaciology, meteorology, speleology, biology, cartography and others were performed. In the late 90s for several years, year-round measurements of glacier mass balance and velocity were conducted. In 2009 we havestarted a continuous measurements of glacier mass balance, velocity and drainage system. New GPR measurements, mapping of supraglacial drainage and modeling of subglacial and englacial drainage system were made. Measurements of outflow and chemical components were studied to get all the information about glacier basin. In 2011, two holes were made by hot steam drill to the bottom of the glacier. In both boreholes pressure sensors, temperature and conductivity sensors were installed. Observations indicate a steady trend of negative mass balance of glaciers in recent decades, it is getting slower and the drainage system is getting stabilized.

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Subglacial drainage of Werenskioldbreen – South Spitsbergen – from numerical modelling

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Werenskioldbreen is a valley-type glacier that has a well-defined basin boundary. Its accumulation field consists of three sections: the northern section producing Skilryggbreen tongue, the central stream of Werenskioldbreen and the smallest southern section forming Angellisen tongue. The tongues are separated by medial moraines, the largest of which separates the central flow from Skilryggbreen. The glacier runs longitudinally with its snout veering to the north. In 1990, the glacier surface was measured at ca. 28 km^2. A distortion of the medial moraine may suggest a glacial surge. The glacier represents a polythermal type with cold ice layer on the top.

In order to determine the subglacial topography, a broad GPR/GPS survey was performed in the spring of 2008. Radar data were obtained by using low-frequency ground penetrating radar (GPR). The low-frequency radars are appropriate for sounding of polythermal glaciers due to their ability to overcome heavy scattering of electromagnetic waves, caused by water inclusions within temperate ice layer. The GPR system consists of a 25 MHz unshielded antenna, a control unit and data acquisition platform.

The DEMs of surface, as well as bedrock topography, were applied to calculate the predicted subglacial waterways. Subglacial drainage system is driven by the hydraulic potential. The hydraulic potential is calculated on the basis of gradients of glacier surface and its bedrock. The hydraulic potential is a sum of bedrock elevation potential and pressure potential (Pw).

The computer program Visual Modflow ver. 4.3 was used for modeling the Werenskiold glacier catchment system. The software is widely used for resolving the different problems in the groundwater environment.The modeling area cover all Werenskiold catchment, which is divided into square blocks with dimension of the 100 m. Model of the Werenskiold glacier is consist from 4 layers.

Model of the Werenskiold glacier catchment confirm the general assumptions of the conceptual model, with reservoir character of the glacier body and possibility of the water inflow through moraine and bedrock formation directly to the sea. In a reason of the high pressures within main glacier conduit it’s also possible the downward water flow to the bottom moraine formation. The presented model of the Werenskiold catchment is a first approximation of this very complicated system. In the future model will be developed for better representation of the heterogeneity of the glaciers body and moraine formation, in respect of conductivity values.

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Chemical weathering in the polythermal glacier of High Arctic (Werenskioldbreen, SW Spitsbergen)

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Modern research in glacier hydrochemistry gives an attention to define a source of protons chemical weathering reactions. Two opposite reaction may be treated as major proton source: sulphide oxidation and carbonation. To understand relationship between both reactions variety of water physicochemical properties is needed. This study aims to define physicochemical conditions associated with chemical weathering in subglacial and proglacial areas of polythermal glacier (Werenskioldbreen, Svalbard). The glacier covers 27 km^2 (total catchment area 47 km^2). This is underlined by highly diversified rocks (quartz conglomerates, phyllites, muscovite-carbonate-quartz schist) with distinct carbonate concentrations (mostly <5%). The fieldwork consisted of measurements of physicochemical water properties such as conductivity, pH, redox potential, dissolved oxygen and water temperature (Hanna Instrument 9828 Multiparameter Water Quality Meter). The work have been carried out at the end of ablation season August 20th and September 25th 2011.There were three types of sampling sites: water gauging station, subglacial outflows (Kvisla River, Black Spring, New Outflow, Angell Outflow) and streams draining to the moulins (Supraglacial Streams). Latter denotes lowest pH (median 6.60) in a whole catchment. Most of subglacial outflows (excluding Angell with medial pH 8.64) exhibit highest pH (medians: for Kvisla pH 9.51 for Black Spring 9.26 and New outflow 9.11) in compare with other sites. In gauging station, medial pH drops substantially to 8.64. Specific conductivity shows lowest values in supraglacial streams (33 µS/cm), chiefly increases in subglacial outflows (60-79 µS/cm, in Angell 122 µS/cm) and achieves 104 µS/cm at the gauging station. Dissolved oxygen shows lowest values in Angell outflow (median 44.5%), with increasing values in other subglacial outflows (in range 80.5-88.1%) and higher than 92% in gauging station and supraglacial streams. Water transfer between supraglacial and subglacial system changes importantly its properties. Highly oxidized water with low pH and low conductivity as well as low transit redox potential is transformed into slight redox condition with pH by 3 units higher and two-fold increase of conductivity. This suggests that in subglacial condition oxidation reaction (in oxic conditions) depleting redox agents may be associated with chemical weathering driven by acid hydrolysis increasing pH. In addition, Angell Outflow with low dissolved oxygen concentration and highest conductivity in basin suggest that oxidation in anoxic condition take place. Considerable increase in conductivity shows that chemical weathering processes are intensified and probably associated to oxidation in oxic conditions.

Permafrost distribution in Hornsund (South Spitsbergen)

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In the era of the observed increase of temperature and increase of the permafrost active layer thickness, studies on the spatial distribution of permafrost are crucial. Geophysical methods allows for non-invasive and extensive research of permafrost. Aim of this study was to determine the spatial distribution of permafrost in costal zone. The measurements were performed in the marine terrace in the vicinity of Polish Polar Station in Hornsund. Three geophysical methods: electrical imaging, seismic refraction and GPR measurements were used. Electrical imaging was conducted using Terrameter SAS 1000 on the length of 200 m. Interpretation of data was performed in RES2DINV software to create two-dimensional electrical resistivity image of the subsurface. Seismic refraction was conducted using Terraloc MK6 System - the multi-channel digital seismograph. The travel-times of waves refracted along the four profiles 55 m long were recorded. Two-dimensional models were created using SeisImager Packed. Ground Penetrating Radar Mala Ramac with 200 MHz antennas was used for this study. The GPR interpretation data was made using RadExplorer Software. The depth of the permafrost active layer was determined based on used geophysical measurements. The depth of permafrost active layer was characterized by high values of electrical resistivity (above 4000 Ωm) and high values of waves velocity (above the 3000 m/s). Analyzed GPR profiles shows the depth of the permafrost and bedrock what was correlated with seismic and electrical data. The depth of permafrost layer is varied from 1 m to 2.5 m. Spatial distribution of active layer thickness was correlated with distance from sea.

This project was completed with the support granted by Iceland, Liechtenstein and Norway by means of co-financing from the European Economic Area Financial Mechanism and the Norwegian Financial Mechanism as part of the Scholarship and Training Fund

Changes of glaciers in Lyngen, Northern Norway

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The aim of this study was to estimate glacier changes of selected glaciers on the Lyngen peninsula in northern Norway around 70°N. For this purpose we have used topographical maps, Landsat imagery, ortophotos and laserscanning. To map the present state of the glaciers totally 13 glacier units in four glacier regions in Lyngen were mapped by laserscanning and air photos in 2010. For analyzing glacier changes elevation contours and glacier outlines were digitized from topographical maps from the 1950s. In addition, a semi-automated method was used to derive glacier outlines from Landsat imagery from 1988 and 2001. Digital terrain models (DTMs) were constructed from the digitized contour lines and from the new laserdata. Whereas the new 2010 DTMs are highly accurate, the ~1950 DTMs have poorer quality, but are nevertheless used to give an estimate of the elevation changes.

Results show that the total glacier area of the studied glaciers has been reduced from 36.9 km^2 in ~1950 to 31.1 in 2010 - an area reduction of 16 %. In the same period all glaciers have decreased in volume; on average the glacier elevation has decreased by 20 m from ~1950 to 2010 according to the DTMs.

The new DTMs from 2010 provide an excellent reference for studying future glacier changes.

Thermodynamics of subglacial water flow in jökulhlaups from the Skaftá cauldrons, Vatnajökull, Iceland

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Regular jökulhlaups in the river Skaftá from western Vatnajökull, that occur at 1–2 year intervals with volumes of 0.05–0.4 km^3 and a maximum discharge of 50–2000 m^3/s, provide one of the best opportunities to study the response of subglacial hydraulic systems to variations in water input. Interest in the dynamics of subglacial water flow has increased greatly in recent years with the realisation that large variations in ice flow velocity in space and time on the ice sheets of Greenland and Antarctica appear to be driven by changes in basal sliding that are most likely caused by variations in basal water pressure. The floods in Skaftá originate from two subglacial lakes below 50–150 m deep and 1–3 km wide depressions (cauldrons) in the ~450 m thick surrounding ice, which together drain approximately 50 km^2 of the ice cap. Discharge and flood water temperature measurements in Skaftá, measurements of lake water temperature and water level in the subglacial lake and mapping of changes in the elevation of the glacier surface in the neighbourhood of the cauldrons at different times within the jökulhlaup cycle make it possible to analyse the dynamics and thermodynamics of the subglacial water flow along the ~40 km long flood path to the glacier terminus. The outflow locations from each cauldron are visible as several km long elongated depressions in the ice surface along the inferred subglacial flood path that are ~10 m deeper shortly after than shortly before jökulhlaups. These depressions are thought to be formed by subglacial melting driven by the initial heat of the flood water in repeated jökulhlaups and the difference in the depth of the depressions before and after jökulhlaups is interpreted as the consequence of melting that takes place in a single flood. The length of the depression is related to the efficiency of heat transfer in the subglacial water flow to the ice walls surrounding the subglacial water flow. The inferred efficiency of the heat transfer is many times greater than assumed in traditional theories of jökulhlaups. This is consistent with measurements of flood water temperature at the glacier margin during jökulhlaups that show the water to be within a few thousandths of a degree from the freezing point.

From an ice cap to a tidewater glacier - towards a 3D full-Stokes flow model of Kronebreen

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Glaciers and ice caps are currently the largest cryospheric contribution to sea level rise and they will dominate the near-future change in sea level arising from ice loss. Tidewater glaciers are major outlet glaciers terminating into the sea with a grounded ice cliff from which icebergs are discharged. Tidewater glaciers have a large potential for instability and to respond to climate warming with continuous retreat. Thus, it is crucial to improve the understanding of their dynamics, in order to assess their current retreat behavior, to predict future changes and consequently their contribution to sea level rise.

It is widely acknowledged that the key internal processes of tidewater glacier dynamics are basal sliding and calving. Both processes are poorly understood. For instance, the interactions between bedrock and the overlying ice is typically described by a Weertman-type power law which relates a constant to the effective normal stress and the shear stress at the base, including two different exponents of the stresses. The exponents and the constant became in practice a tuning parameter where each individual combination represents a unique glacial situation. These unknown parameters are adjusted to the local situation comparing simulated and observed velocities together with a misfit-parameter approach to select the suitable sliding law parameters. A mandatory requirement is an intensive database of in situ measured flow velocities which serves as tuning an validation parameters. We performed these procedure on the well surveyed antarctic ice cap King George Island by applying a 3D full-Stokes flow model. The established concept allows both to constrain model parameters, as well as to validate the model. The model results show, that it is mandatory to include and combine different concepts of basal sliding in the computation of the velocity field.

We will adapt and extend the existing 3D full-Stokes flow model into a numerical model for tidewater glaciers. This numerical modelling approach incorporates the transient thermo-mechanical coupled problem, using a 3D full-Stokes finite element model (COMSOL Multiphysics), an appropriate rheology for temperate ice, a theoretical calving law and an empirical law for sliding. The model will be applied to Kronebreen, the fastest tidewater glacier in Svalbard which is/was retreating and is well surveyed. The expected output will be projections of the response of a tidewater glacier system to climate changes and an assessment of the role of intrinsic glaciological versus climate forcing. Here we are presenting the strategy of our upcoming modelling approach.

An accumulation (hi)story of Austfonna from IGY to IPY: field observations vs model results

T.V. Schuler, T. Dunse, T. Eiken, J.O. Hagen, G. Moholdt and T. Østby
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There is considerable uncertainty about the evolution over the past decades of climatic mass balance of Austfonna, the largest ice cap (~8000 km2) in Svalbard. Recent airborne and satellite altimetry (1996-2008) indicate a marginal thinning concurrent to a thickening of the interior, a behaviour which may be associated with an increase in precipitation and intensified melt in a warming climate. Field measurements of snow accumulation across the ice cap have been made during the IGY 1957/58 and during annual campaigns since 2004. These observations revealed a spatial pattern of snow accumulation which, to a large degree, is associated with the orographic effect on the precipitation field as the dominant moisture flux from the Barents Sea hits the ice cap. Here, we present current progress and open questions related to modeling the accumulation field over the period 1957-2010, based on the ERA40/interim re-analyses.

Glacier, Ice and Snow Section at NVE – a short introduction

Rune Engeset (rue@nve.no)

Head Glacier, Ice and Snow Section at Norwegian Water Resources and Energy Directorate (NVE).

The Glacier, Ice and Snow Section has 17 employees and is one of nine sections in the Hydrology Department at Norwegian Water Resources and Energy Directorate (NVE). The Section was established in 1962 as the Glaciology Office and celebrates its 50th anniversary next year.

The Sections expertise is in glaciology with activities focused on research as well as management of water resources, natural hazards and climate. The Section covers four disciplines in glaciology: glaciers, snow hydrology, avalanches and river/lake ice. Our core activities are:

- National glaciological observation programme – observations of field-based mass balance (15 glaciers), front position (35+ glaciers) and area change (GLIMS regional centre), geodetic mass balance (selected glaciers and ice caps) as well as ice thickness and velocity at selected glaciers.
- Svartisen Subglacial Laboratory – a unique facility located under 200m of ice at Svartisen ideal for subglacial experiments and process studies.
- Snow hydrology – observations and modelling of the snow cover in support of national flood forecasting and hydropower production forecasting, as well as snow maps published daily at www.senorge.no.
- Avalanches – establishing the national avalanche warning service in Norway in collaboration with met.no, NGI and the transport authorities.
- Lake and river ice, including lake ice monitoring, issuing of ice bulletins to the public, and maps of weakened lake ice areas in hydropower reservoirs. National observation programme for lakes and river ice as well as water temperature in lakes (70 locations) and rivers (280 locations)
- Spatially distributed observations and modelling (remote sensing, geostatistics)
- Glaciological research and collaboration with universities, partner in SVALI

As per 27 October 2011, the Section includes:

- Liss M. Andreassen
- Ragnar Ekker
- Hallgeir Elvehøy
- Rune Engeset
- Sindre Engh
- Miriam Jackson
- Bjarne Kjøllmoen
- Ånund S. Kvambekk
- Markus Landrø
- Kjetil Melvold
- Karsten Müller
- Galina Ragulina
- Tuomo Saloranta
- Thomas Skaugen
- Heidi B. Stranden
- Klaus J. Vormoor
- Solveig H. Winsvold

www.nve.no/glacier provides more details.

Calibrating a physically based energy and climatic mass balance model at Austfonna ice cap, Svalbard

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A coupled energy balance and snow pack model has been applied to a glacier surface at the location of an automatic weather station (AWS) situated in the ablation zone of Austfonna ice cap. (~8000 km^2).

The purpose of this study was to investigate the partitioning of energy fluxes, refreezing, the climatic mass balance and climate sensitivity of an arctic ice cap.

Even if the applied model is based on physical principals there are still several empirical parameterizations of processes and material properties which must be determined. In fact, there are more adjustable parameters than existing observations to tune the model, especially since some observations should be left unused for model validation. However, by assuming that some adjustable parameters are constant over time an unique solution for the parameters may be found by treating observations from different years as independent data sets.

The adjustable parameters of the model were calibrated using a Monte Carlo approach with random estimates for the parameters within plausible ranges of values reported in the literature. Results of the Monte Carlo simulations were then compared to observations of radiation fluxes, surface elevation changes and snow and ice temperatures.

Many empirical parameters and material properties may be site specific and caution must be taken when transferring parameter values both in space and time.

Nevertheless, the presented approach contributes to efficiently narrow the plausible parameter space and to quantify the uncertainty related to the calibration.

GPR-measurements of snow distribution on Hardangervidda mountain plateau in 2008-2011

Galina Ragulina, Kjetil Melvold and Tuomo Saloranta
Norwegian Water Resources and Energy Directorate, Oslo, Norway

Hardangervidda, situated in southern Norway, is one of Europe's largest mountain plateaus. Most of the plateau is over 1000 m above sea level, and snow conditions on Hardangervidda are important for such aspects as hydropower production and recreation, and for the population dynamics of wild reindeer and trout. To investigate snow conditions on Hardangervidda, the Norwegian Water Resources and Energy Directorate (NVE) has conducted yearly snow measurement campaigns across Hardangervidda since 2008 using Ground Penetrating Radar (GPR) at the approximate time of annual snow maximum (mid-April). These measurements also provide valuable data for calibration of snow models, such as the *seNorge* model (www.senorge.no). We present snow distribution along west-east transects across Hardangervidda for three years (2008, 2010 and 2011).

Collected data in the form of radargrams were first digitalised and the digital data were averaged to 2, 10, 20 and 100-metre mean values. Measurements over hydrological features (such as small lakes) were filtered away. An empirical method was used for the calculation of snow depth.

The snow distribution over Hardangervidda was analysed both by longitudinal profiles and by separating western and eastern parts. We found a significant west-east trend in snow distribution and almost no difference in the north-south direction.

Investigation of data revealed a rather substantial limitation in the GPR-measurements, as snow depths less than 25-35 cm for 350 MHz-antenna and 15-25 cm for 1000 MHz-antenna were not readily possible to interpret. To rectify this problem, a statistical imputation method was used to replace missing values below this detection limit. Future fieldwork procedure should also be modified in order to better sample areas of low snow depth and bare ground.

Most of the constructed snow depth distributions have a two-peak shape. However it remains unclear whether the secondary peak is a real feature, i.e. a significant low snow depth population or large bare ground fraction, or merely an artifact of the GPR data. A closer investigation of this issue could improve our knowledge of the nature of snow depth distribution in mountain plateaus, and on the sampling and interpretation of GPR-based snow measurements.

Ground based interferometric radar data for calving monitoring

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Data of temporal variation of calving event and velocity directly from the calving fronts are very valuable because they inform about calving processes, which are still poorly understood. However, such data are rare, due to the dangers and difficulties connected to measuring. Ground based interferometric radar at high temporal rate (2 Hz) has successfully been used in the IPY GLACIODYN project for velocity measurements and monitoring of calving events at Kronebreen, Svalbard for four test seasons (2007, 2008, 2009 and 2010). The radar is placed ~4 km from the glacier, and the antenna lobe covers a width of ~700 m of the front. Daily terrestrial optical photogrammetry and continuous visual observation are conducted to facilitate the interpretation of a 116 hour radar data record from August/September 2008. The calving front geometry is extracted from the optical images, and its effect together with the movement of the glacier is identified in a plot of the amplitude of the radar return signal. Detection of calving events is demonstrated by change detection image processing in the radar data set, and 92 % of the total calving events are confirmed from visual observations and registration. Velocities determined from tracking of permanent scatters in the radar data gives an average velocity for the period of 3.2 md^{-1}, and we find in generally good agreement between our measurements and visual observations. In our experimental data set we have observed electromagnetic interference in the radar back scatter data from the calving front, and we explain this to be due to multipath scattering and tidal cycles. The radar has also successfully been tested from Ny-Ålesund research station, 15 km from the glacier front. Continuous radar monitoring of the calving activity of Kronebreen is therefore possible, and seasonal variations can be identified. A new and improved version of the radar is under development, which can map velocities in range and cross range. We investigate the possibilities of monitoring calving glaciers at Iceland.

Digital elevation model and reflectivity maps for a land terminating section of the Greenland ice sheet

Katrin Lindbäck, PhD project, GAP: Subproject A
Supervisor: Rickard Pettersson, Uppsala University, Sweden

Greenland ice sheet is losing mass, which can contribute significantly to rising sea levels on Earth. The warmer climate leads to an increased melting of the ice surface and an acceleration of the ice flow. The latter phenomenon is called dynamic thinning and is caused by the ice sliding and calving at a faster rate, resulting in a greater mass transported from land to sea. The increased sliding at the base is due to more melt-water from the surface reaching the bedrock, but the mechanisms behind this phenomenon are poorly understood.

In respect to this, it is important to get knowledge of the subglacial drainage system on a regional scale. My presentation will focus on the process of establishing a digital elevation model and reflectivity maps for a land terminating section of the western part of the Greenland ice sheet. Two field seasons has been carried out and approximately 2,000 km of low frequency radar data has been collected.

Investigation of $\delta^{18}O$ and δD in Svalbard snow pits

Tõnu Martma
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From 2001 to 2010 a snow pit study was conducted in Svalbard, Norway, with the aim to analyse the winter snow pack of one year for $\delta^{18}O$ and δD. Results give an idea of spatial variation of water stable isotopes in Svalbard winter precipitations. Samples were taken at Lomonosovfonna (springs 2001, 2002, 2010) and from Ny-Alesund area (springs 2003, 2004, 2005, 2007, 2009).

Simulating melt, runoff and refreezing on Nordenskiöldbreen, Svalbard, using a coupled snow and energy balance model

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Simulating ice melt, runoff and refreezing requires treatment of both surface and subsurface conditions. Refreezing of water in snow and firn layers contributes to the mass balance and indirectly affects the heat budget at the surface. To account for this, a distributed energy balance model is coupled to a multi---layer snow model and applied to Nordenskiöldbreen, a large outlet glacier in Central Svalbard. Being forced by output of the Regional Atmospheric Climate Model (RACMO) and weather station data from Svalbard Airport, the surface energy balance computes ice melt, which serves as input for the snow model. The snow model simulates the evolution of vertical profiles of temperature, density and water content. Extensive calibration is performed to estimate poorly constrained parameters. Thorough initialisation is conducted to attain subsurface profiles at the start of the simulation. The model is run for 1989---2010 and the spatial distribution and temporal evolution of the mass and energy balance is discussed in connection to evolving subsurface conditions. The simulated net mass balance ranges from ---0.95 to +0.17 m w.e. a---1 and is on average ---0.39 m w.e. a---1. Refreezing contributes as much as 0.27 m w.e. a---1 to the mass budget, which is equivalent to 69% of the snow accumulation. Refreezing is most pronounced in the accumulation zone, where it effectively raises subsurface temperatures and reduces runoff from the firn pack. The simulated mass balance, radiative fluxes and vertical profiles are validated against stake measurements, AWS data and snow pit profiles and generally a good agreement is found. Climate sensitivity experiments show a non---linear response of the mass balance, refreezing and runoff to temperature and precipitation perturbations. Taking into account seasonality in climate change, with less pronounced summer warming, is shown to have a major impact on the mass balance sensitivity. Finally, output of climate sensitivity experiments is used in combination with a seasonally dependent climate scenario to estimate a cumulative mass loss of 82 m w.e. for 2010---2100. Due to compensating effects the contribution of refreezing hardly changes in a future climate.

Ground-based measurements on Austfonna, Svalbard, for validation of the CryoSat-2 SIRAL data

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A comprehensive ground-based field campaign was undertaken in spring 2011 on Austfonna, Svalbard, to provide validation for the data collected by the new CryoSat-2 satellite. Ground based radar measurements were obtained with a CRESIS Ku-band FMCW radar. The radar was operated to cover the frequency band of the CryoSat-2 synthetic aperture interferometric radar altimeter (SIRAL) and the airborne version, Airborne Synthetic Aperture and Interferometric Radar Altimeter System (ASIRAS) carried by the Danish geophysics plane. Simultaneous profiles were obtained within half a day of each other with all three radars during the spring calibration/validation campaign on the Austfonna ice cap, Svalbard. The profiles, totaling approximately 200 km, span an elevation change of 400 m from the summit down to the ablation area, and cover a range of glacier facies and surface snow conditions. The ground based radar, which clearly images the near surface layering, was supported by snow pits, firn cores, and borehole videos, all of which are used together to validate interpretation of the CryoSAT-2 data.

An analysis of area and elevation changes in Southern Svalbard, 1936-1990-2008

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Area, elevation and volume changes are computed for ~280 glaciers in Southern Svalbard covering ~4000 km2 over two time epochs, 1936-1990 and 1990-2008. Results indicate more negative geodetic balances during the most recent epoch. Smaller glaciers are observed to have experienced large retreat and mass loss during the 1936-1990 epoch but have stabilized since 1990. Alternatively, larger glaciers seem to have experienced an accelerated thinning and retreat since 1990.

Winter WNaMg melting index used to assess the percolation processes affecting nitrate concentrations at the Lomonosovfonna ice core drilling site

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The increase of atmospheric reactive nitrogen over the last decades can be registered in Svalbard ice cores but post-depositional effects may alter the nitrate record mainly by percolation of melt water. Both chemistry and stratigraphy of six different snowpits (1.50 meters deep) sampled during winter at different Svalbard glaciers and the top 8 meters of 3 different ice cores drilled in Lomonosovfonna (in 1997, 2008 and 2009) were studied to estimate the percolation effects on nitrate concentrations. The average melt index (WNaMg=log[Na+]/[Mg+2]) was calculated in each snowpit and in the different cores. The WNaMg experience little variation in the snowpit data as it could be expected for winter when percolation events are rare while in the ice cores the WNaMg show a rather cyclic behaviour which reflex the seasonal melting on Lomonosovfonna. Using the snowpit data an average winter value for WNaMg of 0.87±0.07 was found and used as reference to assess the degree of melting and the percolation depth in each Lomonosovfonna core where the average WNaMg index is about 46% higher in the top 8 m of the LF-97 ice core, a 3% higher in the LF-09 core and a 22% higher in the LF-08 core with respect to the winter snowpack values. The WNaMg indexes calculated in this study will be used to improve the understanding of a novel nitrate isotope record obtained in 2009 at Lomonosovfonna.

Temporal and spatial distribution of surface mass balance on Fimbul ice shelf (FIS), East Antarctica

Anna Sinisalo [1], Helgard Anschütz [2], Kirsty Langley [1,3], Anne Tårånd Aasen [3], Angela von Deschwanden [3] , Elisabeth Isaksson [3], Jack Kohler [3], Tonu Martma [4], Svein-Erik Hamran [1,5], Mats-Jørgen Øyan [5], Ole Anders Nøst [3], Jon Ove Hagen [1] and Kenny Matsuoka [3]

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Continental wide surface mass balance (SMB) studies over Antarctica do not often cover coastal areas or they show data only in very low resolution. We present spatial and temporal variability of SMB over the Fimbul ice shelf measured by a ground based frequency modulated continuous wave (FMCW) radar calibrated with a set of shallow firn cores. Direct stake measurements of the SMB over 2 years 2009-2011 give an insight to more recent SMB, and its internannual variability. These results will be compared with the largely varying previous SMB estimates over the ice shelf.

Glacier surges: controls, processes and distributions

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Surge-type glaciers are characterised by the relatively regular alternation of slow and fast flow regimes, which occurrence is triggered by internal processes and which character (magnitude, periodicity) is influenced by external factors.

Surge-type glaciers are found in several well-defined clusters, most of which form an "Arctic ring" including parts of Greenland, Svalbard, Iceland, Alaska, Yukon Territory, Novaya Zemlya and Arctic Canada. Interestingly, this Arctic ring lies close to the northern limit of temperate glaciers and the southern limit of cold-based glaciers.

In response to the range of surge type glacier constitutions and the variety of surge behaviours observed, two mechanisms of surging have been developed: the thermal switch mechanism applicable to polythermal glaciers, and the hydraulic switch mechanism to warm-based glaciers. Despite the wide acceptance of these two distinct models for surging, the occurrence of surges of both polythermal and temperate glaciers within the St Elias Mountains cluster hints at possibility of a single surge mechanism.

The study of glacier surging is important on many levels as it provides key information on ice flow dynamics, ice sheet instability and relates to significant environmental issues as a surging glacier can cause dramatic floods, dam rivers and fjords, and damage installations and settlements.

This project aims to address the non-random distribution of surge-type glaciers and the controls and processes of surging by developing a new energy-budget approach to model both steady-state and oscillatory glacier responses to climatic and topographic factors. The model will be calibrated using data from a global dataset of surge-type glaciers with an emphasis on their climatic and topographic contexts, and secondly field and remote sensing data from the Svalbard archipelago.

In addition to the creation of a new model of glacier surging, this study will provide up-to-date statistics on the world's population of surge-type glaciers with an emphasis on the Arctic ring, consider the importance of the topographic and climatic contexts in the occurrence and processes of surging, and provide new field data on surging from glaciers currently in late quiescence.

Interaction between Holocene permafrost and glaciers in Norwegian mountains

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Following the last glaciation, cryogenic processes related to valley and cirque glaciers, permafrost and seasonal frost have dominated Norwegian landscape development in high-mountain areas. This is evident by different landscape and landform features like rock glaciers, block fields, palsas, ice-wedge polygons and ice-cored moraines. A recently developed inventory of permafrost-related landforms clearly demonstrates a spatial pattern which is attributed to different climate conditions during Holocene.

While both the glacial Holocene history and the present permafrost situation in Norway are well-known, the interaction between these two members of the cryosphere is not studied to the same degree. Of the inventoried permafrost landforms, a high number is connected to glacial activity, either as ice-cored moraines or as moraine-derived rock glaciers.

Presented here is the results of two mean annual air temperature deviation curves through Holocene that have been compiled to drive a 1D heat flow model over the last 10 ka period for several mountain sites in Norway, to simulate past ground temperature conditions. At each site temperature-monitored boreholes, which were used to calibrate the model, exist. In addition the spatial distribution of permafrost during selected time periods of the Holocene were addressed using a newly implemented version of an equilibrium permafrost model (TTOP). The result of this study indicate an altitudinal zonation of relative permafrost age in Norway, where permafrost has existed continuously since the deglaciation in the highest areas, while large areas that is underlain by permafrost today were degraded during the Holocene Thermal Maximum (HTM). For all the sites the deepest simulated permafrost occurred during the Little Ice Age (LIA), and also the largest areal distribution of Holocene permafrost in Norway is connected to the LIA.

This distributional pattern has implications for the subglacial temperature regime, and subsequently for glacial landform development. Glaciers advancing and terminating in a permafrost environment are polythermal and, at least marginally, cold-based. These conditions favour basal on-freezing of subglacial material and the development of ice-cored moraines rather than distinct bulldozing or push landforms. In southern Norway, many glaciers that developed during the LIA are now retreating or even disappearing, and often situated in high altitudes and close to the present lower boundary of mountain permafrost. Omnsbreen close to Finse is one of these glaciers, and in this presentation we will show that during the maximum position of this glacier, permafrost was probably widespread in the area, affecting the geomorphological response left by the glacier.

An attempt to reduce errors in InSAR deduced DEM of a glacier by applying atmospheric phase correction

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We present work in progress to construct a DEM for the year 1995 of the Hofsjökull ice cap (850 km2), central Iceland, from InSAR data of the ERS1/2 tandem mission. The data include 15 InSAR pairs acquired during the winter 1995-1996 from various tracks, which were topographically corrected with existing DEM's from 1986 and 2008. We developed a data fusion method to extract the topographic residual signal in the interferograms and obtain a DEM corresponding to the autumn 1995. Our first attempt to obtain a new DEM, indicated an unrealistic elevation decrease (~10 m) in the upper part of the ice cap from 1986 to 1995, while direct mass balance observation from this period showed slightly positive average net balance for the ice cap. On the other hand, an elevation rise of similar magnitude was derived for the period from 1995 to 2008 further supporting that the derived elevation change in the upper part of the glacier was indeed artificial due to erroneous data. It is well known that temporal changes of atmospheric conditions between two SAR observations, forming an interferogram may produce significant phase variations in InSAR data. Hence, prior to a second attempt to obtain a DEM for 1995 we use high-resolution atmospheric data from the RÁV-project, based on the AR-WRF mesoscale model to estimate these phase signals. The ECMWF analysis is dynamically downscaled to 3 km x 3 km horizontal resolution and 55 layers from the surface to 20 km height, with a 3 hour temporal resolution. In our presentation we demonstrate the characteristics of the atmospheric phase signals calculated from the atmospheric data and how applying such an atmospheric correction on the InSAR data, prior to our data fusion, changes the accuracy of the resulting DEM.

Evaluation of gridded precipitation for Norway using glacier mass-balance measurements

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The service SeNorge (http://senorge.no) provides gridded temperature and precipitation for mainland Norway. The products are provided as interpolated station measurements on a 1 x 1 km grid. Precipitation gauges are predominantly located at lower elevations such as coastal areas and valleys. Therefore, there are large uncertainties in extrapolating precipitation data to higher altitudes, both due to sparsity of observations as well as the large spatial variability of precipitation in mountainous regions.

Using gridded temperature and precipitation data from SeNorge, surface mass balance was modeled for five Norwegian glaciers of different size and climate conditions. The model accounts for melting of snow and ice by applying a degree-day approach and considers refreezing assuming a snow depth depended storage. Calculated values are compared to point measurements of glacier winter mass balance.

On average for each glacier, modeled and measured surface mass-balance evolutions agree well, but results at individual stake locations show large variability. Two types of problems were identified: first, grid data were not able to capture spatial mass balance variability at smaller glaciers. Second, a significant increase of the bias between model and observations with altitude for one glacier suggested that orographic enhancement of precipitation was not appropriately captured by the gridded interpolation.

Observing ice mass changes with GRACE satellite gravimetry

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The GRACE satellite mission provides observations of gravity changes from 2002 until present and reveals a lot of information about mass changes in the hydrosphere and in the cryosphere. From the time series of observations the corresponding mass changes on the Earth's surface can be modeled.

Due to the attenuation of small scale gravity signals at orbit height and the measurement accuracy of GRACE, the satellite mission is only able to detect gravity signal variations of a certain amount and spatial resolution. Therefore, we set up a forward computation model to estimate the time-variable gravity signal from a previously well-defined glaciological effect. In a first step, this model can be used to check for the observability of signals from the cryosphere in current GRACE observations.

Furthermore, the official science products of the GRACE mission are monthly global maps of gravity changes. Based on those maps, ice mass changes in larger regions, such as Antarctica or Greenland, are studied successfully. Since they are global, the maps are globally optimized best-fit solutions. Thus, they are not necessarily representing a regional signal in an optimal way. With a regional representation, signal may be detectable in the time series that has been masked in the global solutions. Regional data analysis approaches have already shown that GRACE measurements can also reveal information about smaller scale signals. The technique of using radial base functions with local support is presented.

So in a second step, we complete the forward model to a closed-loop simulation. A well-defined synthetic GRACE signal is analyzed and represented in radial base functions. Focus is on smaller-scale cryospheric signals, such as mass changes of individual ice caps. These input signals are modeled using a mascon representation, which has been successfully used by others to represent cryosphere mass changes.

The closed-loop simulation offers the following advantages: First, it demonstrates clearly the strengths and shortcomings of the data analysis method as well as the effect of different error sources. Second, it offers a strong tool to examine the observability of cryosphere signals by GRACE. Thus, third, the studies with the model will provide a helpful tool for the analysis of real GRACE data.

Volume changes of Mýrdalsjökull ice cap in Iceland, deduced from multi temporal DEMs and elevation profiles

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A time series of digital elevation models has been constructed of Mýrdalsjökull (~560 km^2) ice cap in Iceland: in late August, 1998 (the northern parts using EMISAR), 1999 (from aerial photographs and in situ measurements), 2003 (SPOT5 HRS), 2004 (SPOT5 HRG), 2006 (SPOT5 HRS) and 2010 (airborne LiDAR). The surface elevation of Mýrdalsjökull has been surveyed along ~15 profiles every spring and autumn since 1999, from airborne radar and kinematic GPS or on-surface traverses using kinematic or DPGS. We present preliminary results of applying a method, based on Markov random field modeling and simulating annealing optimization, to produce a time series of elevation maps with high spatial coverage. The inputs are the DEMs that describe spatial variability and *in-situ* elevation data providing temporal elevation changes along the surface profiles and sparse point observation. The volume changes during the last decade are estimated using the difference between the derived DEMs. Very limited estimates mass balance has been available so far on Mýrdalsjökull, conducted at only few stakes within the accumulation area.

Measurements of seasonal surface velocity variations by continuous GPS measurements on the Hofsjökull ice cap in central Iceland

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Variations in the subglacial hydrological system are likely to be the main cause for ice velocity variations that have been observed on many glaciers in recent years in connection with increased surface melting caused by climate warming. The relationship between subglacial hydrology and ice velocity variations is being investigated as a part of the Nordic Toppforskningsinitiativet SVALI project. One of the study areas is a partly glaciated watershed on the north side of the Hofsjökull ice cap in central Iceland where two hydrometric stations are located near the ice edge. In order to investigate the seasonal variations in the surface ice velocity on the northern flank of Hofsjökull a continuously recording GPS-station was operated from Mai 2011 to September 2011. The GPS-station was located at the lower edge of a relatively flat area at an elevation of about 1300 m a.s.l., near the equilibrium line of the glacier. Recordings were made at 15 s intervals and the data are processed kinematically relative to a fixed station near the ice edge. These data are intended for comparison to calculations of meltwater input and hydrological data. Hourly river discharge measurements from two hydrometric stations will be presented for comparison. One of the stations is located in the river draining the part of the glacier that the GPS-station was located on but is ~40 km down river from the glacier margin while the other one is located in the highland, ~15 km down river from the glacier, but is draining an adjacent part of the glacier. Precipitation and temperature data from an automatic weather station located in the highland, ~10 km north of the glacier, will also be presented. These data show different velocity variations that can be connected to changes in estimated meltwater input and river discharge.

Sub-shelf morphology of the Fimbul Ice Shelf, Antarctica

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This study focuses on ground based radar profiles, surveying the fast-flowing Jutulstraumen region of the Fimbul Ice Shelf, Antarctica. The profiles are oriented perpendicular to ice flow between the grounding line and the shelf front revealing changes in the sub-shelf morphology.

The basal morphology is found to be rough close to the grounding line, with large basal troughs oriented along flow direction. These troughs become less pronounced towards the shelf front. Internal reflectors are identifiable in the radar profiles 20-100 m above the basal troughs, suggesting a continuation of the troughs upwards through the ice column. A visible correlation between basal troughs and surface flow stripes in satellite radar imagery is found. A mosaic of TerraSAR-X radar scenes, acquired between 2008 and 2010, serves as a base for the detection of surface flow stripes. As flow stripes are observed to form a network of bifurcating troughs, we expect a similar picture for the sub-shelf morphology. The surface flow stripes and the characteristics of the basal troughs allow interconnecting subshelf features between the individual radar profiles.

High resolution meteorological measurements on Kongsvegen glacier (Svalbard)

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Detailed meteorological measurement data are still scarce at high Arctic glaciers, which are still essential to get a better understanding of their response to regional climatic developments. A network of six meteorological stations was established along the central flow line of Kongsvegen glacier. Three of them are equipped as energy balance stations to investigate the snow/ice/atmosphere interaction processes in the accumulation and ablation area of the glacier. Similarly detailed measurements were rarely performed elsewhere and we here present some basic results covering the first observational year.

During April 2010 until May 2011 air temperatures in the glacier domain range from -36°C to +6°C. Notably, air temperature can be positive at almost any time of the year and at any elevation of the glacier. This abrupt increase in temperature is related to synoptic systems which are characterized by high wind speeds and relatively high temperatures. During ablation period typical along glacier temperature gradients are close to the moist adiabatic gradient. More stable atmospheric conditions are found during winter. Wind speed intensity follows roughly the terrain slope with a general increase towards the tongue of the glacier indicating a persistent katabatic regime. Correspondingly, wind direction is characterized by an outstanding directional persistency, which is less pronounced at higher elevations. Water vapor pressure decreases with elevation due colder temperatures. Global radiation shows distinct elevation gradients (around 0.03W/m2m1) as well as reflected shortwave radiation with -0.06W/m2m1. On the other hand, long wave radiation components show a decreasing tendency with increasing elevation. Summarized, radiation balance is slightly positive at lower elevations (+1W/m2) with a linear tendency to negative values towards the crest (-6W/m^2).

The data is also put in context to radio sounding data (Ny Ålesund) what gives informations of the atmospheric stability, which again is linked to Kongsvegens boundary layer and energy balance. Also considered is data that was measured concurrently at the climate station NyÅlesund (8m a.s.l.), which is essentially interesting regarding future mass and energy balance modeling. Finally, the data are also valuable for validation of regional atmospheric model output, remote sensing derivatives and for the interpretation of high resolution snow measurements, which have been conducted in parallel.

Climatic trends in Jotunheimen, Southern Norway: An investigation of variations in equilibriums lines today and during the Little Ice Age using remote sensing and the accumulation-area-ratio method

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A large scale trend analysis of climatic variations in Jotunheimen, southern Norway was investigated based on glacier variations. Equilibrium line altitude elevations (ELAs) were estimated for 92 glaciers for present day and Little Ice Age (LIA) conditions by use of remote sensing and a modified version of the accumulation area ratio method (AAR). A steady-state AAR value of 0.6 and glacier length was used. Results illustrates a continental gradient where ELAs rise and changes in ELA (ΔELA) decrease from west to east both for present day and Little Ice Age conditions. The results, achieved with relatively simple tools and a modified method, emphasizes the importance of temperature and precipitation distribution through the study area and are thus in accordance with earlier research. Glacier size indicates no geographic trend. Glaciers with ELAs at high altitudes have generally experienced less reduction in length at the equilibrium line. Glacier orientation shows a preferred north, northeast aspect which is also true for glacier distribution with a higher number of glaciers in north, northeast and easterly slopes. Glacier form, size, hypsometry and other local topographic factors all influence glaciers response to climate variations in various ways, but for a large scale trend analysis these effects were of less importance.

Real-time monitoring of glacier retreat and ice-front evolution, Virkisjökull, Iceland

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Iceland's glaciers are evolving rapidly in the current period of climate warming (since approx. 1990). Consequently, dynamic glacial and geomorphological processes are now operating at rates that can be monitored and recorded over shorter timescales – years, months and even days. Capturing this high-resolution data is technically demanding but is essential for establishing drivers, mechanisms and rates of glacier change.

The Öræfajökull ice cap, the southernmost portion of the Vatnajökull ice mass, has 13 named outlets. 8 of these glacier margins are monitored annually by the Icelandic Glaciological Society. We present research focusing on the twin outlet glacier of Virkisjökull-Falljökull, visited regularly by members of the British Geological Survey (BGS) team since 1996. Aerial photographs spanning the last 25 years, combined with detailed geomorphological mapping and field measurements have identified successive annual ice-front positions charting continuous glacier recession between 1990 and 2011. Over 400 m of ice-front retreat has occurred in this time, with almost half of this retreat (190 m) since 2005.

Since 2009, BGS have installed a range of instruments to monitor the environment at Virkisjokull in real time. Automated weather stations with a satellite link to Edinburgh are recording glacier-meteorology at the ice margin and at high elevation. These stations have been recently augmented (in 2011) with automatic digital cameras taking 3 pictures a day. A network of 4 broadband seismometers, located around the glacier margin, continuously records seismic events – typically around 200 per day. These events are related to glacier motion and initial analysis suggests a link between glacier seismicity, daily weather patterns, and basal hydrology. An automatic stream gauge has also been installed on the main meltwater river. In addition to these instruments, terrestrial LiDAR surveys of the ice front have been completed each year since 2009. These laser scans capture ice-front change in centimetre-precise detail. Inter-annual comparisons of LiDAR DEMs allow spatial and temporal variations in thinning and retreat of the ice front to be closely examined. Analysis of these high-resolution DEMs, coupled with field observations spanning several years, reveal a highly complex pattern of geomorphological evolution and ice front retreat forced by climate and conditioned by supraglacial debris, buried ice and englacial hydrology.

Subglacial water pressure and relation to subglacial discharge at Engabreen, northern Norway

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The Svartisen Subglacial Laboratory is situated in northern Norway under 200 m of glacier ice. It provides a unique opportunity to gain direct access to the base of the glacier, and to place instruments at the ice-rock interface. Several earth pressure sensors were emplaced at the base of the glacier several years ago and record pressure at regular intervals. Geophones (three-component) have also been placed in the tunnel system, such that they can record seismic events at the base of the glacier and are positioned closer to the ice-rock interface than instruments on the glacier surface. There are several drainage tunnels that transport water from subglacial and subaerial intakes to the reservoir for the Svartisen Hydropower plant. Some of these tunnels are also instrumented such that water discharge is recorded regularly.

The signals recorded by the pressure sensors and the discharge measurements show good correlation during and after the spring speed-up that tends to occur in late May/early June, when the basal water system changes from a linked cavity system to an arborescent, channelised system. Influxes of water discharge to the system, either due to precipitation or increased melting, generally occur at intervals of several days and are registered promptly at the glacier bed. The pressure sensors record this influx first as a sudden drop in pressure, followed by an abrupt rise to a pressure higher than before the event and then a more gradual decrease back to the original pressure. This suggests that glacier uplift occurs, and the pressure increases to above the mean ice overburden pressure. These observations are in good agreement with previous results from the subglacial laboratory and other glaciers.

Uncovering glacier dynamics beneath a debris mantle: its control on surface profile shape

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Unlike normal glaciers, debris-covered glaciers (DCG) have an extensive sediment mantle, whose albedo and buffering effect significantly enhances and reduces ice melt. This last phenomenon suggests that DCGs are less sensitive to climate change and might persist longer than debris free glaciers. Despite the considerable implication of this insulating layer, the origin of DCG and the extent to which the debris mantle impacts on glacier dynamics is relatively unknown.

Although the DCG front seems motionless, the debris-mantled zone shows surface lowering and often low surface velocities compared to the clean ice zone. Supra-glacial sediments appear to be an effect and a cause of such an evolution.

Research on DCG also aims to assess geo-hazards linked to the sudden release of water stored within supra-glacial lakes. As glacier melts down, those lakes generally form at the surface of DCGs within troughs. Their occurrence appears closely linked to the debris-covered zone dynamics.

This project investigated debris cover impact on glacier dynamics and surface geometry through a numerical analysis based on classic glaciological laws and a steady-state flow-line model. The latter couples ice dynamics, mass balance and debris cover feedback on ablation rates.

The model simulates indefinitely flowing debris-covered glacier that shows an inverted mass balance. In the model, the sediment thickness is highly dependent on the glacier turn over around the ELA. Moreover, model insights indicate a bi-modal glacier behaviour. For thin debris cover, glaciers retreat as mass balance gradient steepens whereas glaciers continuously advance when they have enough time to build up a sediment buffering effect. In the light of the model results, the location of the debris cover and the ice sediment concentration strongly affects ablation zone dynamics. This analysis produces a theoretical framework to interpret modern glacier profile.

Nordic Centre of Excellence SVALI - Stability and Variations of Arctic Land Ice

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SVALI (http://ncoe-svali.org) is a part of the Top-level Research Initiative, which is a major Nordic collaborative venture for studies of climate, energy and the environment. The SVALI NCoE is within the TRI sub-programme "Interaction between Climate Change and the Cryosphere".

The NCoE SVALI takes on the task to answer these key questions:

How fast is land ice volume in the Arctic and North-Atlantic area changing, and why?
Will these processes continue to accelerate?
What are the consequences for sea-level and ocean circulation?

The science in SVALI is focused within three themes:

1) Observing the present - baseline and changes,
2) Understanding the physical processes
3) Understanding present changes and predicting the future.

Advanced Earth system modeling will coordinate model development within all themes of the project.

A Nordic SVALI graduate school has been established with joint courses, summer schools, workshops and cross border integration of PhD projects and Post.Doc activities.

SVALI has 17 partners from all Nordic countries and will operate during 2011 to 2015.

Spatial distribution of snow depth at Hardangervidda Mountain, Norway, measured by airborne laser scanning

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Snow depth variability over small distances can affect the representativeness of depth samples taken at the local scale and it will therefore affect number of measurements needed to obtain representative values. It is further difficult to obtain measurements of snow depth distribution over a large area at a resolution that approximates the scale of its "true" variability. Such measurements are needed in order to validate spatially distributed snow simulations at fine- to middle-scale or observations from satellites. Manual data collection using snow stakes or probes, is labour intensive, expensive, and potentially dangerous in steep mountain environments. These issues call for new technology such as airborne laser scanning, which is a powerful tool for surveying large area within a short period. This study presents laser scanner mapping of snow depth in the mountain plateau Hardangervidda, Norway, in two different years (2009 with less snow than normal and 2008 with more snow than normal) at the approximate peak time of snow accumulation during the winter. The extent of the survey area is more than 240 square kilometers.

Here we investigate variability of snow depth as derived from the laser scanning data at local scale with a horizontal resolution of 2 m. The local snow depth measurements were scaled by using averaging scheme to 10, 50, 100, 250, 500 m and 1 km. A scale analysis of the spatial variability of snow depth where performed. The measured variability where compared to simulations snow depth variability from the Snow Maps for Norway available at http://senorge.no, which is run on a 1 km and 1 day resolution. Results shown that the variability decreases as the scale increase however at large scale the picture is not show clear. At a scale of about 500m to 1 km the variability are similar to the seNorge (www.seNorge.no) modeled snow depth variability.

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