Palaeoclimatology, oceanography and glaciology in the Helheim Glacier region

WORKSHOP
March 25 and 26 - 2010

GEOLOGICAL MUSEUM
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Will we lose the southern dome? - the lesson from the geological past

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Recent years' rapid melting of the Greenland ice sheet has shown that the southern dome is the ice sheet's most vulnerable part. The southern ice sheet dome, the area south of c. 67°N, is a highland ice cap with its base c. 500 m a.s.l. It contains c. 15% of the Greenland ice sheet's volume, equal to c. 1 m global sea level, and is characterised by very high accumulation and melting. Two of the most active outlets from the ice sheet, Jakobshavn Isbræ and Helheim Gletscher drain the saddle between the northern and southern ice sheet domes.

Can the southern dome's response to past warming give us a clue to its fate in the future? ODP borings on the shelf have shown that the ice dome has existed, on and off, at least since the Miocene. Recent results from the DYE 3 ice core and other sources indicate that the dome melted away, and gave way to forested mountains for the last time during marine isotope stage 11, c. 400,000 years ago. The southern dome, and of course the northern also, persisted in a reduced form during the warm Eemian interglacial (c. 125,000 years ago), when annual mean temperatures over Greenland were c. 5°C warmer than now for some millenia. During the last ice age the south-east coast of Greenland was one of the areas of major ice sheet growth, reaching the shelf edge at the last glacial maximum, c. 20,000 years ago, as shown by bathymetric studies. During the Holocene thermal maximum, c. 8,000 years ago, when annual mean temperatures were c. 2°C warmer than now for some thousands of years, modelling and GPS altimetry show that the southern dome was the most sensitive part of the ice sheet, retreating as much as 80 km behind its present front in some areas. After this, during the neoglacial the ice margin readvanced. In spite of the large scale changes in ice cover in this area, the Holocene isostatic history is peculiarly muted and characterised by low uplift. This can be interpreted in several ways, but does show an abnormal ice load history, when compared to other sectors of the ice sheet.

In general, the variable behaviour of the southern dome through the geological record contrasts with that of the much more resilient northern dome. Judged from this, we can expect a more direct and vigorous response to warming in the southern dome than in the much larger northern dome, but will it melt away for the first time in 400,000 years? – Probably not.

Rapid ice sheet changes: southeast Greenland and beyond

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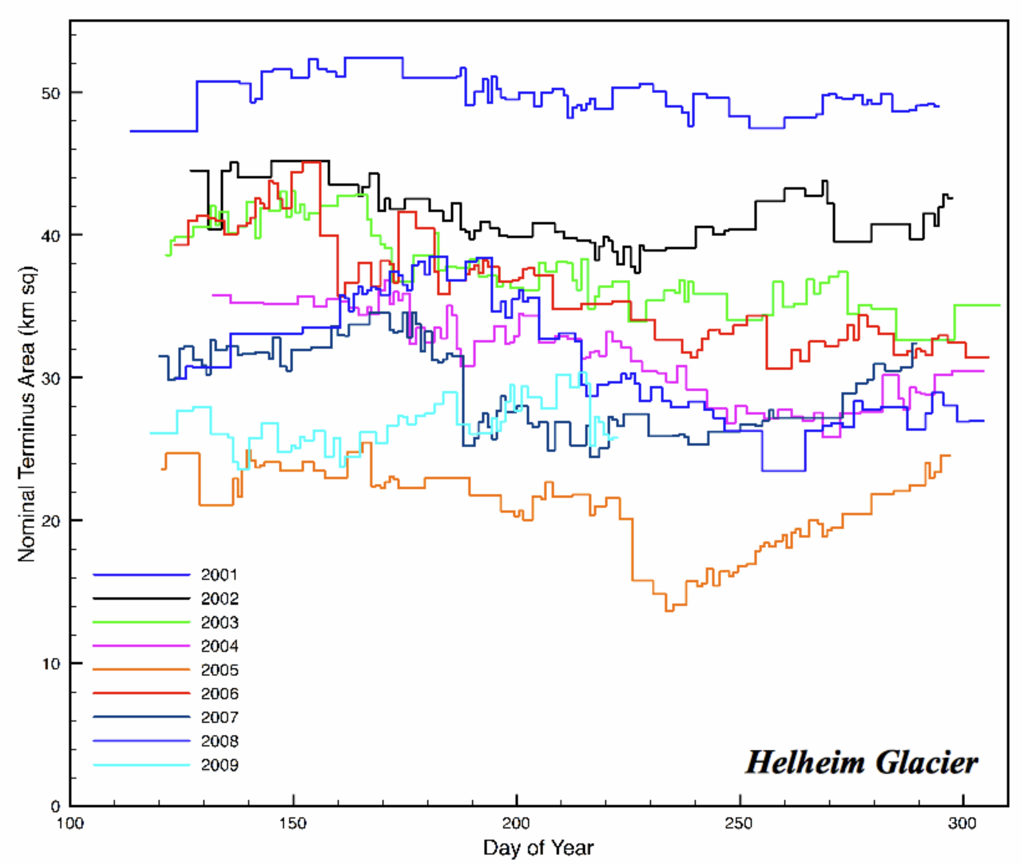
A large section of the southeastern margin of the Greenland ice sheet, including Helheim and Kangerdlugssuaq glaciers, underwent a series of rapid ice dynamic changes in the early years of this century. The near synchronous timing of these changes at different locations indicates a regional ice sheet response to a common climate forcing. Several lines of evidence point to the ocean as being the source of the triggering mechanism, including observations of warm ocean waters deep inside Sermilik Fjord and their rapid replenishment by wind-forced circulation, and the rapid adjustment in the speed of Helheim Glacier following large calving events. Field and modeling studies are now underway to better understand the interaction between outlet glaciers and the ocean, but another way of examining the link is to look for patterns in high temporal-resolution records of terminus behavior (occurrence of large calving events) derived from satellite imagery (e.g., Figure 1). These records show a switch in terminus behavior before and after the ice dynamic changes. Before the changes, terminus positions oscillated around quasi-stable locations in the fjord; after the changes, terminus positions fluctuated rapidly within each calving season and between calving seasons, and there was an increase in the frequency of large calving events (consistent with the increase in teleseismically-detected glacial earthquakes). Changes in ocean heat content might modulate these fluctuations, for example, by weakening the melange of sea ice (sikkusak) at the terminus which might enhance iceberg calving, or by increasing submarine melt rates at the terminus and changing the delicate balance between ice thickness and water depth (which would also lead to calving). The observational basis for a link between sikkusak and the timing of calving events is mixed: a relationship apparently exists for Jakobshavn Isbrae, but not for Helheim Glacier which has year-round sikkusak in front of its terminus, although there is a clear seasonal signal in terminus position (Figure 1). The timing of the maximum rate of change in ocean heat content might be an alternative explanation for seasonal signal in terminus position; this is not necessarily the same as the arrival time of the warmest waters (which our initial observations suggest is during the winter months) because it can also include rapid replenishment of fjord waters by along-shore wind events. Further work is underway to clarify the nature of the fluctuations in terminus position.

If the ocean is indeed the source of the triggering mechanism, other marine margins of the Greenland Ice Sheet are at risk for a similar series of dynamic changes as occurred in the southeast. A potentially vulnerable area is the floating tongue of Nioghalvfjerdsfjorden Glacier (NFG) in northeast Greenland. We are carrying out field and remote sensing studies of the glacier system. Recent observations point to a speed up of ice crossing the grounding line, and a possible increase in the temperature of ocean water adjacent to and beneath the cavity (based on a comparison of summer 2009 data with GEUS/AWI measurements from 1999). Increased submarine melting of the floating tongue might lead to its retreat and/or collapse, which would propagate a large ice dynamic response far into an interior portion of the ice sheet which sits in a deep subglacial trough.


Nominal Terminus Area (km sq)
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2001
2002
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2006
2007
2008
2009
Helheim Glacier

Towards a long-term oceanographic observing capability at Helheim Glacier, Greenland

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A review of past ocean observations in Greenland outlet fjords is presented, as well as an overview of ongoing and future observations. Past studies have revealed that warm, subsurface waters from the North Atlantic Ocean have periodically flooded the foredeepened fjords and triggered rapid retreat of outlet glaciers. These oceanic events have been triggered by changes in the mean wind patterns across the North Atlantic, a phenomenon known as the North Atlantic Oscillation. Going forward, there is a need for a sustained observation network containing meteorological, glaciological, and oceanographic observations along key outlet fjords of coastal Greenland in order to put the current empirical relation between atmospheric forcing, oceanographic response, and glacier retreat onto a firmer observational foundation.

Rapid Circulation of Arctic and Subtropical Waters in Sermilik Fjord

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Summer time oceanographic surveys of Sermilik Fjord collected in 2008 and in 2009 reveal that the fjord's waters are characterized by three recurrent layers: a thin, very fresh glacial melt water layer, a roughly 100-150m layer of cold, fresh polar water of Arctic origin and a 600-800 m thick layer of warm, salty water of subtropical origin. The three layers are present throughout the fjord including in the vicinity of Helheim Glacier where we found evidence that the subtropical waters are driving substantial subglacial melting. Repeat hydrographic surveys, combined with direct velocity measurements, show that the fjord's waters are renewed rapidly – faster than would be expected if the circulation were purely estuarine, driven by the glacial melt water inflow. Instead, using moored observations from the fjord, we found evidence that the flushing and flooding of the fjord are associated with variations on the shelf induced by the transiting storms. The implication is that the properties and renewal of waters at the edge of Helheim Glacier are dominated by the oceanic and atmospheric circulation. Our ongoing monitoring of the circulation within Sermilik and on the shelf seeks to establish which ocean dynamics and which external forcings regulate the circulation in the fjord and the heat transport to the glacier.

Dynamic of tidewater glaciers in the Sermilik Fjord system and fjord-shelf interaction

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Hydrographic surveys accomplished in August 2008 and 2009 (CTD, surface T/S records, oxygen isotopes) over the southeast Greenland shelf and inside 80 km long Sermilik Fjord (SF) allow quantifying properties of water masses and their interannual variability. Fjord-shelf exchange is driven by brackish water outflow in the surface layer and local atmospheric circulation. Five layers structure can be detected in the SF from vertical profiles (fig.1): warm upper summer layer, two layers with negative temperature centered nearby 30 and 150m which are separated by warm interlayer. The lower temperature minimum layer transports cold and fresh water of Arctic origin. Below 200m the Atlantic Water (AW) with temperatures above zero occupies all deep parts of the SF.

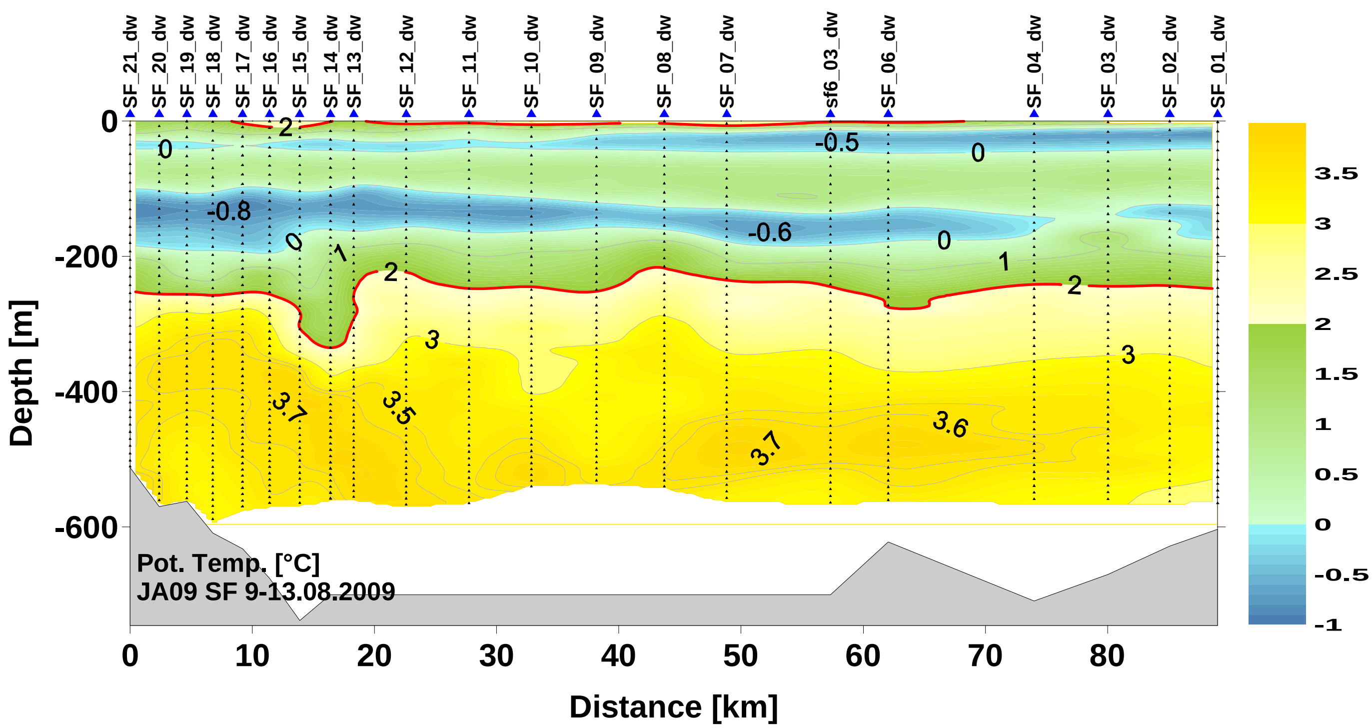

Fig.1 Potential temperature distribution along the Sermilik Fjord. Expedition on board 'Jotun Arctic' in August 2009

In August 2009, 155 CTD stations were completed along 11 sections inside the SF and over the adjacent Greenland shelf. Strong horizontal salinity gradients depict frontal zone which separates the fresh water plume discharged from the SF and shelf water carried by East Greenland Costal Current (fig.2, left). Oxygen isotope analysis allows quantify proportion of the AW, meteoric water and fresh water derived from sea ice melt. The meteoric water fraction on surface changed from 10 to ~80% over the study area (fig.2, right). Oxygen isotope samples taken from 50m show that more than 94% of water composes from the AW. Water mass properties in the mixing zone close to the SF mouth show considerable changes between 2008 and 2009. The AW core with temperature more than 7^{o}C was registered in 2008 close to the SF entrance, but was replaced by cold Arctic water in August 2009. It is unclear how far such pulses can penetrate into the fjord. Inside the SF the meteoric water fraction in 2009 increased by 25% in comparison with previous year, while it is unclear if it determined by seasonal or interannual variability. Findings that the SF is a deep fjord with AW circulated below 200m stimulated studying of connection between glaciers dynamic and variable oceanographic conditions.

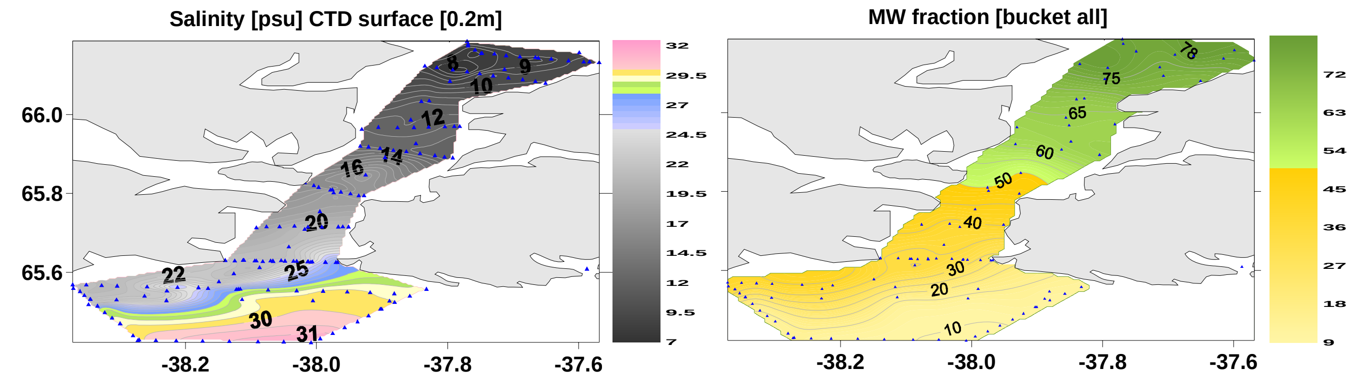

Fig.2 Surface salinity [psu] from CTD (left) and meteoric water fraction [%] derived from oxygen isotope analysis (right). Expedition on board ‘Jotun Arctic’ in August 2009. Blue rectangles – position of CTD stations and oxygen isotope samples.

Several glaciers in the SF contribute to the total discharge into the sub-polar North Atlantic in the form of melt water and icebergs including the third biggest in Greenland the Helheim glacier (HG). During the stable period (prior 2001) the HG calving front was grounded above the 550 m depth sill in the Helheim fjord *(Joughin et al., 2008)*. It means that considerable part of the subsurface ice front was in direct contact with the AW. Submarine melting depends on AW temperature and intensity of the buoyancy convection along the ice front driven by sub-glacial discharge *(Motyka et al., 2003)*. The first factor is controlled by the AW properties advected from source region that can be traced back to the Irminger Sea. The second factor is governed by influx of water that infiltrates to the base from the glacier surface and therefore depends on surface air temperature (SAT). To find explanation of the HG rapid retreat that started in 2002, we analyzed the upstream AW properties in the Irminger Sea. Results show that since the end of the 1990s warm and low density anomaly prevailed in the upper 500-800m layer. The anomaly picked during 2005-2008 with 0.5^{o}C excess over long-term mean. Advection of the anomaly into the SF is the most probable mechanism that could trigger rapid retreat of the HG ice front, its thinning and acceleration. Tasiilaq SAT records also reveal positive anomalies since the late 1990s, peaked in 2003 with more than 2^{o}C excess. Therefore both factors reinforced submarine melting of the HG ice front and triggered amplified calving front retreat over the seal to the bottom depression. Although, some studies show that submarine melting is much more efficient than surface melting *(e.g. Mayer et al., 2000)*. Total retreat of the HG ice front for 2001-2005 exceeded 7 km. Retreat acceleration after 2002 can be connected with increase of ice area exposed to submarine melting above the bottom depression. After the re-advance in 2006 all three main glaciers in the SF (Helheim, Fenris, Midgard) reveal unstable advance/retreat behavior.

We conclude that glaciers dynamics in the SF during the 2000s is a non-linear constrained equilibrium among the long-lived AW/SAT anomalies which drive forced convection along the ice front and fjord bed topography. Similar climate conditions and glaciers response were observed in the 1930s, while during the late 1960s the main contribution was from the increased AW temperature. The AW anomaly found in the Irminger Sea in 2000s is not unique. Reported process of the Greenland’ tidewater glaciers ‘retreat/acceleration/thinning’ propagation to the north *(Howat 2008, Hanna 2009, Nick, 2009)* can be linked to the similar anomaly circulated in Norwegian, Return Atlantic and East Greenland currents system.

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Interaction between oceanography, climate and Helheim Glacier calving: studies from the marine sediment archive

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Evidence is emerging that rising temperatures of subsurface ocean currents play a vital role in the recent acceleration of large fast flowing glaciers, such as Jakobshavn Isbrae in West Greenland and Helheim Glacier in Southeast Greenland. An important question is whether these incursions of warmer waters are part of a recurrent phenomenon and indeed how exactly they influence the glaciers. In this study sedimentary deposits from Sermilik Fjord are analysed in order to reconstruct past hydrographic and glacier calving variability.

All together 19 cores ranging between 0.5-1.5 m length were retrieved on a cruise conducted in the fjord in August 2009 and three cores positioned in a distal to proximal transect were chosen for further analyses. The cores were x-ray photographed and analysed with regard to sedimentological variability and the sea ice proxy IP25. The lithofacies is glaciomarine mud with sand content varying along-transect and within-core and this variability is interpreted to reflect variability in iceberg rafting. In the distal cores layers of decreased sand content are interpreted to reflect periods with increased occurrence of shorefast sea ice in the fjord, stabilizing the glacier and preventing icebergs from drifting out of the fjord. A comparison of the time interval covering the Little Ice Age and the Medieval Warm Period with a record from Nansen Fjord further north along the East Greenland coast supports this hypothesis.

Greenland ice loss continues to accelerate

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Greenland's main outlet glaciers have more than doubled their contribution to global sea level rise over the last decade. Recent work has shown that Greenland's mass loss is still increasing. Here we show that the ice loss, which has been well-documented over southern portions of Greenland, is now spreading up along the northwest coast, with this acceleration likely starting in late 2005. We support this with two lines of evidence. One is based on measurements from the Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission, launched in March, 2002. The other comes from continuous Global Positioning System (GPS) measurements from three long-term sites on bedrock adjacent to the ice sheet. The GRACE results provide a direct measure of mass loss averaged over scales of a few hundred km. The GPS data are used to monitor crustal uplift caused by ice mass loss close to the sites. The GRACE results can be used to predict crustal uplift, which can be compared with the GPS data. In addition to showing that the northwest ice sheet margin is now losing mass, the uplift results from both the GPS measurements and the GRACE predictions show rapid acceleration in southeast Greenland in late 2003, followed by a moderate deceleration in 2006. Because that latter deceleration is weak, southeast Greenland still appears to be losing ice mass at a much higher rate than it was prior to fall 2003. In a more general sense, the analysis described here demonstrates that GPS uplift measurements can be used in combination with GRACE mass estimates to provide a better understanding of ongoing Greenland mass loss; an analysis approach that will become increasingly useful as long time spans of data accumulate from the 51 permanent GPS stations recently deployed around the edge of the ice sheet as part of the Greenland GPS Network (GNET).

Freshwater runoff and mass-loss from the Greenland Ice Sheet – from regional to local scale

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The Greenland Ice Sheet (GrIS) is the Northern Hemisphere's largest terrestrial area with a perennial ice and snow cover. The GrIS gains mass from surface snow accumulation and loses mass by two main processes: meltwater runoff and iceberg calving. The ice sheet was close to equilibrium during the relatively cool 1970s and 1980s, but lost mass rapidly as the climate warmed in the 1990s and 2000s, with no sign of deceleration. Both surface melting and glacier outflow have accelerated during the past decade, likely in response to atmospheric and oceanic warming. The GrIS is currently losing mass at a rate of around 250 km^3/yr, enough to raise global sea level by about 0.8 mm/yr, responsible for nearly 25% of global sea level rise in the past 13 years (1995–2007).

In order to predict the impact of climate changes on the GrIS, it is essential to simulate the present-day surface mass balance (SMB, the difference between annual accumulation and ablation) and surface melt extent. Relatively modest temperature changes can bring about large changes in melt volume and extent. Since 1995, the year with the minimum GrIS surface melt extent was 1996, while the most extensive melting occurred in 2007. The 2007 melt extent was 20% greater than the average for 1995–2006. In regional modeling simulations, the year-to-year variability in melt extent was in excellent agreement with observations. The year 2007 had the highest simulated surface runoff (approximately 520 km^3/yr) and the lowest surface mass balance (close to zero). Through the period 1995–2007, the SMB varied from -5 (2007) to 310 km^3/yr (1996), averaging 124 (±83) km^3/yr.

On local scale for the Sermilik Fjord the simulated runoff varied from 2.45×10^9 m^3 in 1999 to 5.53×10^9 m^3 in 2005, indicating an average increase of 1.02×10^9 m^3 in annual runoff (R^2=0.14), however, the increase is not statistically significant. An uneven spatially simulated runoff distribution occurred, yielding a cumulative annual maximum runoff at the Helheim glacier terminus of more than 3.8 m w.eq. The Helheim glacier catchment runoff accounted for ~25% (10.4×10^9 m^3) of the overall runoff to the Sermilik Fjord for the period 1999–2008. To assess the overall freshwater flux modeled runoff was merged with previous available estimates of ice discharge, indicating an average annual freshwater flux from the Helheim Glacier catchment of ~31.8 km^3/yr, of a total freshwater flux of ~35.2 km^3 to the Sermilik Fjord. Only ~4% of the freshwater flux from Helheim originated from the surface runoff, and for the Sermilik Fjord it was ~14%. For Helheim a linear regression between meltwater runoff and ice discharge (R^2=0.68) indicated that high runoff values cause high ice discharge rates, however, the understanding of the processes that link climate to changing surface conditions, glacier surface runoff, ice sheet dynamics and velocity, and ice discharge are still weakly understood.

Local glaciers on Ammassalik Island and mass balance studies and monitoring of the Mittvakkat Glacier

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During the past 150 years the mean global and marine surface air temperature has increased about 0.8 ºC. As visible evidence of the effects of climate change many mountain glaciers and ice caps have lost substantial amounts of mass and ice cover during the period. Recently, a marked thinning and retreat of the south Greenland Ice Sheet margin has been observed and has been attributed to a late response to the termination of the Little Ice Age (LIA). Observations at local glaciers in South Greenland has evidenced that they have receded from their most advanced positions, often marked by terminal moraine ridges during the last 100 years. During the LIA glaciers also expanded in Southeast Greenland and many glaciers in the area were close at their outermost moraines early in the 20th century, but since then most of them have receded substantially. Mittivakkat Gletscher (65º 41´ N, 37º 48´ W) is a 31 km^2 temperate ice field situated in the western part of the Ammassalik Island, Southeast Greenland. The area is drained mainly to the west by several valley glaciers and the mountains around it to the south and east have a strong alpine relief containing the accumulation areas. Mass balance observations have been made on a 17.6 km^2 area draining from two accumulation basins below the mountains Mittivakkat (931 m a.s.l.) and Vegas Fjeld (1096 m a.s.l.) towards the Sermilik (Egede og Rothe Fjord). The valley glacier has a length of about 6 km and is oriented E-W with an altitudinal range of about 130 – 900 m a.s.l. The mean ice thickness was 115 m and the ice volume 2,024 x 10^6 m^3 in 1994. The period since the first observations in 1933 by Keld Milthers has been one of almost continuous retreat from the LIA maximum. As the retreat probably started from the outermost moraine ridges about year 1900, the recession rate of the terminus based on the observations of moraine ridges, photographs and direct measurements was 8 m a^{-1} (1900-1933), 19 m a^{-1} (1933-1958), 24 m a^{-1} (1958 -69), 34 m a^{-1} (1969-1981) and 4 m a^{-1} (1981-1999). Until about 1969 the glacier mainly retreated across a flat alluvial plain, whereas since 1981 the terminus has retreated up through a steep and narrow gorge. Since the LIA maximum an area of about 4 km^2 mainly west and north of the present glacier margins has become deglaciated. A comparison between a topographic map showing the altitude of the glacier surface during 1932/33 and a map constructed from aerial photographs taken in 1972, showed a surface lowering at the 1972 margin of more than 100 m, indicating an ice loss of up to 2.5 m a^{-1} below about 300 m a.s.l. Observations of mass balance at Mittivakkat Gletscher was started in 1995 and continued through to 2009 in order to create detailed information to be used to model the relation between climate and glacier development in Southeast Greenland both forward and backward in time.

During the period of observations from 1995-2006 the glacier lost about -0.78 m w. eq. y^{-1} corresponding to about 13.7 x 10^6 m^3 y^{-1}. This is close at 7 % of the volume measured in 1994. A simple extrapolation of this trend implies that the glacier could diminish and probably almost disappear during the next 150 years. This is emphasized because the ELA was above the highest glacier levels in 4 out of 11 years. During the period of mass balance measurements from 1995-2002, the glacier lost about 4% of the ice volume, and recent modelling of the mass balance during the period with standard synoptic meteorological data from 1898-2005 recorded at the Danish Meteorological Station in Tasiilaq about 20 km from the glacier shows that out of 105 balance years the 89 years had a negative mass balance and the cumulative estimated balance was – 57 m w.eq. During the period 1995-2009 the cumulative ice loss was 11 m water.

At other outlets from the ice field the retreat is also pronounced but observations and measurements are sparse and at several non-existing. The outlet about 10 km to the north from Mittivakkat Gletscher can be taken as an example. The retreat since the glacier reached its most advanced position probably around 1900 where a large terminal moraine was formed is marked. The distance measured using GPS between the most advanced position of the terminal moraine and the present glacier margin in 2009 was close at 1250 m corresponding to a retreat about 12 m a^{-1}. Between 2000 and 2009 the ice margin retreated 150 m across a very flat valley bottom covered by till and meltwater sediments corresponding with about 16.5 m a^{-1}. A few hundred meters behind the present margin the glacier surface also lost mass witnessed by an increase in rock surfaces now visible through and surrounded by ice.

During field observations in August 2005 antler remains of a reindeer were found at a recently deglaciated site at about 500 m asl., and bones from a polar bear were found at about 300 m asl. close at the margin of Mittivakkat Glacier. Radio carbon dating determined the age of the samples to 720 ^{14}C years and 350 ^{14}C years, respectively. In August 2006 old surface vegetation and peaty material became exposed due to ice recession close at the site where the antler was found. The radio carbon age of small roots from the material was determined to 1530 ± 27 years, which is in agreement with dating of woody remains of *Salix glauca* found close by at the top of a nearby nunatak in 1999. The antler indicates that reindeer lived in the area when the glacier began to advance from a position where it was close to or smaller than today. The vegetation surface and peaty material indicate that the climate was warmer before the onset of the Little Ice Age in Southeast Greenland (c. 1150-1920) than today as similar vegetation cover today is only found below about 300 - 400 m asl.

Freshwater runoff and sediment transport on Ammassalik Island – processes and monitoring

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The runoff from the Mittivakkat Glacier was first measured in 1958. In 1972 the measuring programme was extended to include measurements of sediment transport and runoff from nearby streams. Since then measurements have been carried out in connection to field trips in the area. This contribution describes the development of the monitoring programme through time and the problems related to the harsh climate conditions. Automatic measurements are nearly impossible during thawbreak and freeze up periods. Hydrological modelling may be a solution for calculation of runoff during these periods. Runoff varied from 1640-2280 mm w.eq. y^{-1}, corrected for the observed negative net balance of the Mittivakkat Glacier the average annual runoff is 1422 mm w.eq. y^{-1} compared to an average annual uncorrected precipitation of 984 mm w.eq. y^{-1}, indicating the need for correction to obtain a realistic water balance.

Sediment processes and geomorphological dynamics in the Mittivakkat Glacier delta, Ammassalik Island

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The Mittivakkat glacier retreated at a rate of 18 m/year since 1933. At the same time, the morphology of the Mittivakkat delta at the end of the former glaciated valley changed considerably. The present study will describe some actual processes at the delta and on the delta front, followed by a detailed description of morphological changes over the last decades.

Fluvial, estuarine and coastal processes determine the actual sediment transport rates and associated budgets around the delta. The extension of the actual fresh water outflow on the delta front is estimated by measuring the fresh water plume during different stages of the tidal period during a field campaign in July 2009. The fresh water plume is clearly visible in cross-delta transects of salinity, temperature and sediment concentration of the coastal waters. The variations in the extension of this plume are used to determine the dominance of current processes affecting the delta.

The changes in the morphology of the delta were studied with the use of aerial photographs and satellite images with the oldest observations dating back to 1943. Besides, several regularly measured cross-delta profiles were used with the oldest dating back to 1989. The delta has developed from an open system with multiple distributaries in to a single channel system in 2009. At the same time, a spit and a tombolo were formed on the delta platform. The change of a multiple channel to a single channel outlet on the delta during low-tide may be caused by a reduction of the fluvial influx or an increase of wave activity. Nowadays, almost all sedimentation occurs on the inner delta plain during high tides and on the delta front during low tides.

Late Holocene land-fjord fluxes in the Mittivakkat Glacier catchment documented in a near coastal/delta marine sediment core from the Sermilik Fjord; southeast Greenland.

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Fjord sediments in the Sermilik Fjord are influenced by one of the most productive outlet glaciers from the Inland Ice, the Helheim Glacier, from land-fjord fluxes driven by run off from the landscape and by processes in the fjord water column under the influence of exchange processes between the Sermilik Fjord and ocean currents in the North Atlantic. A near coastal fjord sediment core from a position close to a major melt water stream from the local Mittivakkat Glacier on Ammassalik Island is expected primarily to reflect a variable land-fjord flux. The 60 cm long sediment core was collected from a water depth of about 100 mete and show finely layered sediment covering the latest about 500 years. C^{14} and Pb^{210} dates are used to calculate variable sedimentation rates, and XRF based element analysis and analyses of grain size distributions and carbon and sulphur contents further support the interpretation of a changing sedimentary environment.

The sedimentation during the late part of the Little Ice Age (LIA) is characterized by highly variable sedimentary conditions, low sedimentation rates of both organic and poorly sorted silt dominated inorganic substances (1-2 kg m^{-2} y^{-1}), and of varying Fe, Mn and S contents reflecting periods of more stagnant water masses at the site, allowing the development of oxygen depletion. After the termination of the LIA, sediments change. Slightly finer and more well sorted silt sized materials accumulate at rates varying between 2-5.5 kg m^{-2} y^{-1}. Three periods, during the 1940^{th}, around 1970 and after the mid 1990^{th} show the highest sedimentation rates presumably reflecting periods of raised run off, carrying more wash load to the near coastal fjord site. Low and stable SI/Al ratios support the interpretation of a fine grained wash load dominated sediment source, and indicate that coarser sediments are trapped more efficiently in the proglacial sinks on land, formed after the retreat of the Mittivakkat glacier. In addition, low and less varying contents of chemical elements indicates oxygen deficiency in bottom waters and give the impression of a more efficient mixing of water masses at the site after the termination of the LIA.

Holocene environmental terrestrial changes documented in lake sediments and polysequent soil profiles on Ammassalik Island, Southeast Greenland

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Organically enriched Holocene lake sediments on Ammassalik Island, above the upper marine limit, date back to about 11.200 YBP. This supports a hypothesis of a fast deglaciation of thin, mostly local ice covers in the mountainous landscapes between huge Inland Ice driven ice streams in the fjord systems of east Greenland. The initial lake sedimentations appear to reflect considerably higher lake productivity compared to later parts of the Holocene, indicating warm summers during the early Holocene insolation maximum, which terminated the last cold spell of the Weichselian, the Younger Dryas. After the mid Holocene, prolonged ice covers in lakes, generally colder summer periods, increasing nivation activity controlled by dominating northerly winds and neoglacial appearance and advances of glaciers in coastal landscapes strongly influence on lake sedimentation and periglacial soils. Sedimentary conditions generally appear to be more variable during the Holocene neoglacial (> about 4500 BP), sedimentation rates go down and periglacial landscape processes both form widespread erosive landscape features and polysequent accumulative soil profiles.

A near coastal lake studied in 2009, presently about 12.5 m above sea level, was isolated from the Sermilik Fjord 8000-7000 YBP. Based on glacial materials, followed by a fine grained fjord sediment, again overlaid by brackish and sulphur enriched sediments, a freshwater sequence was found in the lake ranging from about 1-1,5 m in thickness. C14 dating was used to calculate variable sedimentation rates, and XRF based element analysis support an interpretation of changing sedimentary environment in this lake during the latest c. 7.500 years.

A still colder climate, especially summer temperatures, appear to have influenced on lake sedimentation, and during periods the landscape seems to have been under the influence of pronounced, both cold and dry climatic conditions, low snow coverage and low influxes of mobilized materials from the catchment. The LIA period (c. 1500- 1900 AD) appears to be the most dry and cold era during the Holocene, preceded by a slightly more unstable but significantly warmer and more snow rich era from c. 1000-1500 AD. The latter period probably reflect an era of a much stronger but also highly varying influence from circulation of warmth and moisture from lower latitudes to the SE-Greenland region. Especially during 1000-1200 exceptionally warm and humid conditions seem to prevail, which also is reflected in the formation of a thick and humus enriched upper soil layer, which during LIA climates and destabilizing landscapes became covered by wind and water deposited materials. Chemical indicators of low latitude atmospheric influx suggest an increasing but unstable influx after c. 4500 YBP culminating during c. 1000-1500 AD.

As mentioned, orbital changes during the Holocene determine a still lower insolation at high latitudes and a still stronger insolation and energy gradient towards lower latitudes. Catchment leaching indicators (Fe and Ca) and redox indicators (Fe/Mn) in the studied lake sediments give the possibility to outline a more detailed sequence for the late Holocene, of warmth and precipitation periodically driven into the region, under a generally still colder late Holocene of East Greenland.

Results from GLIMPSE: Historical changes in geometry of Helheim Glacier

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Since the widely publicised thinning and acceleration of Jakobshaven Isbræ, the stability of the Greenland Ice Sheet (GrIS) and its future contribution to sea level have been in question. Over the past decade, improvements in remote sensing techniques revealed a period of accelerated mass loss[1,2], increased melt rates[3,4], marginal thinning[4-7] and increased discharge from many outlet glaciers due to rapid changes in ice dynamics[3,5,8-11]. The southeast region in particular was highlighted as a region of strong mass loss[12]. Despite our improved observational record, the physical processes driving these changes are not well understood[13]. In particular, there remains uncertainty whether they reflect profound adjustments to changes in climate or fluctuations that follow a yet unknown natural cycle. To understand better these changes, we urgently need to extend the observational time frame in order to place contemporary observations in a broader temporal context.

Nowhere are efforts to improve our understanding of southeast Greenland's mass loss and dynamics more obvious than at Helheim Glacier. We use historical stereo aerial photography, contemporary satellite imagery and airborne laser data (lidar) to create an historical series of digital elevation models (DEM) and ice margin positions up to 60 years in length. Aerial photography, collected by Denmark's National Survey and Cadastre (Kort & Matrikelstyrelsen), are available for a number of Greenland's coastal areas from the 1940s and in the 1980s a complete survey of the island's coastal regions was carried out. As with satellite data, these images hold important spatial information about the changing geometry of the Helheim catchment. However, in order to use them quantitatively, it is necessary to provide a link, in the form of ground control, between the two dimensional imagery and the three dimensional real world. For this we turn to high resolution airborne lidar collected between 2007 and 2009 by both the Natural Environment Research Council Airborne Research and Survey Facility (NERC ARSF) and the Cryospheric Sciences Branch of NASA's Goddard Space Flight Centre. The combination of these data sources enabled the production of high quality DEMs with vertical errors below about ±2.0 m in snow-free areas[14]. The resulting topographic models are used in sequential DEM analysis to provide a long-term sequence of volume change and, together with calving front positions, important insight into the recent changes of geometry of Helheim Glacier.

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Results from *GLIMPSE*: Constraining past geometry at Helheim Glacier using remote sensing and field observations

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Over the last decade Helheim Glacier, in concert with the majority of marine-terminating outlets of the southeast Greenland Ice Sheet (GrIS), has exhibited dramatic changes in speed, thinning and retreat rates. The regional nature of these changes has raised concerns about the stability of the ice sheet and its potential contribution to rising sea levels. However, the long-term history of the tidewater glaciers of the southeast GrIS is largely unconstrained, hindering our ability to assess the significance of the changes at these outlets and understand the driving processes. Furthermore, appropriate palaeoglaciological evidence is essential to improve and constrain ice sheet models necessary to generate accurate future sea-level predictions. We present ongoing work to extend the record of thinning and retreat at Helheim Glacier beyond the limits of satellite imagery and aerial photographs, thus providing a legacy dataset suitable for testing and constraining models of outlet glacier response.

Vegetational trimlines (distinct transitions between bare rock and vegetated ground) marking the former extent of outlet glaciers are clearly visible in aerial photographs and satellite imagery from the margins of the GrIS. These trimlines provide the means to reconstruct former ice margins of the late Holocene; thus extending and quantifying the record of retreat beyond the limit of satellite imagery and available historical aerial photography. Discernable spectral differences between bare and lichen colonised rock surfaces, below and above the trimline respectively, have been used successfully to identify the Little Ice Age margins of Jakobshavn Isbrae in West Greenland (Csatho *et al.* 2005; Knight *et al.* 1987). We are applying these techniques at Helheimfjord to ascertain whether the same approach using supervised classification of Landsat imagery is possible across the whole ice sheet margin. Surface spectral measurements, to be collected in summer-autumn 2010, will be used to validate and assess the accuracy of classification maps delineating trimline locations.

To provide chronological constraints on the retreat of Helheim Glacier, in July 2009 we collected samples for terrestrial cosmogenic nuclide dating from six sites spaced along the full length of the Sermilik Fjord, using a mixture of point sampling and vertical transects in order to capture retreat and thinning rates. These new dates will complement and extend recently published results from a tributary close to the fjord mouth that indicate retreat up the fjord from the present-day coastline commencing at ~11 ka BP (Roberts *et al.* 2008). Eight key samples are currently being analysed for ^{10}Be, and we expect results to be ready by autumn 2010.

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The Programme for Monitoring of the Greenland Ice Sheet

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The Greenland ice sheet has been losing mass at increasing rate during recent years, with possible impact on global sea level rise and climate dynamics. With this in view Programme for Monitoring of the Greenland Ice Sheet (PROMICE) has been launched by the Danish Ministry of Climate and Energy. The overall aim of PROMICE is to quantify the annual mass loss of the Greenland ice sheet and track changes in the extent of the glaciers, ice caps and ice sheet margin. In Southeast Greenland, near Helheim Glacier, activities have so far included the establishing and maintenance of two automatic mass-balance stations (AMS) in a transect on the ice sheet margin by Isortoq, south of Sermilik. The first aerial survey carried out by PROMICE in 2007 likewise includes a flight track downstream of Helheim Glacier, providing elevation and, with variable success, ice thickness. The aerial survey will be repeated in 2011 or 2012. The two AMS provides all climatological parameters as well as ice sheet ablation and snow height over the entire year. The stations were first erected in 2004, but the severe weather conditions of this part of Greenland have caused stations to break down several times and the data series are therefore not continuous despite regular maintenance visits. PROMICE also utilizes radar satellite data for derivation of glacier velocities from offset tracking in combination with InSAR. This method is still in its test phase with test sites in Kangerlussuaq, West Greenland, and 79-fjord glacier in Northeast Greenland. Eventually, it will also be applied to the Helheim region of the ice sheet to determine the ice flux. In order to better capture the seasonal velocity variation, there are plans to extend the outlet glacier monitoring with transmitting GPS' on selected glaciers, combined with geodetic camera systems deployed in collaboration with the Extreme Ice Survey (EIS).

Within the SEDIMICE project, a similar AMS has been erected by GEUS on the local Mittivakkat Glacier on Ammassalik Island south of Sermilik. This station transmits data via satellite, with the possibility of near-real time inspection on the internet. Wintertime transmissions are reduced to a daily mean value, whereas summertime transmissions show hourly values.

Strain Rate and Force Balance Results on Helheim Glacier

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Helheim Glacier has undergone a series of large changes in past decade. These changes include large-scale acceleration, dynamic thinning and retreat in 2003, followed by slight deceleration, thickening and advance starting in 2006. The mechanisms driving the changes of Helheim Glacier dynamics are not fully understood, yet the changes have had a substantial impact on global sea level rise. By examining the force balance characteristics – preceding, during, and following the 2003 acceleration – we investigate where changes originate and how they propagate.

Insight into the large-scale mechanisms controlling glacier motion can be obtained from calculations of the stresses that drive and resist flow. Resistance can come from the bed, the sides, or from along-flow obstacles. Changes over time in the velocity field of a glacier should be explained by a subsequent change in the balance of forces controlling the flow. The force budget technique (described by *Van der Veen and Whillans*, 1989) allows us to calculate forces at depth using measurements of surface velocity and estimates for surface slope and ice thickness. We use satellite remote sensing techniques to derive spatially-extensive measurements of ice velocity and surface elevation, necessary to complete the force balance analysis.

Perturbations of ice flow on Helheim Glacier vary in scale, both in time and space. Ice velocity measurements derived from satellite imagery can capture glacier-wide changes that occur on longer time-scales (seasonal; or the time difference between the two images used). Field based GPS can identify perturbations that are both local and occur on short time-scales (hourly or less). By investigating these two data sets simultaneously, we can differentiate between perturbations that affect flow on small scales and perturbations that have a long-term and glacier-wide effect on ice dynamics. The force balance technique will allow us to tie changes in surface strain rates (on both local and glacier-wide scales) to changes in specific resistive stresses. The results from this study will help determine the sensitivity of Helheim Glacier to a range of perturbations.

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Geodetic and seismic observations of variations in flow at Helheim glacier on multiple time scales

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Greenland's outlet glaciers exhibit variations in flow on a wide range of time scales, with both accelerations and decelerations occurring more rapidly than previously appreciated. Helheim glacier provides well- constrained examples of such variations. Many abrupt changes in flow are linked to large-scale calving events and glacial earthquakes. Other variations are observed on daily and subdaily time scales, associated with meltwater flux and tidal forcing. Some of these short-time-scale variations may also be linked to seasonal and interannual changes in glacier flow speed and strain rate. We present results from a GPS network we have operated at Helheim Glacier, in East Greenland, during four summers and a limited fall/spring operation period, as well as related seismological data.

Surface Melt and its Effect on Helheim Glacier Dynamics

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When estimating sea level rise, understanding the behavior of the large, fast-flowing outlet glaciers found in Greenland is crucial. Based on measurements from an automatic weather station (AWS) on the surface of Helheim Glacier, we have developed a distributed energy balance model for the Helheim catchment, enabling us to estimate the melt volume spatially and temporally. A comparison of the modeled melt to daily surface displacement measured by GPS receivers located on the glacier yields positive temporal correlations. The highest correlation values are found when delaying accelerations one day with respect to the melt signal. We interpret this as a 'lubrication effect', i.e. melt water reaching the bed of the glacier and once there, enhancing the flow of the already fast flowing glacier. We seek to understand whether changes in melt water generation have an effect in priming the glacier for major calving events that have been shown to coincide with glacial earthquakes. This could happen either through the enhanced flow towards the front, or the melt water filling crevasses, thereby enhancing calving processes.

Concluding thoughts: Helheim Glacier's place in the effort to move from understanding processes to predictions

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Observations from Helheim Glacier have greatly advanced our understanding of the processes driving rapid outlet glacier change. We have learned, specifically, that the stability of outlet glaciers is dependent on a highly sensitive balance between stress conditions at ice front, so that small perturbations can lead to rapid, non-linear response. Continued observations from Helheim Glacier, as well others, now must help us, firstly, determine what processes and, their associated impacts to glacier mass balance, are important on timescales relevant to societal concerns of accelerated sea level rise and, secondly, how those processes may be incorporated into prognostic ice sheet models. In this talk I will summarize what has been learned and how those new understandings are being employed to improve predictions, as well as direct new observational programs to fill remaining gaps in understanding.

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