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PROMICE 2011-2012

Final report for the 2011-2012 operational phase of the Programme for Monitoring of the Greenland Ice Sheet

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

G E U S

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Final report for the 2011-2012 operational phase of the Programme for Monitoring of the Greenland Ice Sheet

Signe B. Andersen[1], Andreas P. Ahlstrøm[1], Morten L. Andersen[1], Jason E. Box[1], Michele Citterio[1], Robert Fausto[1], Horst Machguth[1], Dirk van As[1], Karen Edelvang[1], René Forsberg[2], Henriette Skourup[2], Louise S. Sørensen[2], Steen S. Kristensen[2], Jørgen Dall[2], John P. M. Boncori[2] & Dorthe Petersen[3]

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

GEUS

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Dansk resumé af PROMICE resultater

Siden årtusindskiftet har man konstateret et accelererende massetab fra Grønlands indlandsis. Manglen på observationer fra Grønlands indlandsis medfører store usikkerheder på de skønnede tab af ismasse og således også på bidraget til havniveaustigninger. Af denne grund blev først ICEMON og siden det mere ekstensive PROMICE program til overvågning af Grønlands indlandsis langs isranden støttet.

Rettidigheden og nødvendigheden af programmet understreges af, at vi siden etableringen af PROMICE har oplevet rekordhøje temperaturer i Grønland gentagne gange. Som konsekvens har tabet af is ved smeltning og produktion af isbjerge været rekordstort. De høje temperaturer er blevet målt med PROMICE automatiske vejrstationer (AWS), som er enestående in-situ målinger i randen af indlandsisen, hvor afsmeltningen finder sted. I Sydgrønland har vi målt rekordhøj smeltning på henholdsvis -9,3 og -8,1 meter i 2010 og 2012. Selvom 2012 havde højere temperaturer, blev der observeret mere afsmeltning i 2010 ved de fleste stationer. Analyse af PROMICE AWS data viser, at dette skyldes ekstraordinært lavt nedbør af sne i vinteren og foråret 2010.

For nogle regioner er den totale afsmeltning blevet beregnet. For 2010, der har varmerekorden, beregnede vi en overfladeafsmeltning og efterfølgende smeltevandsafstrømning fra Kangerlussuaq området, som var 150 % højere end normalt. Resultater fra Nuuk området viser, at afsmeltningen her i løbet af de sidste 20 år er steget med omkring 50 %. I Kangerlussuaq området blev afsmeltningen kraftigt forstærket på grund af 'smelte-albedo' feedback. Dette er en selvforstærkende proces, hvor afsmeltning gør isens overflade mørkere, hvilket yderligere forstærker afsmeltningen. Overfladen forbliver mørkere i adskillige år, og dette havde betydning i forbindelse med den rekordhøje afsmeltning i 2012, hvor broen i Kangerlussuaq blev skyllet væk. Resultaterne ikke bare bekræfter andre forskningsgruppers beregninger af istab fra storskala-modellering, men giver den bagvedliggende fysiske forklaring på det forøgede istab. Vi er i øjeblikket ved at udvikle en model, som kan beregne afsmeltning for hele Grønlands indlandsis baseret på observationer fra AWS og satellitter.

Flybårne målinger af isoverflade og grundfjeld langs hele randen af Indlandsisen blev gennemført med succes i 2007 og 2011. Programmer til at beregne isens overfladehastigheder fra satellit (SAR) er blevet udviklet, og kort med isoverfladehastigheder er blevet produceret. Yderligere er hastigheden af et antal udløbsgletchere blevet målt in-situ med GPS-instrumenter. Vi har således nu samlet alle data til beregning af istabet fra produktion af isbjerge og er tæt på at kunne beregne det totale istab.

Yderligere er tilbagetrækningen af Grønlands indlandsis blevet vurderet ved kortlægning, idet vi fornylig inden for PROMICE har færdiggjort et kort over Grønlands ismasser baseret på flyfotos. Det viser, at indlandsisen i midt-1980'erne dækkede 1.716 x 10^3 km^2, og at iskapper og gletchere dækkede 88 x 10^3 km^2. Baseret på satellitbilleder er kortet blevet opdateret til 2011, og vi har beregnet, at det isdækkede areal på Grønland er blevet reduceret med mindst 2.560 km^2. Dette kortlægningsarbejde havde afgørende betydning i forbindelse med korrektionen af Times Atlas, da de offentligjorde en fejlagtig stor reduktion af Grønlands indlandsis.

Summary of PROMICE results

Climate change in the Arctic has resulted in accelerated mass loss from the Greenland Ice Sheet. The shortage of observations on the Greenland ice sheet infers large uncertainties in estimates of the ice mass loss and in predicting the contribution to sea level rise. For this reason the ICEMON project was supported, followed by the establishment of the more extensive Programme for Monitoring of the Greenland Ice Sheet (PROMICE) in 2007.

The timeliness and necessity of the programme is emphasized by the fact that since the establishment of PROMICE, we have experienced several years of record-high temperatures in Greenland. As a consequence, record high mass loss of the Greenland ice sheet has occurred through melt and calving of icebergs. The high temperatures and melt rates were measured by the automatic weather stations (AWS) in PROMICE, as unique in-situ measurements in the ice marginal areas where the melt is taking place. In southern Greenland we measured record-high melt of -9.3 m and -8.1 metres in 2010 and 2012, respectively. Although 2012 had the highest air temperatures, more melt was recorded in 2010 in most locations. Analysis of the AWS data from the PROMICE network shows that this was due to low amounts of snow accumulation in the winter/spring of 2010.

For some regions the distributed melt has been calculated. For the record-warm year of 2010 we calculated surface melt water to run off from the Kangerlussuaq catchment, exceeding ‘normal’ values by about 150%. Results from the Nuuk region show that over the past 20 years ice sheet melt here has increased by roughly 50%. In the Kangerlussuaq area melt was heavily amplified by the melt-albedo feedback, because melt darkens the snow and ice surface, further increasing melt. The effect of darkened ice surface will linger for several years or more, and already had implications for record runoff year 2012, during which the Kangerlussuaq bridge was washed away. These results not only confirm large-scale mass balance modelling results from other groups, but also reveal the physical explanation behind the recorded increase in mass loss.
Presently we are developing a model that can calculate surface melt across the entire ice sheet based fully on observations from AWSs and satellites.

Airborne campaigns were carried out successfully in 2007 and 2011 yielding ice elevation and thickness along a flux gate around the Greenland ice sheet margin. Software for calculating ice surface velocities from satellite (SAR) has been developed and ice surface velocity maps have been produced. Additionally, the seasonal velocity variation at a number of outlet glaciers has been retrieved from GPS-instruments. Thus we now have data needed to estimate the mass loss from calving, bringing us closer to the PROMICE goal of estimating the full mass loss of the Greenland Ice sheet. Additionally the retreat of the Greenland ice sheet has been assessed by mapping. We have recently completed the PROMICE map of Greenland ice masses based on aero-photogrammetric maps. It shows that in the mid-1980’s, the ice sheet covered 1,716 x 10^3 km^2, and ice caps and glaciers covered 88 x 10^3 km^2. Based on satellite imagery, we updated our 1980’s ice margins to 2011, and we found a net combined area loss of 2,560 km^2 from the 128 sites of larger detected change, excluding known glacier surges. The mapping effort of PROMICE was pivotal in the timely correction of the Times Atlas by the global scientific community, when they erroneously claimed a large retreat of the Greenland ice sheet based on a flawed analysis of available data.

Introduction

PROMICE is as an on-going effort to monitor changes in the mass budget of the Greenland Ice Sheet and is operated by the Geological Survey of Denmark and Greenland (GEUS) in collaboration with the National Space Institute (DTU Space) and the Greenland Survey (ASIAQ).

Specifically, PROMICE aims to estimate the mass loss derived from three fundamentally different sources:

1. Surface melt water runoff from the ice sheet margin
2. Iceberg discharge and submarine melt from ice sheet outlet glaciers
3. Mass loss of individual glaciers and ice caps surrounding the ice sheet

The first is accomplished through a combination of observations from a network of automatic weather stations (AWSs) on the ice sheet surface and numerical modelling

The second is determined by establishing a so-called 'flux gate' along the entire ice sheet margin and keeping track of the ice passing through this gate. The flux gate is established from airborne surveys of ice sheet surface elevation and thickness, which are repeated as the surface elevation changes over time. The volume of the ice passing through the gate is derived from maps of the surface velocity of the ice sheet, produced from satellite radar images with *in situ* GPS data from selected outlet glaciers providing the temporal variability.

The third is investigated through regular mapping of area and elevation, combined with mass balance modelling designed for the approximately 20.000 individual glaciers and ice caps in Greenland. Mapping is carried out using recent satellite imagery as well as aerial ortho-photos. Area-volume scaling and comparison of maps from different years allow an estimate of the mass loss over time.

PROMICE is also committed to maintain an accessible, safe and thoroughly documented database for storing and disseminating the data. This is one particular aspect in which PROMICE differs significantly from regular research projects. Building and running such a database is done within the existing framework of GEUS, which is the national data repository for a range of geological, geophysical and hydrological data.

Additionally, PROMICE is dedicated to outreach, disseminating knowledge and inspiration to the public at all levels, from primary school pupils to politicians, inquisitive journalists and fellow scientists.

This report summarizes the results and experiences of the programme since its start in 2007and serves as final report for the 2011-2012 operational phase.

The report also contains a final section on results and progress within the add-on project 'Monitoring the outlet glaciers of the Greenland Ice Sheet (IVEL).'

Results

PROMICE automatic weather stations

A central part of PROMICE is the network of automatic weather stations (AWS) situated in the ablation zone of the Greenland ice sheet. The key function of the network is to provide ground-based observations of surface melt and atmospheric conditions. The PROMICE AWS network provides

- Direct daily observations of ice sheet melt and near-surface conditions
- Crucial validation and calibration data for global and regional circulation models
- Ground-truth for satellite products

The PROMICE network has an active partnership with the NASA-sponsored Greenland Climate Network (GC-Net) that mainly covers the accumulation zone of the Greenland ice sheet. Both networks send real-time observations to the Danish Meteorological Institute (DMI) for re-distribution to the WMO, which in turn makes them available for global use.

The value of the monitoring effort will increase with time as the impact of climate change on the ice sheet melt is recorded continuously, especially since the comprehensive datasets from the AWS (see Figure 1) makes it possible to pinpoint exactly what is causing an observed change.

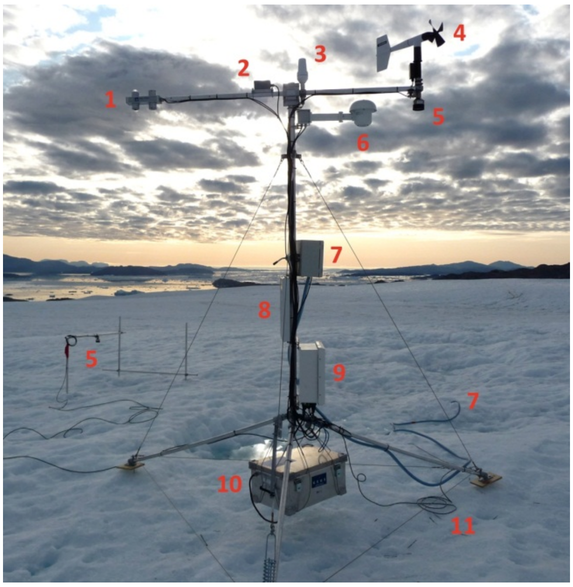

Figure 1. *PROMICE automatic weather station UPE_L. 1: radiometer. 2: inclinometer. 3: satellite antenna. 4: anemometer. 5: sonic rangers. 6: thermometer and hygrometer. 7: pressure transducer. 8: solar panel. 9: data logger, barometer and GPS. 10: battery box with 4 × 28 Ah batteries. 11: 8-level thermistor string.*

The network currently consists of 19 AWS on the ice sheet margin and 5 AWS on separate ice caps or glaciers. Some of these AWS are co-financed by related projects, but they all deliver data to the common PROMICE database at GEUS. Locations of the weather stations on the ice sheet are seen on the map in Figure 2, where each dot represents two or three AWS placed at different elevations near the ice margin.

Figure 2. *Location and identification codes of PROMICE automatic weather stations. Dotted lines are elevation contours in m above sea level. Red dots represent PROMICE stations, blue dots others.*

Results from the observational network have been presented in several scientific publications by the PROMICE team (Van As et al., 2009; Van As, 2011; Van As et al., 2011; Van As et al., 2012; Fausto et al., 2012a; Fausto et al., in prep.). The unique melt recording system developed by GEUS glaciologists has provided extensive and reliable data on ablation from the extremely hostile environment of the ablation zone on the ice sheet (Fausto et al. 2012b). An example is shown in Figure 3, showing the ice melt from late summer 2008 to present day at the lower SCO station.

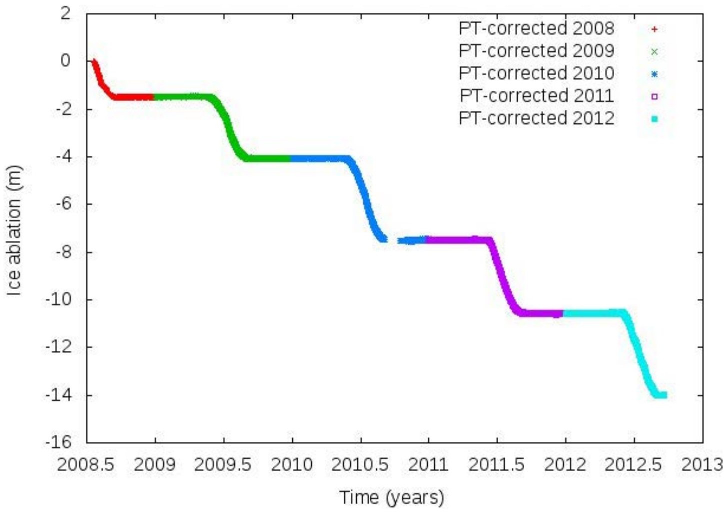

Figure 3. *Ice melt recorded continuously at an AWS located in central East Greenland (SCO in Figure 2).*

An important accomplishment in PROMICE has been the observation records from the two extreme melt years 2010 and 2012. A scientific publication on this subject is currently in production (Fausto et al., submitted). In July 2012, a melt-extent map derived from NASA satellite data hit the media showing that a historically large area of 97% of the surface of the Greenland ice sheet was subject to melt. The extent of surface melt alone does not give the magnitude of melt in terms of ice mass lost, however this event was also recorded by the PROMICE AWS network (Fig 4), allowing for a quantification of the actual melt and surface weather conditions leading to the extreme melt event detected by NASA. On July 11, the lower QAS station measured an air temperature of 12.1°C while the lower NUK station reached an unprecedented 17.1°C – this is extreme when considering that the measurements were recorded a few meters above an ice surface at the melting point. Only a few weeks later on July 27, these temperature observations were matched (13.1°C and 17.0°C, respectively). Although 2012 had the highest air temperatures, more melt was recorded in 2010 in most locations (especially in South and Southwest Greenland) as seen in Figure 4, illustrating a 12-year record of melt from the lower QAS station.

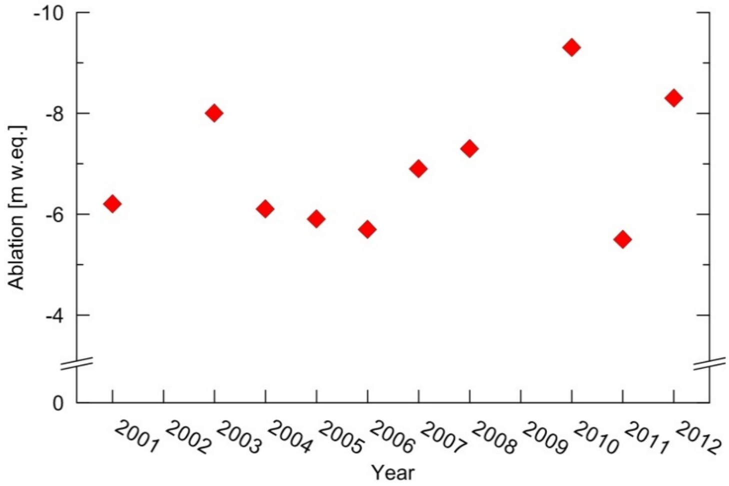

Figure 4. *Observed ice melt at the lower QAS station 2001–2012 on the ice margin near Qassimiut, South Greenland. Note the record-breaking year 2010 with 9.3 meters of ice melt.*

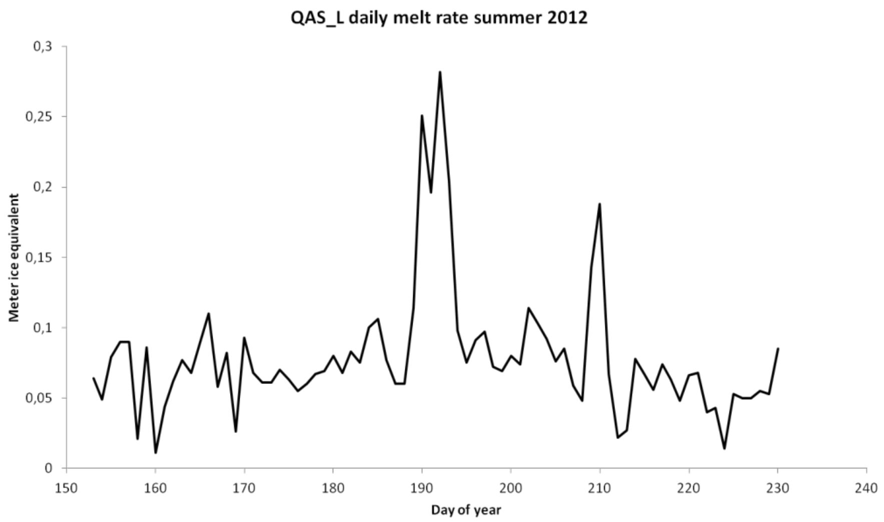

Figure 5. *Daily melt rate for June, July, August 2012 at the lower QAS station.*

Analysis of the AWS data from the PROMICE network shows that this was due to low snow amounts and warm conditions in the winter/spring of 2010 and a subsequent long melt season, whereas the winter/spring of 2012 was cold with a normal amount of snow (around 1.5 m at QAS_L) to delay the melting of the underlying ice. PROMICE observations thus not only confirm the satellite-derived indicators of climate change, but also establish the underlying causal relationship and provide a quantification of the impact on the ice sheet.

Figure 5 underlines the abilities of the AWS to record short-term variability in the conditions on the ice sheet by showing the daily ice melt rates with peaks on the two dates in July mentioned earlier, reaching up to 28 cm of ice equivalent melted in a single day (11 July 2012).

In total, more than 60 annual ice sheet melt observations have been retrieved so far from the PROMICE network, as shown in Figure 6. These melt measurements and the accompanying climate data offer a unique insight into the climate-ice sheet interaction on a spatial scale never seen before. Already with a few years of measurements, modeling groups have become eager to access the PROMICE database in order to validate their results or utilize data directly in melt estimates for the entire ice sheet.

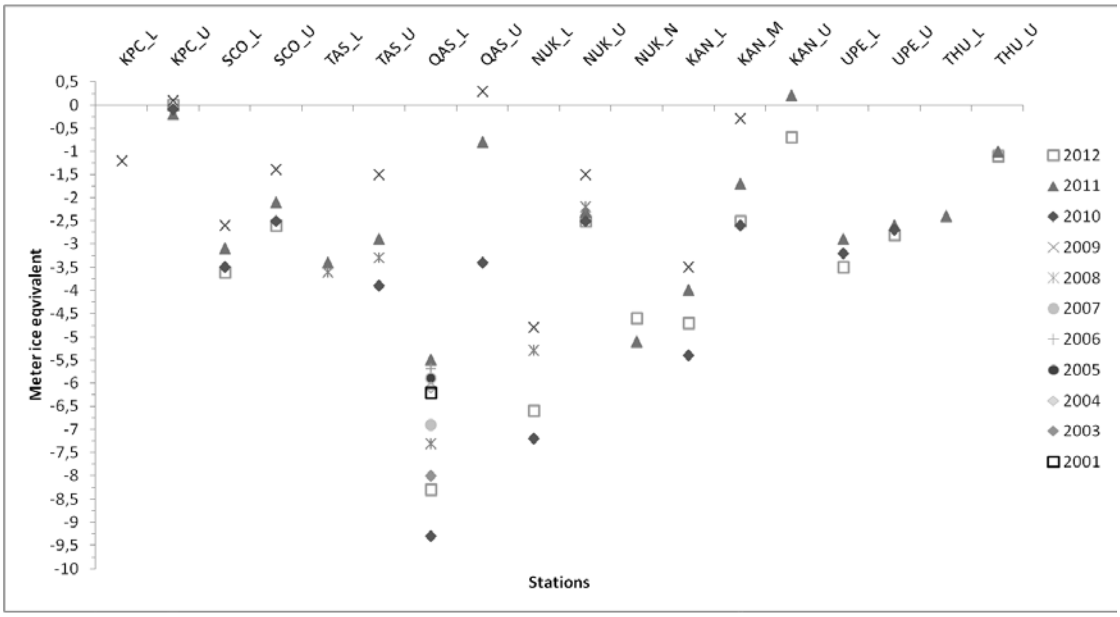

Figure 6. *Net annual ablation records for all PROMICE stations 2002-2012.*

Other data measured by the AWS, such as air temperature, have provided important results by proving insights in e.g. the extremely cold event of late February / early March 2012, the extremely warm event of mid-July 2012, and the over-all warm year 2010. As an example, the monthly-mean temperature at QAS_L is shown in Figure 7. This plot illustrates how 2012 had a relatively warm summer (June, July, August), but a cold spring, while the melt-record year 2010 was very warm throughout the year. Other data that have been of interest to scientists around the globe are for instance the solar radiation measurements, which can be used to investigate the current darkening of the ice sheet (Van As. et al. 2013).

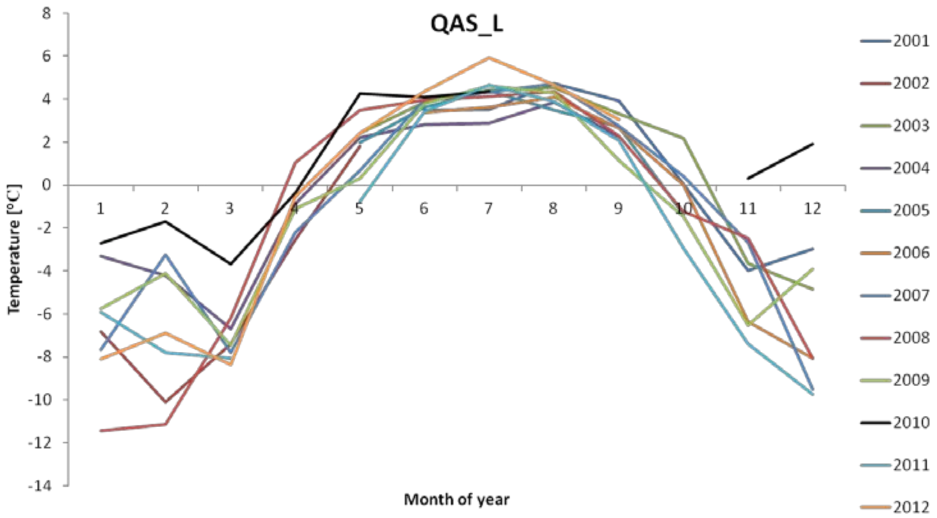

__Figure 7.__ Mean monthly air temperatures measured at the lower QAS station, South Greenland.

Melt modeling

The AWS observations can be used to calculate the energy exchange between the atmosphere and the ice sheet surface. The stations measure certain energy fluxes directly, such as the solar or terrestrial radiation, in other cases the measurements can be used to calculate them, such as the turbulent heat fluxes from temperature, humidity, wind speed and air pressure. Knowing all energy fluxes tells us if the melting point is reached and how much snow or ice melts away. These calculations can then be validated by the direct measurements of melt. Doing so, we know exactly which energy source (e.g. a warm atmosphere) contributes how much to melt. Even more importantly, we can determine which of these energy sources cause the observed changes in melt in Greenland.

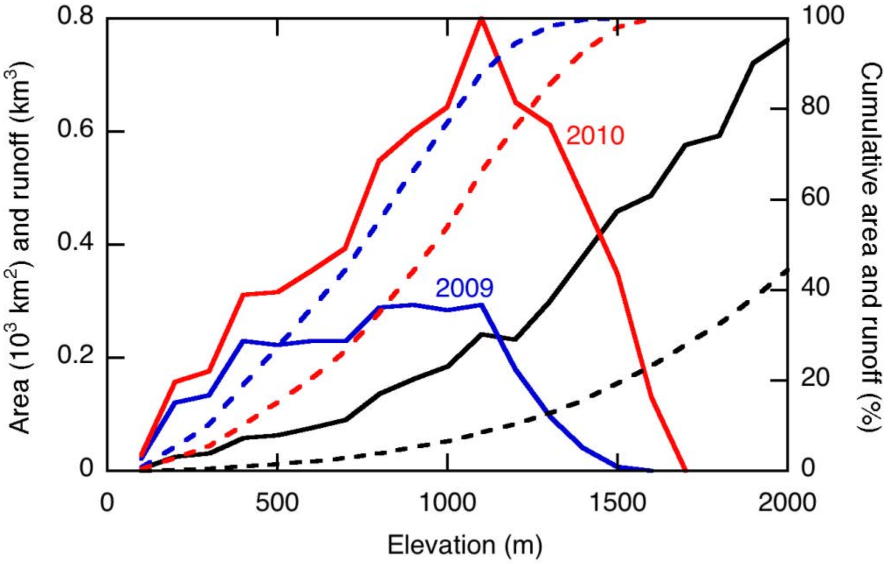

__Figure 8.__ Kangerlussuaq catchment surface area (black), and surface melt-water runoff for 2009 (blue) and 2010 (red). Dashed lines illustrate cumulative

A surface energy balance (SEB) model was specifically developed for this purpose, and thoroughly tested for an AWS site on Steenstrup Gletscher in northwest Greenland (Van As, 2011). Here, glaciers are retreating substantially (Dawes and Van As, 2011) and temperatures are rising by 0.2 °C per year on average. Results show that even at this northerly location (75°N) 2-3 m of ice ablates every year, primarily caused by solar radiation. Based on DMI data at the distant village Kitsissorsuit, we conclude that melt has roughly doubled since the 1980s. Our model shows that a large share of the melt occurs internally in the upper layers of the ice as solar radiation is partly absorbed at depth. This is a more efficient way to produce melt from solar radiation; models without radiation penetration in ice may underestimate mass loss.

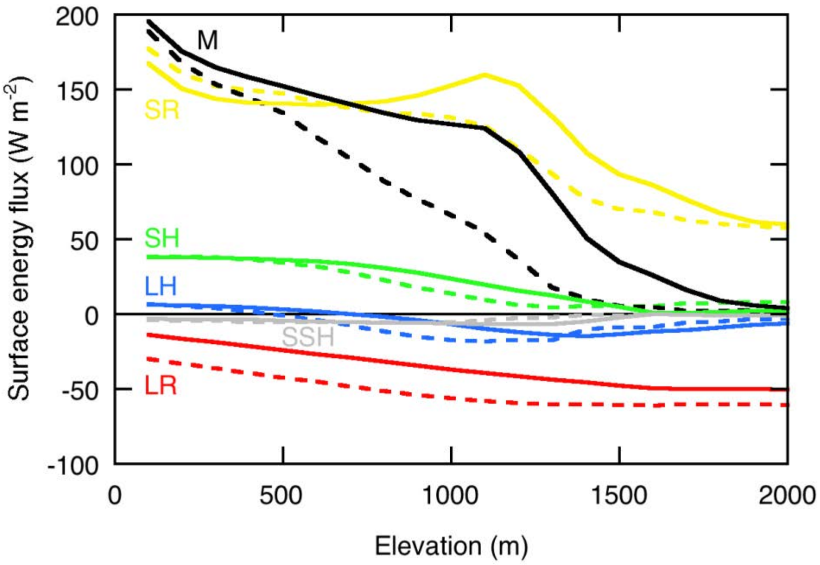

Figure 9. *Mean SEB components for June, July and August in 2009 (dashed lines) and 2010 (solid lines) versus elevation. Net shortwave radiation: yellow, net longwave radiation: red, sensible heat flux: green, latent heat flux: blue, sub-surface heat flux: grey, and energy available for melt: black.*

The SEB-model approach works very well for the locations of the AWSs. The next step is to calculate the SEB for areas/regions – in order to eventually upscale further and obtain estimates of the SMB for the entire ice sheet. If AWSs are positioned close enough to each other (if correlation of their measured parameters is not lost) we can interpolate the measured quantities over the area in between. This allows us to accurately calculate the amount of melt over a whole region, while still obtaining the full SEB telling us what causes the melt.

This approach was successfully applied to the Kangerlussuaq region of the ice sheet, where we have a fruitful collaboration (in terms of publications) with the Greenland Analogue Project, which binds several foreign research institutions. For the record-warm year 2010 (Box et al., 2011; Van As et al. 2011) we calculated 6.6±1.0 km^3 of surface melt-water to run off from the catchment, exceeding ‘normal’ reference year 2009 by about 150% (Figure 8) (Van As et al., 2012a). We identified that apart from the high temperatures increasing the melt over the entire domain, this was heavily amplified by the melt-albedo feedback in the large upper ablation zone, in which melt darkens the snow and ice surface, which in turn increases melt. This darkening of the ice sheet surface caused a doubling of surface melt in large regions in the summer of 2010 (Figure 9). By this we identified a process of which the effects (dark ice) will linger for several years or more, and already had implications for record runoff year 2012, during which the Kangerlussuaq bridge was washed away (Mikkelsen et al., 2012).

For ice-sheet scale surface energy balance (SEB) and surface mass balance (SMB) calculations, the distances between AWSs become too large to use spatial interpolation, and instead we use state-of-the-art regional climate models with coupled surface snow modules instead. These models are excellent tools to obtain SMB estimates, and our AWS network provides the potential for crucial model validation. Modellers become increasingly interested in PROMICE data now that the AWSs have produced data series of respectable length, because short observational time series are of less interest to modellers. We have actively sought collaboration with three modelling institutes (amongst which DMI), the Greenland Survey (Asiaq), the Greenland Climate Research Centre (GCRC) and US and UK universities. Currently, we are performing two studies of the SMB of the glaciers in the Nuuk region of the ice sheet (Van As et al., 2012b). Results show that over the past 20 years, ice sheet melt has increased by roughly 50%, and freshwater input into the fjord by 100% (Figure 10), which may have consequences for the fjord hydrology and thus livelihood for those living in the Nuuk Fjord system. In 2010, the high melt caused the Nuuk region of the ice sheet to lose an estimated 20 km^3 of ice. In our current perspective this was a high-melt year, but these warm conditions are likely to prevail or intensify.

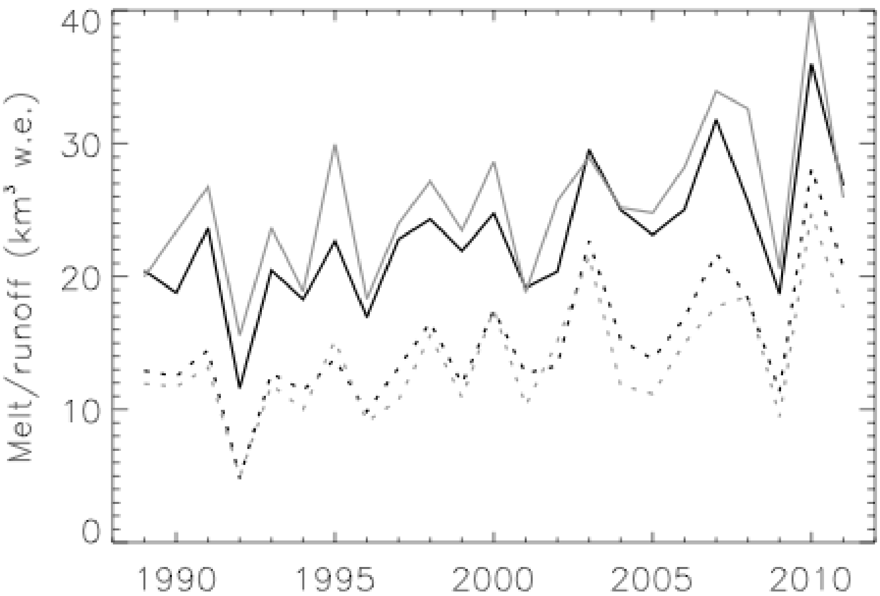

Figure 10. *Annual surface melt (solid lines) and runoff (dotted lines) for the Nuuk Fjord region of the ice sheet from the models MAR (black) and RACMO2 (grey) 1991-2011. The offset is due to refreezing of melt water in the ice.*

Through the participation of ASIAQ in PROMICE, three long-term hydrological series receiving large relative shares of melt-water have been made available. These data span up to more than 30 years and thus constitute a rare opportunity to assess the current efforts to model the runoff from the Greenland ice sheet. The hydrological data effectively record the runoff from a considerable stretch of the ice margin and are thus ideal for comparing to the output from distributed melt models. ASIAQ and GEUS are currently working on a scientific publication on this subject and have established contact to all the major melt modeling groups to facilitate a comparison. Such an exercise carries a considerable potential for subsequent improvement of the various melt models participating, an important aim for PROMICE.

PROMICE will be taking a prominent part in regional climate model studies of the entire ice sheet in coming years, producing SMB estimates for Greenland. In addition, we are developing a model that can calculate surface melt across the entire ice sheet based fully on observations from AWSs and satellites. The procedure will make use of remotely-sensed ice sheet albedo and surface temperature to calculate melt. The AWS data will be instrumental in the development of the melt algorithm, especially in the case of cloud masking, and in the validation of the result. By-products of this procedure are daily surface temperature maps, which can also serve the modelling community of ice dynamics (see next section).

Near-surface air temperature parameterizations

The PROMICE AWS network has established a valuable dataset of near-surface air temperatures covering the ablation zone of the entire ice sheet. Parameterizations of this parameter has previously been limited by the scarcity of such observations. The near-surface air temperature is one of the important boundary conditions in large-scale ice dynamics models. It is considered to be a relatively straightforward meteorological variable to extrapolate or interpolate on climatic time scales. Despite their broad application, it is a false assumption that free-atmospheric lapse rates offer an appropriate estimate usable in ice dynamics modelling. Observations from the PROMICE AWS network, the GC-Net, the K-transect and the AWSs from DMI were used in order to determine a new present day near-surface air temperature parameterization for the Greenland Ice Sheet (GrIS), based on the mean temperatures at the various AWS sites (Fausto et al., 2009a, Fausto et al., 2009b, Fausto et al., 2011). The new parameterization is widely used, with 19 references to our manuscript in 3 years.

Air borne surveys of surface and bottom elevation of the ice sheet

Ice flow transfers mass from the interior of the ice sheet toward the margin, where surface ablation and calving at marine terminating outlet glaciers discharge melt-water and icebergs into the ocean. Iceberg calving from the outlet glaciers of the Greenland Ice Sheet is responsible for about half of the mass loss during the last decades. To quantify this mass flux we need to know the velocity of the ice and the cross section through which it flows. This is achieved by combining airborne surveys yielding ice-sheet thickness along the entire ice sheet margin, with surface velocities derived from satellite synthetic-aperture radar (SAR). The ice-dynamic mass loss may then derived by calculating the ice flux from the interior of the ice sheet towards the outlet glaciers, while correcting for the surface melt between the flux gate and the calving front of the glacier.

To properly measure the flux gates, the flight route is charted to cross the ice flow at a right angle, roughly following the 1500 m a.s.l. elevation contour line around the entire perimeter of the ice sheet. Surface elevation was measured by lidar and the bedrock was imaged by icesounder radar, while position and attitude of the aircraft were determined by GPS (Global Positioning System) and INS (Inertial Navigation System) techniques.

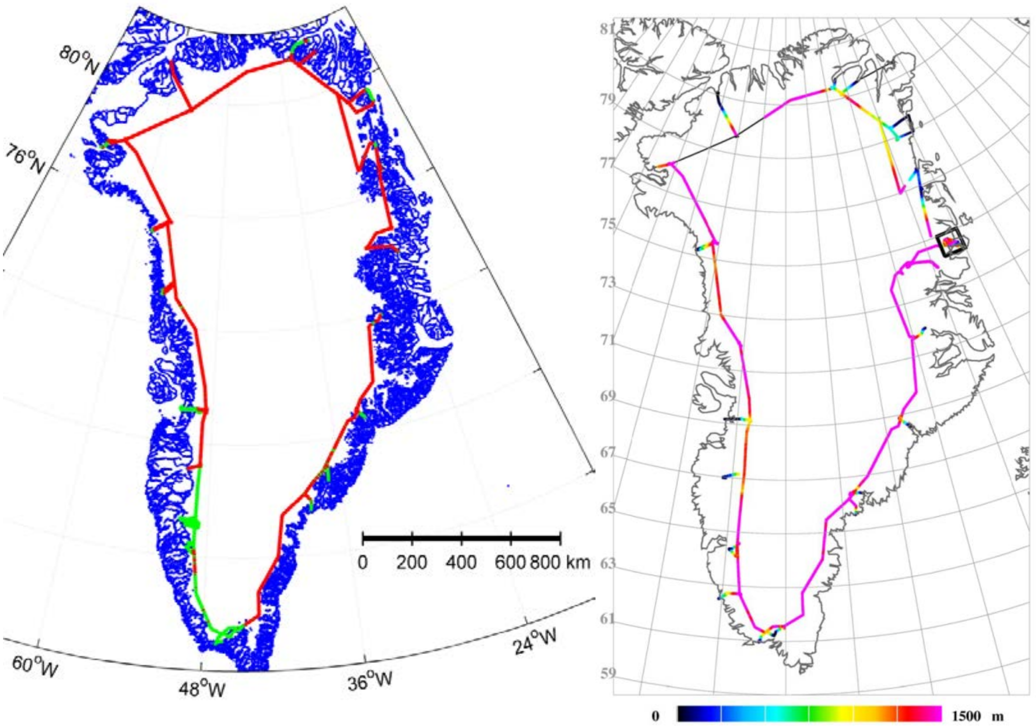

Figure 11. *The 2007 (left) and 2011 (right) flight paths with transits excluded. Red segments on the 2007 map show where a bottom echo was detected, while green segments show where a bottom echo was not detected. The 2011 radar data is currently being processed and the colour scale shows ice surface elevation measured by lidar.*

Successful campaigns have been carried out in 2007 and 2011 by DTU-Space (Figure 11). During the 2007 campaign the radar did not penetrate to the bedrock over parts of Southwest Greenland, but the 2011 campaign confirmed that some property of the ice is preventing successful radar survey in the area, an issue also reported by others. In the future, it will be relevant to measure surface elevation changes along the flux gate with regular intervals by air borne lidar (e.g. 4 years). However we do not believe further radar surveys (with the current technical performance) will yield new results.

The airborne campaign in PROMICE differs from the relatively short-lived NASA-funded campaigns (IceBridge being the latest series of missions) in several ways. Firstly, PROMICE flights are carried out in the late summer when the ice sheet surface along the flight track will have a minimum of snow, which constitutes a significant source of error for ice sheet surface elevation measurements. NASA flights are usually scheduled when the snowpack is at its maximum thickness, because the chance of successfully retrieving ice thickness from ice-penetrating radar is best when the surface is cold from last winter. Also, PROMICE flights are designed to establish a homogenous flux gate along the ice margin to facilitate subsequent calculation of the amount of ice lost through outlet glaciers. The NASA plans focus on the retrieval of detailed bedrock elevation from ice-penetrating radar, to support the ice-dynamics modeling community. Hence they do not duplicate PROMICE efforts. The PROMICE route includes flights down along the flowline of 20 major outlet glaciers primarily to capture elevation change and is closely connected to the PROMICE need for calculating ice fluxes. There is a great potential in comparing the NASA spring elevations with the PROMICE summer elevations, to see whether results agree where flight lines overlap.

Ice surface velocities

Producing velocity maps over a region as large as the Greenland Ice Sheet is a major undertaking, relying on the existence and availability of radar remote sensing data. Foreign research groups and international research projects have produced ice sheet velocity maps in parallel to the efforts in PROMICE, but we cannot rely solely on such efforts to continuously assess changes in the Greenland Ice Sheet on a monitoring basis.

In order to derive ice sheet surface velocities from SAR, a processing chain has been developed for GEUS by DTU Space based on a commercial software package distributed by GAMMA Remote Sensing. The processor, named SUSIE (Scripts and Utilities for SAR Ice-motion Estimation), can use both differential SAR interferometry and offset-tracking techniques to measure the horizontal velocity components, providing also an estimate of the corresponding measurement error.

Surface velocities have been derived for the areas along the Greenland Ice Sheet margin shown in Figure 12. Figure 13 presents an example from West-Greenland. The velocity maps have been validated against ground based GPS measurements with good agreement (Ahlstrøm et al., 2012).

Presently GEUS has become involved in the ESA Climate Change Initiative, Ice Sheets project where one of the two major products to be provided is Ice Velocity from ESA's SAR missions. One of the main objectives of the project is to produce velocity maps from data up to 2011 and the project has the benefit to PRMOMICE of providing easy access to ESA data.

There are presently no ESA missions or third party missions in operation providing SAR data over Greenland after failure of both the ENVISAT and the ALOS satellites in 2011. Hence there are no affordable present time data available. The situation will improve in 2013 when the Sentinel 1 satellite will be launched followed shortly after by Sentinel 2, with both satellites providing cutting edge SAR data.

The future existence of satellite radar data over Greenland is not a given fact. PROMICE team members actively engage in hearings on future satellite missions organized by the European Space Agency to stress the need for radar data over the Greenland Ice Sheet. Without this data, assessing changes in the ice sheet contribution to sea level change ends up relying on even more peripheral satellite missions aimed at altimetry and gravity measurement. These have proven useful in highlighting ice sheet volume and mass changes over very large areas, but crucially lack the explanatory power to drive the process-based studies needed to improve modelling capabilities.

Estimation of ice loss through calving

With a flux gate available from the airborne survey along the majority of the ice margin and the capabilities to produce velocity maps and melt maps established, we are now at the stage where it has become feasible to calculate the amount of ice passing by assuming a velocity profile from the surface towards the base of the ice sheet and estimate the loss of ice through calving. Data from the GPS-trackers will assist in quantifying the variability of the ice flux seasonally and from year to year. To assess the dynamic loss of ice to the ocean, it is necessary to deduct the surface mass balance between the flux gate and the ice margin. Therefore the melt maps are needed to assess the ice loss directly to the ocean through calving and bottom melting of floating glaciers.

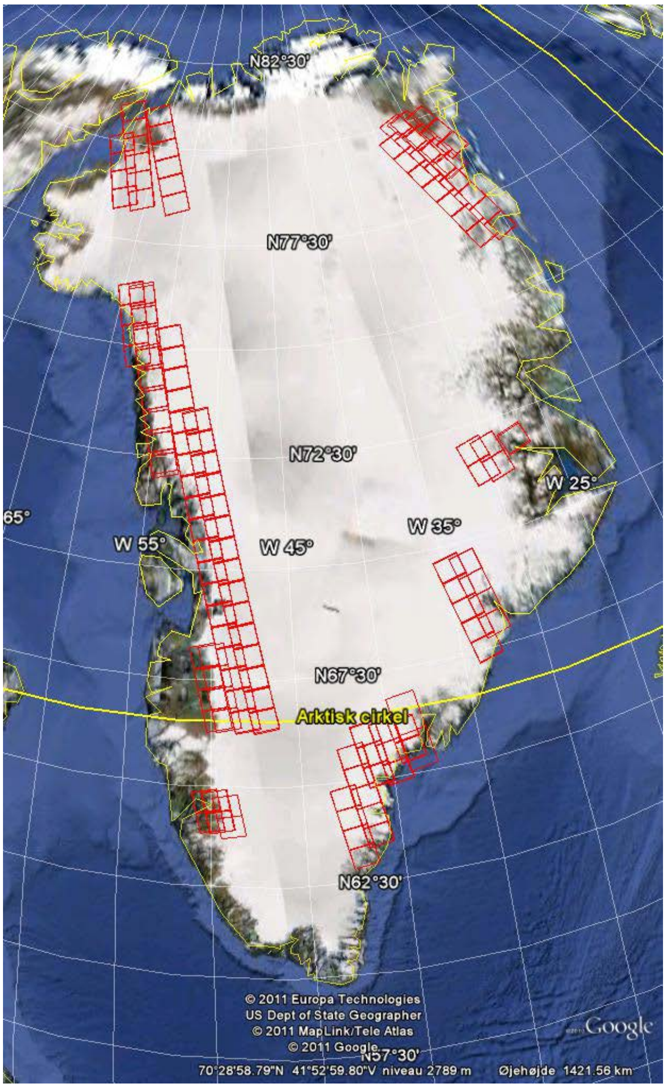

***Figure 12.** Frames for which PROMICE ice-velocity maps have been produced*

This work has started and focus will initially be on the dynamic mass loss of the Northwest drainage basin. The mass loss estimations will together with DTU-Space be compared to regional estimates of mass change from independent methods based on GRACE data and ICESat data, to improve the understanding of the causes the mass changes.

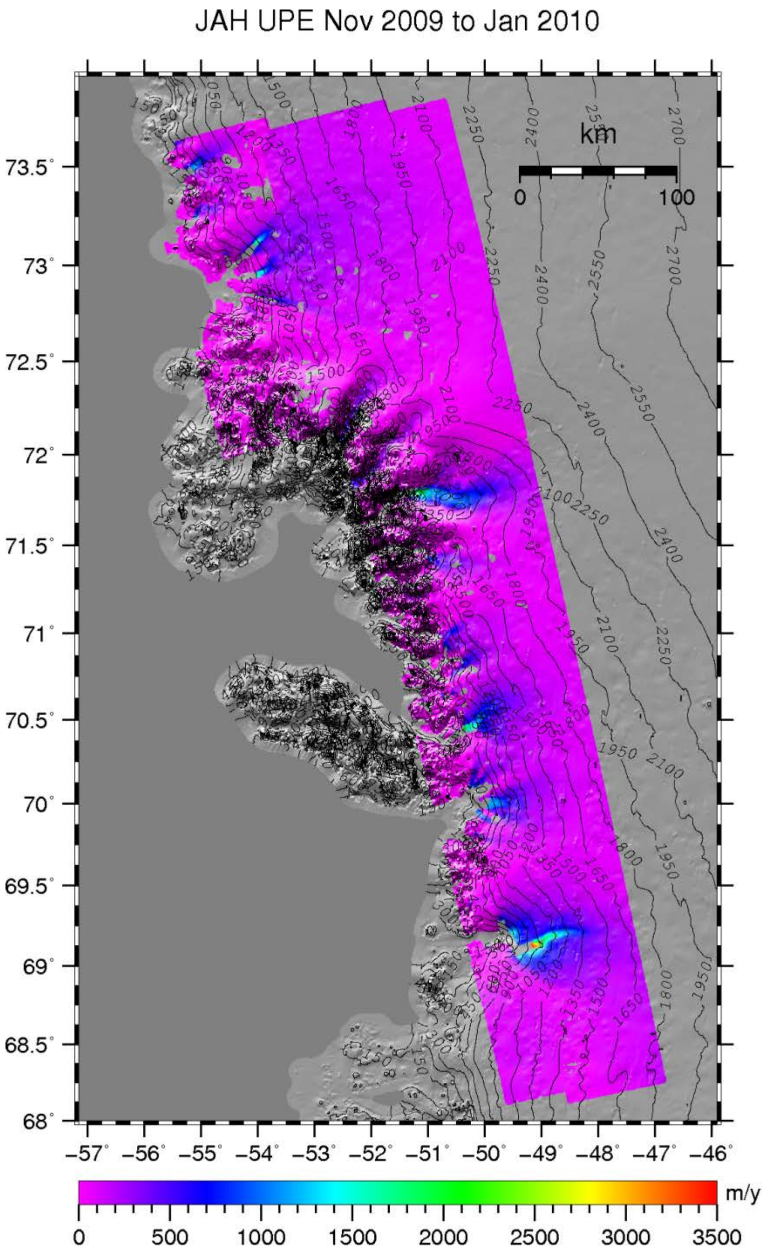

Figure 13. *Ice velocities in West Greenland covering the area from Ilulissat in the south to Upernavik in the north November 2009 to January 2010.*

GPS (AWS GPS + IVEL tillægsprojekt)

An important part of the scientific discussion regarding the reaction of the Greenland ice sheet to climate change has been the relationship between surface melt-water and ice dynamics. For this reason, all AWS in PROMICE have been equipped with GPS instruments recording the movement of the station. The GPS instruments are robust, single-frequency systems that have low power-consumption and require a modest amount of data to be stored and transmitted. This means that the overall movement is tracked continuously throughout the year, but also that high-precision/sub-daily analysis is not possible. The ice dynamics of the outlet glaciers are quite different compared to the ice margin where the AWS are deployed. Thus, an add-on project to PROMICE was launched to specifically quantify the seasonal velocity fluctuations of the outlet glaciers, as this may impact PROMICE calculations of the dynamic ice loss which is based on satellite velocity mapping on necessarily capturing this effect. To accomplish this, transmitting GPS instruments were deployed on 5 major marine-terminating outlet glaciers: Upernavik Isstrøm, Kangiata Nunata Sermia, Qajuutap Sermia, Helheim Glacier and Daugaard-Jensen Glacier. Additionally, rugged camera systems have been deployed in collaboration with Extreme Ice Survey and Byrd Polar Research Center in order to obtain 2D velocity fields over the entire width of the glacier tongues. Preliminary results show large and sudden seasonal fluctuations in the glacier velocity, particularly in the summer time (see example in Figure 14). This implies that one must carefully consider the seasonal coverage when deriving velocity maps from satellite image analysis in order to account for the error introduced by the seasonal variation in glacier velocity.

Further details of the IVEL project may be found in the last section of this report.

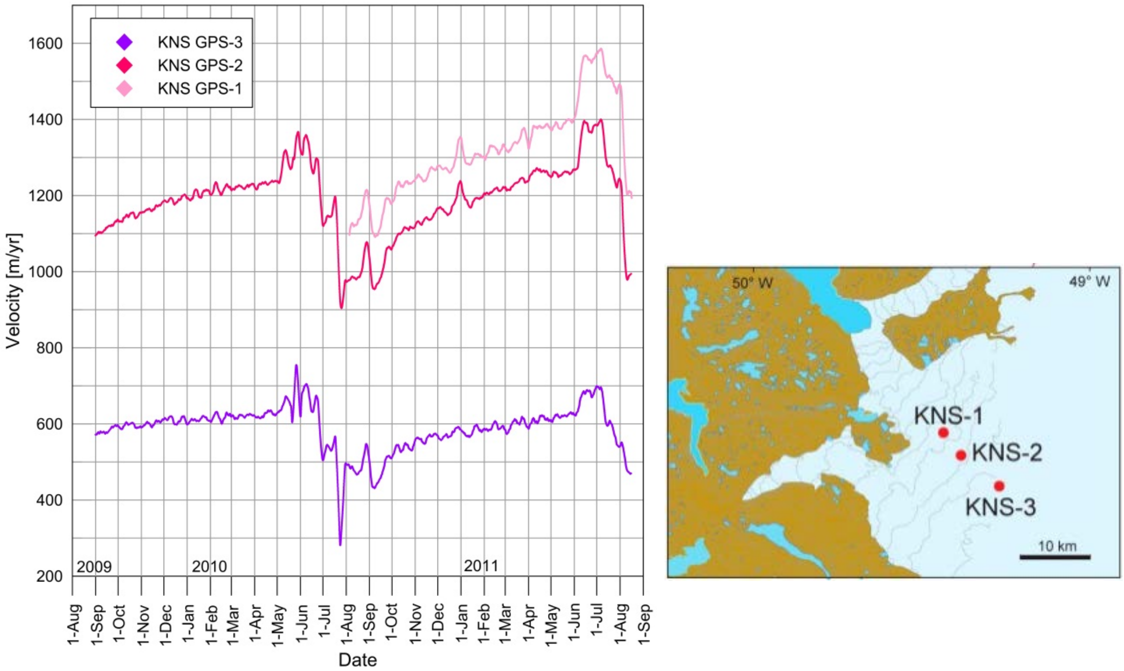

Figure 14. *Seasonal velocity variations on the outlet glacier Kangiata Nunata Sermia in Godthaabsfjorden near NUK as derived from weekly averaging of single-frequency GPS data from three instruments at increasing distance from the glacier front (Ahlstrøm et al., in press 2013).*

Mapping of Greenland ice masses

We have recently completed the PROMICE map of all Greenland ice masses (Citterio & Ahlstrøm, 2013), based on the highest detail existing data source covering all Greenland: the aero-photogrammetric maps produced by GEUS and KMS (National Survey and Cadastre) from the mid-80's aerial photographs (Figure 15).

Until summer 2012, no complete glacier inventory existed of Greenland glaciers, and the best ice cover grids did not explicitly separate the ice sheet from the glaciers and ice caps and contained significant mistakes. Even the total extent of these local ice masses was unclear, with modelling studies in the glaciological literature using estimates between less than 50,000 and 150,000 km^2. Our final PROMICE map of Greenland ice masses (Citterio

& Ahlstrøm, in review) shows that, in the mid-1980's the ice sheet covered 1,716,555 ± 947 km^2, and ice caps and glaciers covered 88,083 ± 1,240 km^2.

Last year the lack of a reliable ice extent dataset resulted in a high profile incident involving the famed Times Comprehensive Atlas of the World http://www.guardian.co.uk/environment/2011/sep/19/times-atlas-wrong-greenland-climate-change
The publisher HarperCollins had to retract their map of Greenland misrepresenting vast areas as de-glaciated land. The Atlas was then amended and a new map of Greenland http://www.timesatlas.com/Documents/Greenland%20Insert%20HIGH%20RESOLUTION%20DOWNLOAD%20FOR%20PRINTING.pdf based on the correct ice extent map provided by PROMICE, was inserted in the already printed volumes. Based on NASA LANCE Rapid Response MODIS imagery, we updated our 1980's ice margins to 2011 (Figure 16), and we found a net combined area loss of 2,560 ± 260 km^2 from the 128 sites of larger detected change, excluding known glacier surges (Kargel et al, 2012).

Bolch et al. (in review) estimate that 20% of the current sea level contribution from Greenland comes from glaciers and ice caps, and find these ice masses to be 2.5 times more sensitive to warming air temperatures than the ice sheet. Knowing the precise extent and geographic distribution of ice masses other than the ice sheet will allow partitioning between ice sheet and glaciers the GRACE mass changes.

Glacier length in the mid-1980's is another parameter easily extracted from the PROMICE map. This is an important contribution in regions where long and detailed glacier length fluctuation records are lacking, because they are an indication of climate change as glaciers react with geometric adaptation to changes in climatic forcing (Leclerq et al., 2012).

GEUS is the GLIMS Regional Centre for Greenland and the new PROMICE map will be delivered to the GLIMS database. Another Greenland-wide dataset is also becoming available (Rastner et al., in review). It is the end result of a process started within the ESA GlobGlaciers Project with the mapping of glaciers and glacier change (Figure 17) in the Disko-Nuussuaq-Svartenhuk region (Citterio et al, 2009), and continued within the Ice2Sea Project using the same thresholded band ratio method with Landsat ETM+ imagery. The Rastner et al. (in review) inventory contains ice sheet, ice caps and glaciers outlines around year 2000 and can be used with the PROMICE map to quantify 1980's-2000 glacier change. We are currently starting to produce glacier change from at the scale of all Greenland. In a regional study focusing only on the Geikie Plateau region between the 1980's and 2005 (Jiskoot et al., 2012) we already found generalized retreat (Figure 18) and different behaviour between 'outer' fjord-terminating and 'inner' fjord-terminating outlet glaciers. The Jiskoot et al. (2012) regional inventory is also being contributed to the GLIMS database.

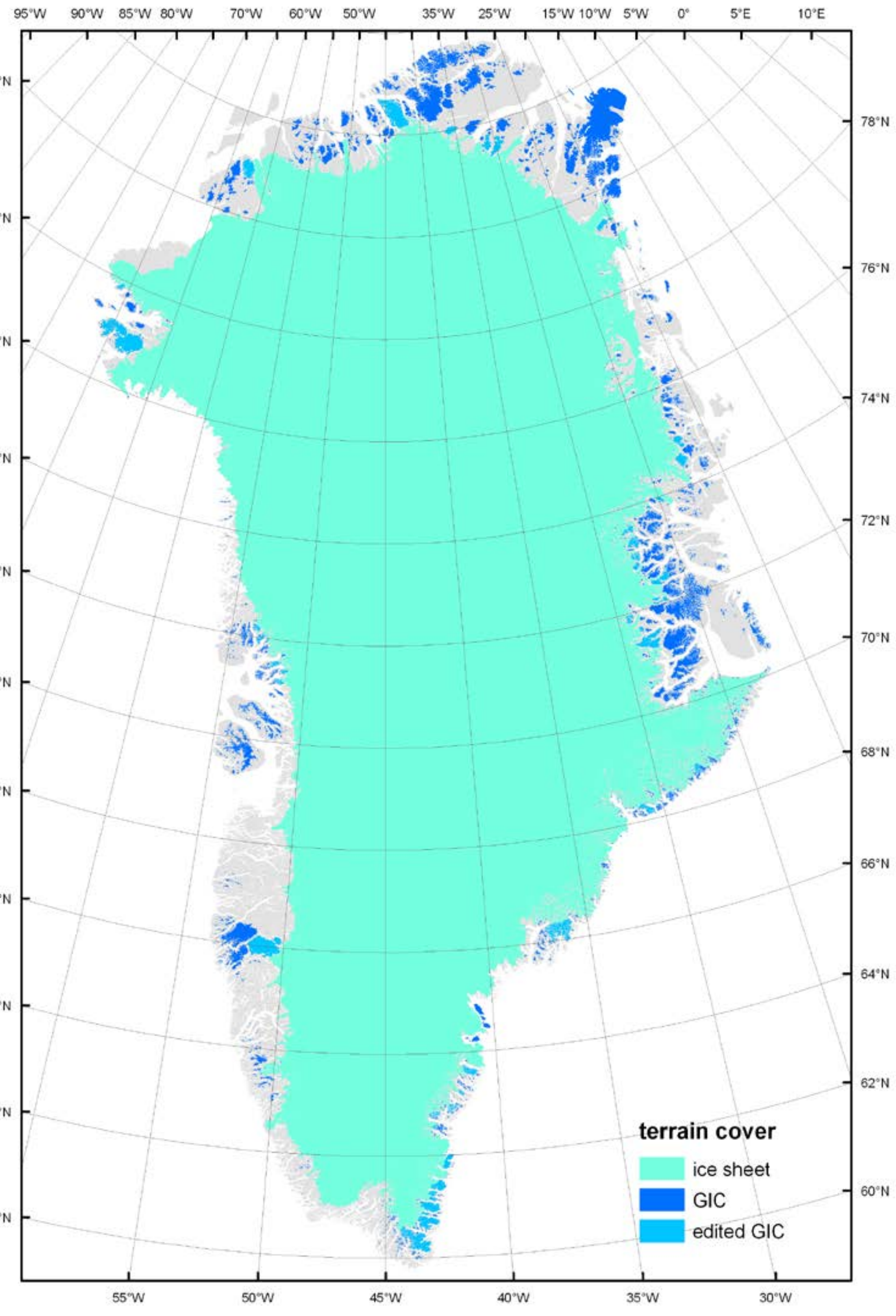

__Figure 15.__ Map of glacierized terrain classified as 'ice sheet', 'Glaciers and Ice Caps (GIC)' and 'edited GIC'.

Alongside the main task of glacier mapping and inventorying, the history of repeated filling and emptying events of the glacier dammed lake Isvand on the western flank of Kangiata Nunaata Sermia outlet of the ice sheet in West Greenland has been reconstructed using ASTER and Landsat visible and thermal infrared imagery up to the most recent, and likely permanent emptying occurred in 2009 (Weidick and Citterio, 2011). An exception-ally long record of documentary information on the lake and the glacier are available for this site, which allowed reconstructing the fluctuations of the glacier and the discharge routes of the lake over about 250 years.

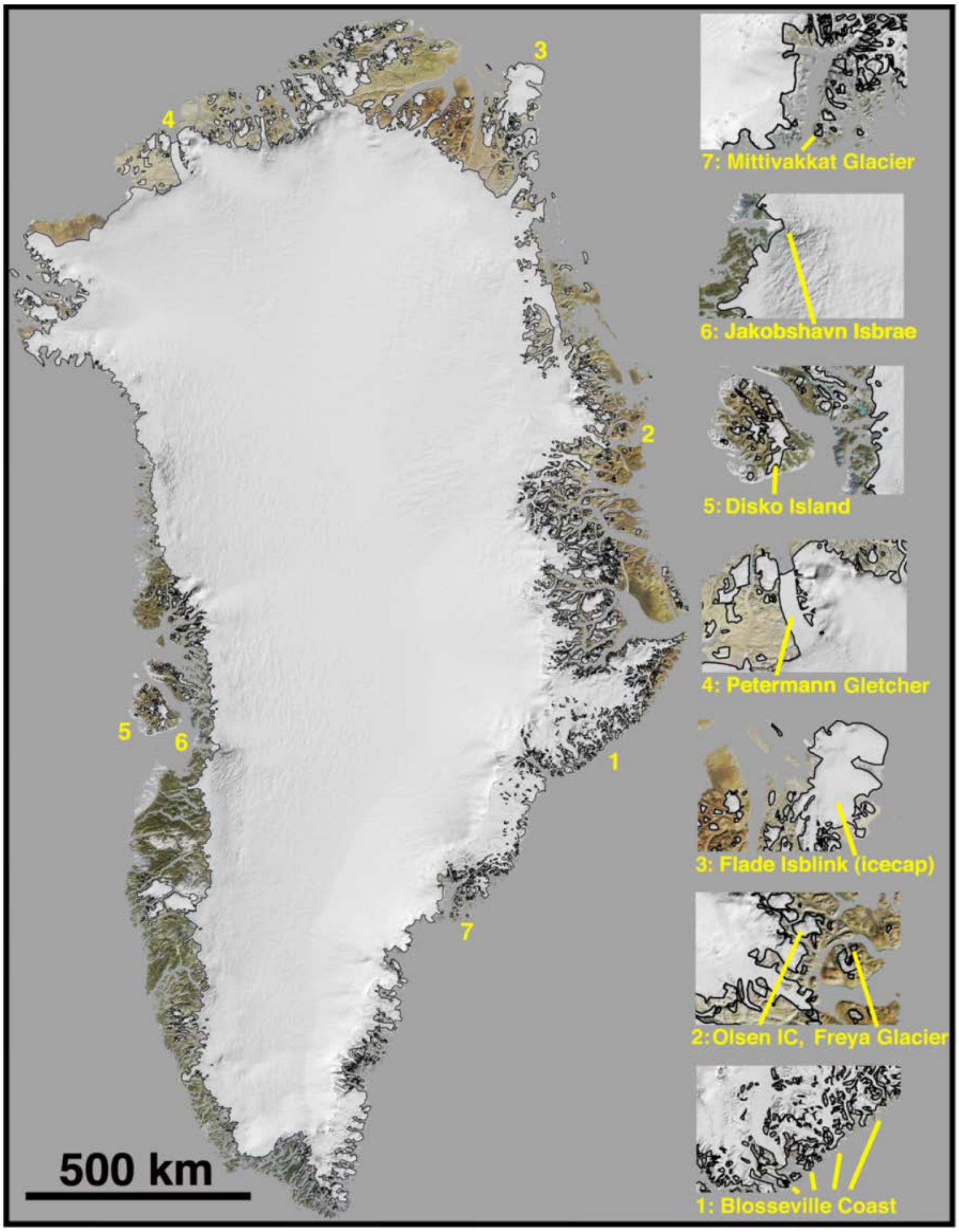

Figure 16. *Greenland ice outlines, from Citterio & Ahlstrøm (2012), updated to 2011 based on NASA LANCE Rapid Response MODIS and overlain on a 250 m MODIS mosaic by Paul Morin (U. Minnesota). Insets highlight a few sites of ongoing research activity (Kargel et al., 2012).*

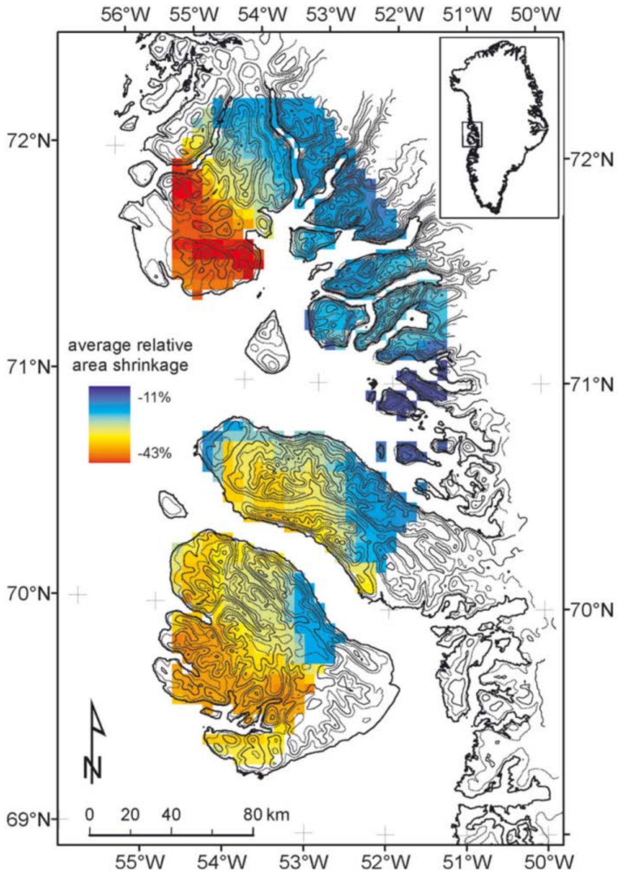

Figure 17. *Spatial variability of the Little Ice Age (LIA) to 2001 relative area change over the entire region computed as 50 km x 50 km average of glacier change. Yellow to red colours mark areas with larger change, blue areas smaller changes (Citterio et al., 2009).*

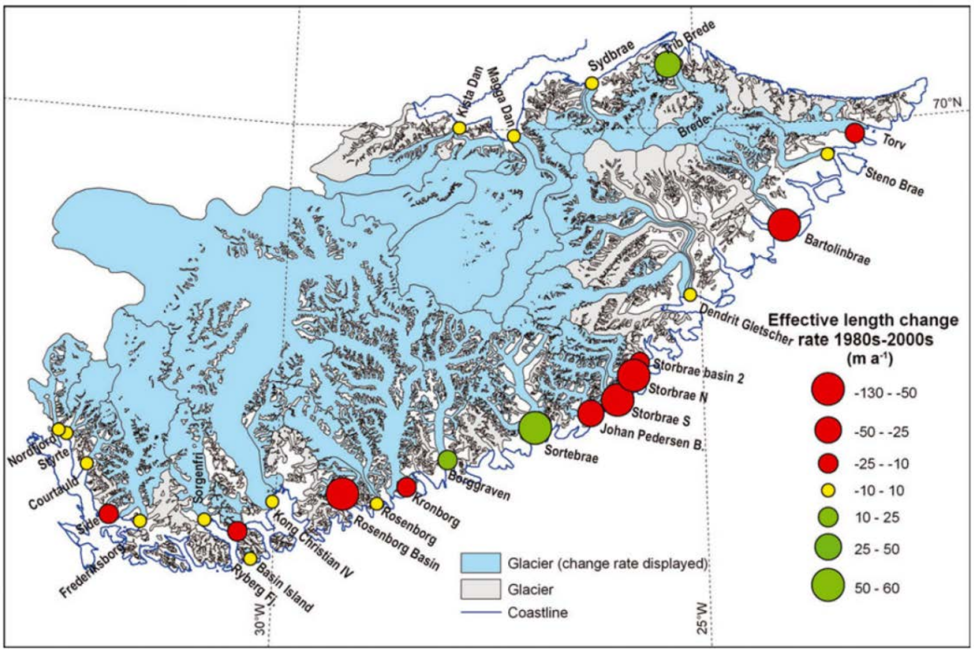

Figure 18. *Effective length rate of change between the 1980s and 2000/01 for 16 fjord systems and 11 of the largest single glaciers (Jiskoot et al., 2012).*

These concerted efforts by PROMICE and Swiss, Canadian, Dutch and US colleagues provide state of the art regional and Greenland-wide snapshots of past and present ice extent produced from independent methodologies and data sources. Moving forward, PROMICE as a monitoring programme will work toward an operational land ice extent product based on archived and real-time imagery from moderate and high resolution satellite sensors. We envision an operational system delivering periodic updates of two main products: a) terminus position of Greenland's marine terminating outlet glaciers, and b) updates to the PROMICE map of the Greenland Ice Sheet, ice caps and glaciers. The tentative target periodicity of product (a) is monthly and of product (b) is annual. Once in place, the products of the operational system will be made available online as image maps and downloadable science grids.

Historical stake measurements

The PROMICE weather station network provides a view on today's melt conditions on the ice sheet margin, but stands in a tradition of intensive historic mass balance observations on the margin of the Greenland ice sheet. These historical mass balance observations provide a unique view on variability of melt in the past, a view that cannot be derived from any other data source. Hence historical measurements are crucial to validate modelled mass balance distribution as provided by state of the art coupled atmospheric/snow models.

While the PROMICE data are freely available for download, the historical data are unavailable to the scientific community because only very few series are published and the raw data are scattered over various archives. Collecting all available historical data and compiling them into a database would have major benefits: (i) the data become available to the community, (ii) several PROMICE stations have been placed at sites of historical mass balance observations providing an excellent possibility to study changes in mass balance over longer time periods, and (iii) unifying data from various sources will result in the longest mass balance records in Greenland.

Preliminary explorations revealed that mass balance observations on the ice sheet margin and local glaciers and ice caps were performed on at least 47 sites (Figure 19). The most important part of historical mass balance data has been obtained in the framework of extended GGU (Grønlands Geologiske Undersøgelser) and GEUS campaigns and is stored in the GEUS archives. In spring 2012, PROMICE started an initiative to make this heritage of high quality data available to the scientific community: mass balance observations from all sites in the ablation area of the ice sheet as well as local glaciers and ice caps will be compiled into a database subject to publication in a peer reviewed journal. The GGU/GEUS data form the core of the database but other sources are included whenever available and agreed with the data owners.

At the current stage the largest part of the GEUS archives has been sifted and relevant documents are registered. By 1 April 2012, a total of 1,800 stake readings have already been added to the database which is about 80% of the expected final number of readings. Particular attention is paid to collecting data at high temporal resolution (so called winter and summer balances instead of only annual balances) and for each individual reading a comprehensive set of meta-data is stored in the database.

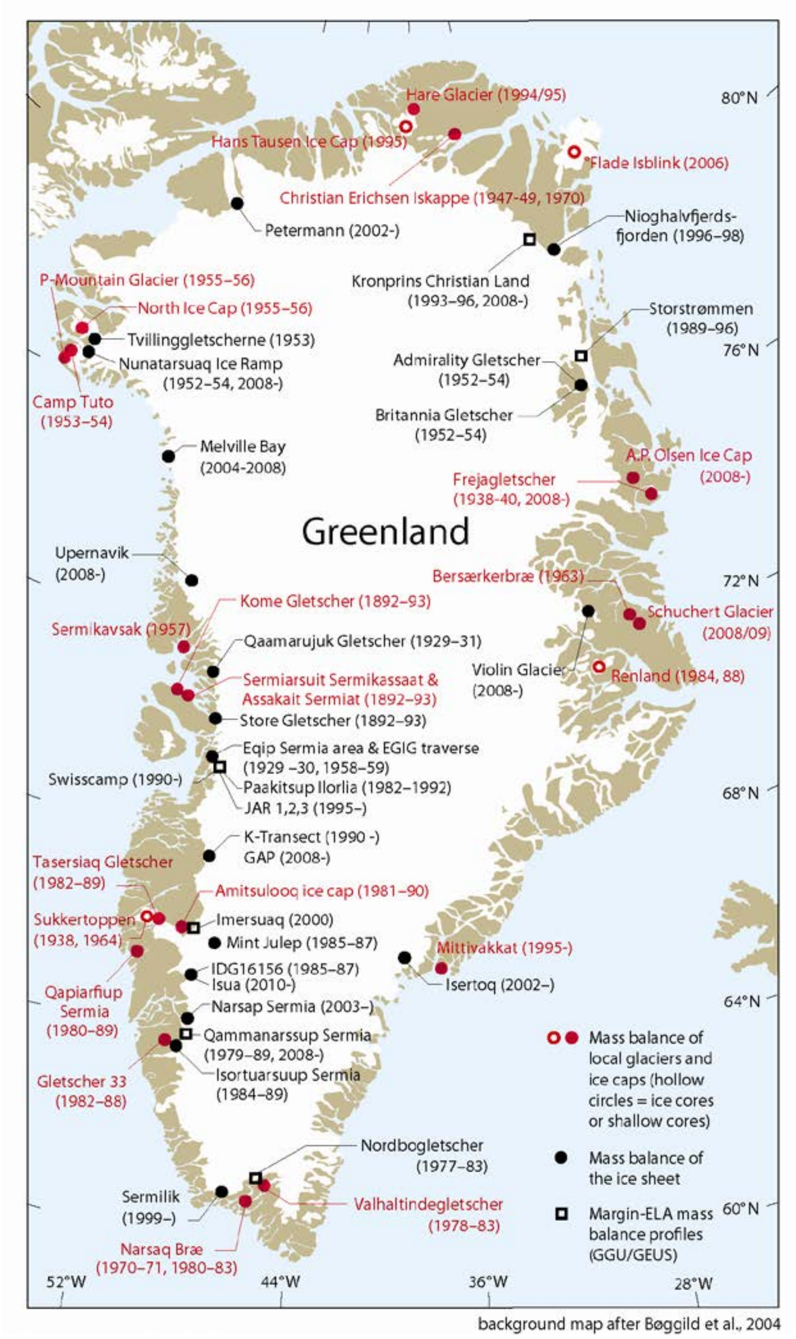

Figure 19. *Overview to all mass balance observations from the ablation area of the ice sheet as well as local glaciers and ice caps.*

It was planned to finish the data base by end of 2012. This goal could not be achieved because the amount of discovered data is larger than originally expected and reconstructing the exact locations of measurements from the pre-GPS area took more time than planned. Nevertheless, the data base is about to be completed and a manuscript about the data is currently in the writing. The data are made available to the scientific community as an integral part of the PROMICE database. Hence PROMICE will become the first research effort providing (i) a long term perspective of measured mass balance and (ii) offering a near complete coverage of the Greenland ice margin. These two aspects form a major contribution for assessing the past and present mass balance of Greenland.

Fieldwork and data collection

There are three groups operating AWS networks on the Greenland ice sheet. The American GC-Net (~15 active stations) is largely situated in the accumulation zone, where no substantial melt takes place. The Dutch K-transect (3 stations) focuses on one region in southwest Greenland. PROMICE operates in the entire ablation zone and hence solved the problem of having too few measurements in the region of the ice sheet where mass-turnover is at its maximum. Still, the combined measurement network is coarse; we currently have less than one AWS per area equivalent of Denmark. The PROMICE data from the melt zone are of particularly high value to the SMB modelling community. It should be noted that the future of GC-Net is currently uncertain, as the Professor Konrad Steffen the project leader of the GC-Net has moved to Switzerland and NASA has promised only two more years of funding as he is no longer eligible for receiving their grants.

The ablation zone is a much more dynamic environment than the high elevation interior. In the ablation zone several meters of surface ablation, crevasses, surface melt-water channels, high katabatic and Piteraq winds, frequent cycles of freezing and thawing, burial by deep seasonal snow and sensors melting out are common threats to the weather stations. Most of these processes are absent in the high elevation interior. The location of the PROMICE AWSs is the best compromise between minimizing dangers related to difficult terrain, maximizing ease of access, and maximizing the scientific significance of the observations. We have successfully mitigated some of the causes for high costs by developing instruments and sensors specifically designed to operate unattended even in the highest ablation sites.

Large experience build up over the years resulted in an AWS design capable to operate reliably for several years with periodic maintenance visits (data collection, sensor replacement, redrilling of stakes, general check-up). The required frequency of station revisits depends on the local conditions at the monitored sites. The surface and meteorological conditions at several of the PROMICE sites are very demanding on the waterproofing and mechanical strength of the PROMICE AWSs, requiring annual maintenance visits (e.g. Tasiilaq region with frequent extreme wind events). Stations in less dynamic environments do not require annual maintenance visits, such as the KPC stations at high latitude. This is a benefit given the high cost of visiting these remote sites.

The PROMICE field plan is defined every year based on an analysis of the data received by satellite. A list of required maintenance and recalibration tasks is compiled early in the year and a PROMICE member is appointed as the responsible field leader for each campaign. The fieldwork plan is finalized to achieve the best compromise between maintenance needs, economic effectiveness and affordability of the campaign. Logistics planning is then started to secure helicopter charters, sled dogs or snow scooters, flight tickets, shipping contracts, arranging accommodation in the field, and to procure scientific and safety equipment. The list of required sensors is handed over to the AWS workshop at GEUS, so that all materials can be made ready for shipment by the required dates.

The fieldwork occasionally suffers from adverse weather conditions and limited logistical infrastructure at most sites. We have mitigated some of these sources of uncertainty in fieldwork planning and expenditures by choosing alternative means of transportation, such as dog sledding. The actual maintenance at the AWSs has been made fast and efficient by devising a checklist that takes the field crew systematically past all required tasks.

The success rate of the PROMICE AWS in the field is high, e.g. 85-90% for temperature measurements; a very respectable value compared to the other AWS network success rates. Data losses are due to random hardware failure, damage by harsh conditions, and human error - all three causes contributing approximately equally to data gaps. In particular, the Tasiilaq stations have been repeatedly damaged by very strong Piteraq winds, being typical for that region. On the contrary, stations like UPE and KAN located in more sheltered sites had 100% reliability over 5 years.

In 2012 all PROMICE stations were visited. This was possible due to synergy with other projects. The NUK stations were visited in collaboration with the Greenland Climate Centre project ImGlaco, QAS stations were visited in collabotation with the GEUS REFREEZE project.and finally the KAN stations were funded by the Greenland Analog Project (GAP).

Database

For a long term monitoring project such as PROMICE it is important that the acquired data is stored in a systematic way. For that purpose the PROMICE database has been developed to keep track of all data acquired in the PROMICE project, including specifications on the instruments the data was acquired with and what processing has been done to it. The database is maintained by the GEUS Geological Data Centre which is already the national repository for a range of geological, geophysical and hydrological data.

The PROMICE AWS data consist of measurements from a number of instruments. The measurements are stored locally in a data logger and also transmitted through Iridium satellites to GEUS. What sets PROMICE apart from other groups with AWSs is that all metadata information on the station, instruments (type, serial number, accuracy, calibration, etc.) and conversion/correction factors are also stored, preserving a log of all relevant information and data mutations. The data flow is illustrated in Figure 20.

In order to make data from the PROMICE project publicly available a website interfacing the database has been made. The website is accessible through http://jupiter.geus.dk/promiceWWW/home.seam or via a link on http://www.promice.dk

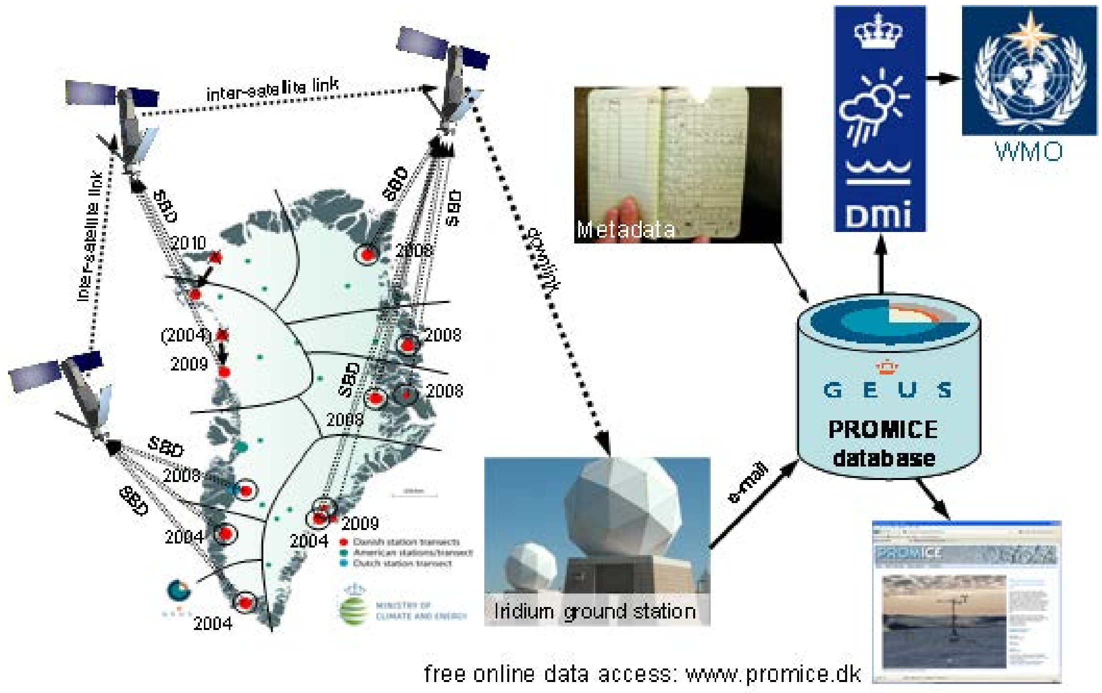

Figure 20. *Overview of the data flow within the PROMICE monitoring network*

The website offers the data that were transmitted by all PROMICE weather stations, and the opportunity to see the latest transmissions from the ice sheet. The PROMICE data are free to download for everyone; all that needs to be done is to complete a short registration form including contact information and a short statement on the intended use of the data. The terms of use are provided with the data, ensuring that credit for the data goes out to PROMICE. Users of the data belong to a wide range of research.

The database effort has been concentrated on data from the AWSs as this had priority. Other PROMICE data such as airborne altimetry data, radar surface velocity data, GLIMS glacier map and historic stake measurement data are also stored securely in the GEUS system and will be made available to the public through the database website.

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Outreach

Communication with the public is done in a number of different ways:

The PROMICE team participates in the public debate nationally and internationally, disseminating results and providing expert opinions on issues related to glaciers and ice sheets. PROMICE project team members appeared 129 times in the media since the start of the programme.

The PROMICE Newsletter aims at being published two times a year and is a means of actively engaging with the press and the public. A collaboration with the News Department of Experimentarium, an institution devoted to, and specialized in, popular science outreach has successfully been established to enhance the interest of the media and reach a larger audience. So far three news letters have been distributed one in 2011 and two in 2012. Newslatters are available in appendix D.

Three major e-leaning programmes aimed at different audiences have been completed. This was done in collaboration with Context Consulting, a firm specialized in web-based science communication and with external funding of nearly 1 mio. DKK. The first project (in English) presents PROMICE broadly to the international public audience and was launched for the COP15 meeting in Copenhagen in 2009. The two following projects are programmes aimed at Danish school teachers and children.

Three websites related to the PROMICE programme are maintained the website www.promice.dk (and www.promice.org), the e-learning platform www.isskolen.dk and the PROMICE database website.

The PROMICE website which is targeted at a general audience is updated a few times each year. It contains information about the programme, newsletters, access to e-learning programmes and the PROMICE database website for data viewing and download. The table below shows the increasing number of visitors each year it has been in operation.

Year	**2008**	**2009**	**2010**	**2011**	**2012**
Unique Visitors	76	659	1120	2432	3031

Table 1. *Number of unique visitors to the PROMICE websit.*

The site www.isskolen.dk is directly aimed at primary school children, ages 10-12 years and 13-16 years, respectively, complete with exercises and teachers manuals. The programmes are registered at the Danish educational portal EMU which is the main site used by school teachers in Denmark to retrieve educational material. During the period January-September 2012,1920 unique visitors visited www.isskolen.dk

In addition the PROMICE database web page, which was described in more detail elsewhere, is accessible to the public and offers the possibility of viewing the measurements from the weather stations on the Greenland Ice sheet in real time.

As a new initiative, the measurements from the weather stations on the Greenland Ice sheet will in the near future be shown on the home page of ASIAQ together with the observations of DMI and Grønlands Lufthavnsvæsen to the benefit of the Greenlandic population.

The number of visitors of the PROMICE web sites is relatively modest. Synergy with the new PolarPortal website is expected to enhance the visibility.The PolarPortal is a joint outreach effort with DMI and DTU Space to provide updated online information on the state of GrIS. Real time observations, related climate indicators and news based both on own and international efforts, will be shown in a timely manner making it easy for the general public to follow the development of the mass loss of the Greenland ice sheet. The website will be launched in June 2013.

The PROMICE website is being updated in 2013.

Collaboration

PROMICE interacts with a range of institutions, agencies and programs as well as scientific projects. DTU Space and ASIAQ have been contributing partners delivering airborne measurements of ice thickness and elevation, processing software for deriving ice sheet velocity maps and extended hydrological time series of ice sheet runoff. Collaboration with DMI on producing operational mass balance estimates with input from the PROMICE network of weather stations is currently being explored as is the development and improvement of mass-balance related parameterizations in DMI's regional climate model

Other close scientific partners have been University of Copenhagen, Universität Zürich, University of Colorado, Universiteit Utrechtand and Université Libre de Bruxelles, with which we have had extended research collaboration and exchange of scientists. We have had or have shared supervision of PhD students with Cambridge University, Uppsala University and University of Copenhagen.

PROMICE is linked to research activities within Greenland through participation in the Greenland Climate Research Centre located at the Institute of Natural Resources in Nuuk, Greenland. This has led to several research projects with aims parallel to those of PROMICE, such as FreshLink (Linking ice sheet thinning and changing climate) and the project Impact of Glaciers near the Coast, which both primarily focused on the ice sheet-ocean interaction in the Godthaabsfjorden area.

As a monitoring program, PROMICE delivers near-real time observational data directly to the Danish Meteorological Institute (DMI) in order to improve atmospheric circulation modeling, mass balance data to the World Glacier Monitoring Service (WGMS), vector maps of ice sheet and glacier extent to the Global Land Ice Measurements from SPACE (GLIMS) and campaign datasets to the National Snow and Ice Data Center (NSIDC). Through WGMS, GLIMS and NSIDC we deliver to the Global Terrestrial Network for Glaciers (GTN-G) authorized under the Global Climate/Terrestrial Observing System (GCOS, GTOS) in support of the United Nations Framework Convention on Climate Change (UNFCC). .

PROMICE is involved with the European Space Agency through the ESA project GlobGlacier (global ice extent) and specifically the Ice Sheets part of the ESA programme Global Monitoring of Essential Climate Variables (also known as the Climate Change Initiative or CCI) which focuses on the Greenland Ice Sheet. PROMICE team members lead the ESA_CCI Ice Sheets as well as several work packages ensuring that knowledge and data products pass seamlessly both ways.

Involvement with NASA has been on a variety of issues: the combination of observations from the NASA-supported Greenland Climate Network (GC-Net) and PROMICE was the focus of a recent extended research visit; ice mapping efforts of NASA and PROMICE where recently pooled in a mutual scientific and public response to the erroneous new Times Atlas; airborne measurements of ice sheet elevation and thickness from the NASA IceBridge mission as well as ICEsat laser altimetry data are utilized by PROMICE with personal contacts to the key scientists and programme administrators.

The PROMICE team is engaged in the Nordic Centre of Excellence - Stability and Variations of Arctic Land Ice (SVALI) through theme leadership, PhD supervision and outreach, providing a solid Nordic dimension to PROMICE.

On the European level, the PROMICE team is taking a leading role (on the Steering Committee) in the €10M EU Framework 7 project, ice2sea, in which 24 institutional partners work together to quantify the contribution of continental ice to sea-level rise over the next hundred years. Ice2sea has specifically been set the task of providing input to the upcoming Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC). Through ice2sea, results from PROMICE are linked directly with the effort to predict future sea level rise and reporting it to the UN. Key scientists in ice2sea are also lead authors on the relevant chapters in the next IPCC report.

A number of research projects incorporating PROMICE team members have provided PROMICE with additional knowledge and field instrumentation, enhancing the monitoring effort: Greenland Analogue Project (GAP), Linking sediments with ice-sheet response and glacier retreat in Greenland (SEDIMICE), Quantification of meltwater refreezing on the Greenland ice sheet (REFREEZE), GlacioBaisis witin the Greenland Ecosystem Monitoring framework and several more. In this respect, PROMICE serves as a way to utilize the scientific insights, instruments and data obtained in related research projects.

Outlook

PROMICE has succeeded in establishing a research and monitoring capacity in Denmark on the current state of the Greenland Ice Sheet, an issue of urgent interest to the Danish society, feeding directly into policy-making nationally as well as internationally.

PROMICE is maturing to a level where it in the coming year is ready to launch a series of products indicating the impact of climate change on the Greenland ice sheet. Such indicators are in high demand from this remote, yet important region, especially as they are based on ground-truth observations. Examples of indicator products available or under development include:

- Near-surface air temperature maps
- Surface type maps for the ice sheet
- Monthly means of AWS data
- Length of melt season
- Annual observed melt

A primary goal of PROMICE is the mass loss and we expect the first results to be available for a sector of the ice sheet within a short time, including both the surface mass balance and the dynamic mass loss from the outlet glaciers to the ocean. Once the procedure is established for a sector, it will be rolled out to the remaining part of the ice sheet. With the mass loss calculation procedure in place, PROMICE will benefit immediately from the satellite radar data that will become available from the ESA satellite-series Sentinel in 2014. Already now, PROMICE personnel participates in an ESA effort, the Climate Change Initiative, to produce legacy velocity maps over the Greenland ice sheet and we are expected to participate in the follow-on project involving Sentinel data. These data will alleviate the present data shortage experienced outside Canada and the US (where scientists have access to Canadian Radarsat data at no cost).

On the lines of surface mass balance modelling, we are pursuing the following paths. A new surface mass balance model utilizing a combination of AWS observations and satellite-derived data is under development within PROMICE aiming at establishing the surface energy balance over the entire ice sheet. At the same time we are collaborating with DMI on developing a coupling between our AWS network and physical parameterizations based on the AWS observations with their regional weather forecast model. Crucially, the same methodology can be used in the regional climate model at DMI which is used for predictions. Thus, through collaboration with DMI, PROMICE will participate directly in the development of predictive models based on emission scenarios. In addition, PROMICE is currently collaborating with international mass balance modelling groups to explore ways to maximize the use of the new and extensive dataset that is emerging. PROMICE AWS data is extremely valuable for validation purposes, but also carries a strong potential for direct use in models to provide observation-based mass-balance products. The AWS data also provides new possibilities for developing physical parameterizations that may be utilized in models. As an example, PROMICE is currently engaged in the REFREEZE project funded by GEUS to establish a new parameterization for the refreezing of meltwater in the snow on the ice sheet, a process that is currently inadequately modelled and which will be a major factor in determining the future contribution to sea level rise from the Greenland ice sheet.

Comparison of ice loss calculations using the mass budget method with bulk estimates derived from gravity satellite data (GRACE), GPS (GNET) and satellite altimetry (ICESat and CryoSat II) has an interesting potential that we aim to explore internally in PROMICE with DTU Space and externally with University of Copenhagen (NBI) and international partners. Such collaboration has already begun in the EU-project Ice2sea mentioned above.

PROMICE has actively engaged in current international research, policy-advising and monitoring coordination activities on a range of levels. An example of this is Ice2sea, a large-scale EU FP7 project running 2009-2013, that is currently delivering the best estimate of recent and future mass loss from the Greenland ice sheet to deliver to the upcoming IPCC report. PROMICE is at the centre of this effort through a seat in the Steering Committee, leading the observational side of the project, but also through data delivery and scientific collaboration. Recently, PROMICE has been invited by the World Meteorological Organization General Secretariat to join the planning and implementation process of the new Global Cryosphere Watch activity CryoNet.

This year, PROMICE team members have already successfully contributed to several briefing notes requested by the Danish Minister for Climate, Energy and Building on the state and fate of the Greenland ice sheet in a changing climate.

PROMICE will continue to adapt to ensure that we fulfil the aim of delivering the highest quality advice to Danish and international policy-makers on the issue of the Greenland ice sheet contribution to sea level rise now and into the future.

Organisation

The project is lead and coordinated by GEUS. PROMICE is anchored in the GEUS glaciology group which is situated in the Department of Marine Geology and Glaciology, headed by Karen Edelvang who is responsible for the project. Project leader of PROMICE is senior scientist Signe Bech Andersen. The glaciology group presently includes a professor, four senior Scientists, two scientists, two postdocs, one PhD student, one master student and two technicians (one part time). All are involved also in other research projects (most of them mentioned in the above sections) this provides the monitoring effort in PROMICE with valuable additional knowledge and in some cases field instrumentation, enhancing the monitoring effort. GEUS has recently hired research professor Jason Box to further strengthen the research profile and the relations to international projects working with the Greenland ice sheet. ASIAQ and DTU-Space are also partners in the project.

In late 2012 a reference group was established consisting of the most important stakeholders and collaborators:

Following institutes/persons were invited and accepted:
DTU-Space: Rene Forsberg, Louise Sandberg Sørensen, Henriette Skorup
DMI: Jens Hesselbjerg Christensen, Ruth Mottram, Peter Langen
KU/NBI: Dorthe Dahl Jensen, Aslak Grinsted
ASIAQ: Kjeld Hornbæk Svendsen, Dorthe Petersen
GCRC: , Søren Rysgård, Peter Scmidt Mikkelsen

The group is expected to follow the monitoring program and give advice about national and international interests, including coordination with other programs having activities on the Greenland ice sheet.

Monitoring the outlet glaciers of the Greenland Ice Sheet

Andreas P. Ahlstrøm and Jason E. Box

This section of the PROMICE report presents results and progress within the project 'Monitoring the outlet glaciers of the Greenland Ice Sheet' (from here on abbreviated IVEL). IVEL is considered as an add-on to PROMICE with additional financial support from DANCEA under the Danish Energy Agency over the period 2010 – 2012. As such, IVEL was considered as an activity within PROMICE designed to acquire additional data supporting the overall aim of PROMICE, i.e. to determine the mass loss of the Greenland Ice Sheet. Briefly, the purpose of IVEL was (and is, now under PROMICE) to collect near-continuous velocity data from a number of major outlet glaciers of the Greenland Ice Sheet. These data would in turn be used to improve our knowledge and understanding of the seasonal variation in the ice-loss at the glacier front and thus eventually improve not only the estimate of the dynamic mass loss produced in PROMICE, but also projections of future mass loss in related research projects.

The IVEL project is synergistic with a similar activity, also headed by GEUS, running in parallel in the EU-project ice2sea under Framework Programme 7 over the period 2009-2012. This synergy has increased the number of glaciers monitored and the temporal duration of data gathering. The data from the ice2sea project has been published in Ahlstrøm et al. (2013). Several other national and international projects have contributed to provide data and logistics: Additional logistical support was provided by Project no. GCRC6509 of the Greenland Climate Research Centre granted by the Danish Agency for Science, Technology and Innovation. Prof J. E. Box was supported by US National Science Foundation grant AGS-1061864 managed by D. J. Verardo and The Ohio State University's Climate Water Carbon initiative managed by D. E. Alsdorf. While Motorized Yacht Arctic Sunrise provided field logistics for Dr. A. Hubbards GPS deployments in 2009 on Petermann, Humboldt & Rink Glacier and field/logistical support was granted from the Aberystwyth University Research Fund & NERC Grant NE/G005796/1.

Background

Fundamental knowledge gaps confound our ability to predict the mass loss from the Greenland ice sheet, particularly regarding marine terminating outlet glacier dynamics (Vieli & Nick, 2011; Price et al., 2011). Since the dynamic mass loss is believed to constitute roughly half the contribution to sea level rise from the Greenland ice sheet over the last decade (Van den Broeke et al., 2009) and appears to be highly variable with time (Andresen et al., 2011; Bevan et al., 2012; Bjørk et al., 2012), understanding this mechanism is of paramount importance to reduce uncertainty in predicting the impact of future climate change on the Greenland ice sheet and in turn, global sea level.
The increasing focus on the dynamic mass loss from the Greenland ice sheet has been driven by a combination of in situ observations and remote sensing data analysis, docu-

menting a fast and widespread retreat and acceleration of the outlet glaciers of the Greenland ice sheet. Although recent advances in computer simulation of calving outlet glaciers is advancing (Nick et al., 2012; Vieli & Nick, 2011), such studies require observational data to determine the model performance and to identify as-yet un-accounted physical mechanisms of glacier behaviour (Moon et al. 2012).

Estimates of current and recent mass loss from the Greenland ice sheet relies largely on remote sensing analysis, either of the gravitational changes (Rignot et al., 2011), uplift of the surrounding land (Bevis et al., 2012) or elevation change (Pritchard et al. 2009; Sørensen et al., 2011) or by the mass budget method, i.e. by deriving the individual parts of the Greenland ice sheet mass balance separately (Van den Broeke et al., 2009; Rignot et al., 2008). The mass budget method requires an understanding of the interaction of the Greenland ice sheet with the climate system as well as a wealth of observations, which in turn provides an improved capability to model future mass balance changes with more confidence. This is the philosophy behind selecting the mass budget method for PROMICE since the aim is to be able to inform policy-makers in the present on the implications of current policies on the global and regional climate and sea-level of the future.

The increased accuracy of the mass budget method has been facilitated partly by improved regional climate models (Ettema et al., 2010) and partly by the recent advances in producing large-scale velocity maps of the ice sheet surface using radar imagery (Ahlstrøm et al., 2011; Merryman Boncori et al., 2010; Joughin et al., 2010; Rignot & Kanangaratnam, 2006). These recent velocity maps cover almost the entire Greenland ice sheet, but are limited in their temporal coverage. Generally, they yield the mean velocity over the time between two image acquisitions which cannot be too far apart in time (Joughin, 2002). The maximum time between two images depends for example on the velocity-derivation method and on the physical properties of the target, such as surface velocity and rate of change of ice/snow surface properties, but rarely exceeds 3-4 weeks. A series of velocity maps have been produced to observe the pattern of seasonal change (Joughin et al., 2008). Such techniques have also been applied to fast moving glaciers such as Jakobshavn Isbrae (Joughin et al., 2012), but in the limited areas where sufficient satellite data are collected. Furthermore, presently operating satellites limit temporal resolution (>10 days) so satellite remote sensing cannot provide the higher temporal coverage required to resolve the individual acceleration events occurring on the scale of days (van de Wal et al., 2008).

In the IVEL project and its sibling projects, glaciologists from GEUS and our international partners have collected 34 continuous velocity records derived from in situ stand-alone single-frequency Global Positioning System (GPS) receivers placed on a total of 13 major marine-terminating ice sheet outlet glaciers in South, West, East and North Greenland, covering varying parts of the period summer 2009 to winter 2012. Of these, 17 of the velocity records from 7 of the glaciers were recorded on GPS instruments developed, purchased and maintained through IVEL and retrieved through logistics funded directly by IVEL.

Figure 21. *Outlet glaciers in Greenland equipped with GPS instruments during the IVEL and Ice2sea projects 2009-2012. Many of the sites have been equipped with several GPS instruments and some IVEL GPS trackers are currently active. Glacier names are provided in Table 2.*

The IVEL GPS tracker

Placing GPS instruments on outlet glaciers implies taking a significant risk of losing the instruments. The glacier surface is typically highly crevassed and experiences significant melt and severe storms during the deployment period. In addition to this, the GPS moves closer to the front increasing the chance of losing the instrument into a crevasse (see e.g. Fig. 22). Retrieval is only possible by helicopter and inherently depends on the experience of the pilot. Even when the helicopter pilot has managed to land or hover in the vicinity of a GPS, it is not always possible to retrieve it (see Fig. 23). For these reasons, it was decided from the onset that the IVEL GPS instruments needed to live up to a range of requirements. Specifically, they needed to:

1. transmit the data by satellite
2. be environmentally safe in case of instrument loss
3. have the capacity to last for at least two years with no maintenance
4. be extremely rugged to sustain some of the most extreme weather on the planet
5. be reasonably cheap to construct
6. be able to return data sufficiently accurate to calculate seasonal velocity variations

To achieve these specifications we turned to Dr. Alberto Behar of the Robotics Section of NASA Jet Propulsion Laboratory at the California Institute of Technology who developed a tailor-made GPS tracker system including a web interface.

Figure 22. *A GPS tracker fallen into a crevasse during the deployment period on Daugaard-Jensen Glacier (DJG in Fig. 21). Photo: Søren Nielsen © GEUS.*

Figure 23. *Two GPS trackers on Qajuutap Sermia (QAJ in Fig. 21), illustrating the difficult working conditions on glacier tongues. Photo: Martin Veicherts © GEUS.*

The GPS tracker developed is a low power consumption instrument capable of transmitting data via an integrated Iridium satellite modem. It can send a GPS report at a pre-programmed interval ranging from once every four seconds to once every seven days. The interval can be changed remotely while the unit is in the field. The trackers have the following features:

Satellite modem specifications

- Standby Current: < 65μA
- Average Current (Report): 200mA @ 5V
- Input Average Current (Sleep): < 65μA @ 5V
- Operating Temperature: -40°C to +85°C (-40°F to +185°F)
- Operating Humidity: < 75% RH
- Iridium Frequency: 1616 to 1626.5 Mhz

GPS specifications

- GPS Sensitivity of -160 dBm
- Ublox processing engine
- GPS Frequency: 1575.42 MHz (L1 carrier)

Battery specifications

- Saft lithium-thionyl chloride (Li-SOCl2), 13.5Ah per cell, 3.6V
- 15 D Cells per pack, so 10.8V, 67.5Ah
- Operating temperature: -60°C to +60°C

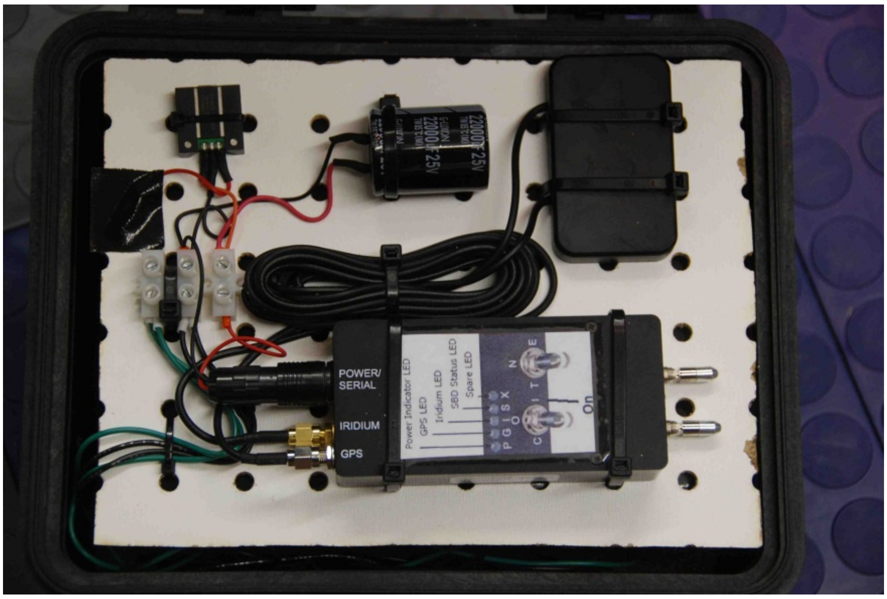

Figure 24. *A look inside the IVEL GPS box with a view to antennas and the controller unit. The battery pack is situated below the board. Photo: Alberto Behar.*

During IVEL operations, the units are turned on for 3 minutes every 12 hours in order to let the GPS system settle, average its position and pick up any new ephemeris data for a more accurate position. The position report from the GPS is then converted into a suitable satellite message format and transmitted via the Iridium satellite network where it is received as a binary attachment of an email that comes in to a central server. Once the position reports are in the server, a front-end website reads them in and places positions in a Google Earth-based layout. The data is also provided via a table and downloadable comma-separated file.

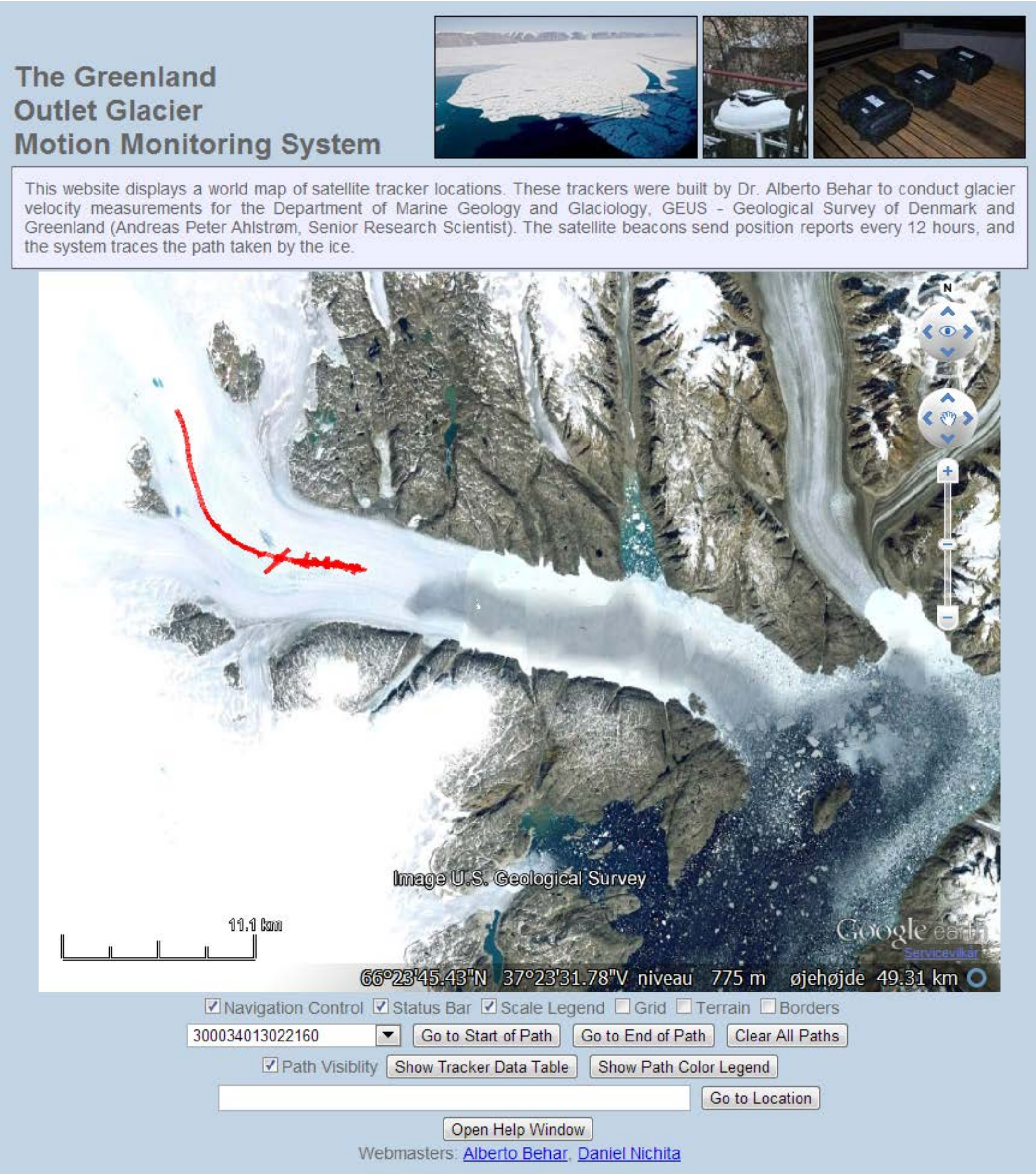

Figure 25. *Screen shot of the website, showing the trace of the GPS tracker deployed on the Helheim Glacier (HEL on Fig. 21). The background is provided by a Google Earth plug-in facilitating easy orientation and navigation in the transmitted data from various GPS trackers.*

Table 2. *Temporal coverage of the GPS data collected. Abbreviations and ID's refer to the map in Fig. 21.*

Glacier	Abbrev.	ID	Start date	End date
Akullersup Sermia	AKS	AKS1-2011	Aug 23, 2011	Aug 27, 2012
Akullersup Sermia	AKS	AKS1-2012	Aug 27, 2012	Apr 9, 2013*
Daugaard-Jensen Glacier	DJG	DJG1-2010	Jul 27, 2010	Aug 27, 2012
Daugaard-Jensen Glacier	DJG	DJG1-2012	Aug 28, 2012	Apr 9, 2013*
Daugaard-Jensen Glacier	DJG	DJG2-2010	Jul 27, 2010	Aug 26, 2012
Daugaard-Jensen Glacier	DJG	DJG3-2010	Jul 27, 2010	Aug 27, 2012
Daugaard-Jensen Glacier	DJG	DJG4-2012	Aug 28, 2012	Apr 5, 2013
Helheim Glacier	HEL	HEL1-2010	Aug 7, 2010	Apr 5, 2013
Kangiata Nunata Sermia	KNS	KNS1-2010	Jul 27, 2010	Aug 22, 201
Daugaard-Jensen Glacier	DJG	DJG5-2012	Aug 28, 2012	Apr 9, 2013

Kangiata Nunata Sermia	KNS	KNS2-2011	Aug 22, 2011	Aug 27, 201
Kangiata Nunata Sermia	KNS	KNS2-2012	Aug 27, 2012	Apr 9, 2013*
Narsap Sermia	NSP	NSP1-2011	Aug 23, 2011	July 15, 201
Qajuutap Sermia	QAJ	QAJ1-2010	July 20, 2010	Mar 28, 201
Qajuutap Sermia	QAJ	QAJ2-2012	Aug 21, 2012	Apr 9, 2013*
Upernavik Glacier	UPE	UPE1-2011	July 29, 2011	Dec 2, 2012
Upernavik Glacier	UPE	UPE2-2011	Aug 7, 2011	Apr 9, 2013*

** Download date, GPS currently transmitting.*

Figure 26. *Deployment of a GPS tracker on Daugaard-Jensen Glacier in 2012. Photo: Søren Nielsen © GEUS.*

GPS data processing

GPS systems comparable to the IVEL GPS Tracker has been deployed in the Ice2sea project (Ahlstrøm et al., in press) and elsewhere (Den Ouden et al., 2010; Dunse et al., 2012) and experience from working with data from these units has benefitted the subsequent data processing. The IVEL GPS is a single-frequency (L1 band) system meaning that it is not possible to perform corrections relying on phase carrier information, double differencing or between-satellite differencing that could otherwise improve the precision. Thus effects from ionospheric delay and inaccuracy in satellite orbital and clock information will deteriorate the precision of the positional information, as no post-processing is possible. The estimated error of a single GPS measurement is on the order of 3-4 metres as derived from similar data from Svalbard (Den Ouden et al., 2010).

As discussed previously, the raw data consists of measurements of time and geographical position transmitted every 12 hours. Due to the high signal-to-noise ratio, it is necessary to perform several averaging steps: first, the positions are averaged and then the velocities derived from these positions are again averaged. This approach yields robust average velocities at the expense of temporal resolution and has been employed in previous studies (Ahlstrøm et al., in press; Den Ouden et al., 2010; Dunse et al., 2012).

Den Ouden et al. (2010) found a combined horizontal accuracy of this system of 1.62 m over the period 2006-2009 in central Spitsbergen. As the ionospheric effect changes over time and position, this result can only be indicative of the accuracy of the measurements presented here. Error analysis of similar GPS instruments in Greenland at 67˚N show a combined horizontal accuracy of 2.1 m in 2010-2011 for hourly measurements of a fixed position, so slightly higher than the values in central Spitsbergen. The Greenland data yield a typical error of 5 m/yr, if 7-day running averages over hourly measurements are considered. The IVEL GPS Tracker system has not been tested against high precision GPS systems in Greenland yet, but a similar magnitude of the error is expected.

As discussed in Den Ouden et al. (2010) and Dunse et al. (2012), the presence of spurious oscillations in the processed time series cannot be excluded due to the noisy nature of the raw data and spectral leakage caused by the averaging procedure, as well as other unknown position or time dependent error sources. Following the conservative estimate of Dunse et al. (2012), we should only consider periodic fluctuations with amplitude over 30 m/yr.

Results

Following the processing procedure above yields time series of averaged velocities presented below. The plots each represent a separate data record of a GPS tracker from deployment to retrieval, implying that plots are not combined or stitched. Some of the records have suffered from transmission problems, suddenly switching to a very high transmission frequency which has been filtered out for the initial results presented here. Each plot has a title containing the data record ID which also shows where in Fig. 21 they are located.

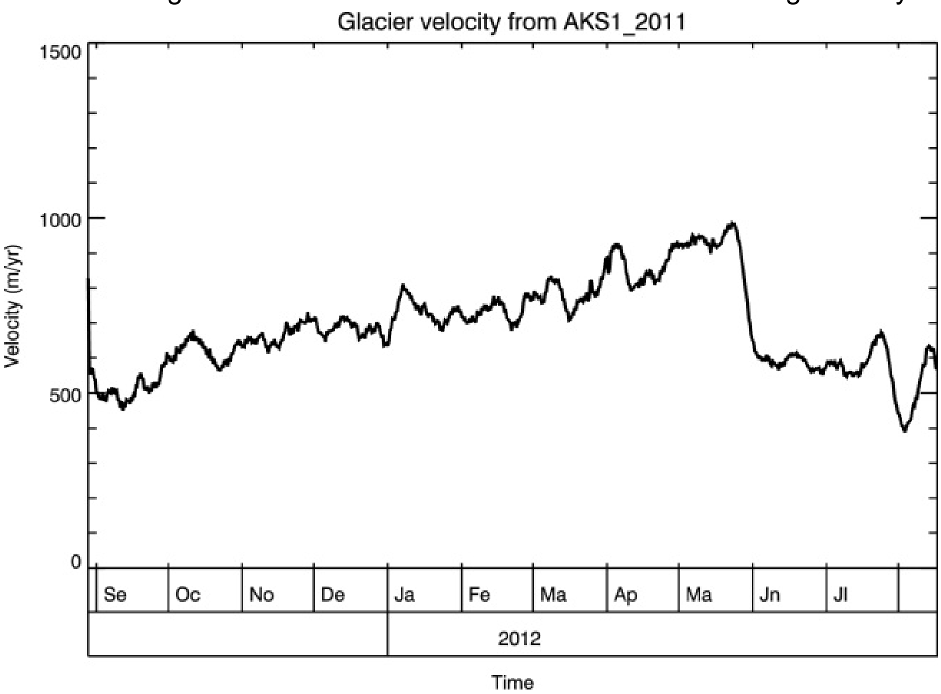

Figure 27. *Velocity record from Akullersup Sermia, Southwest Greenland, in Godthaabsfjorden neighbouring Kangiata Nunata Sermia (KNS). The pattern of a slow speed-up over the winter/spring, followed by a rapid decline in the mid-summer is a feature found on a number of the glaciers measured in Ice2sea and IVEL.*

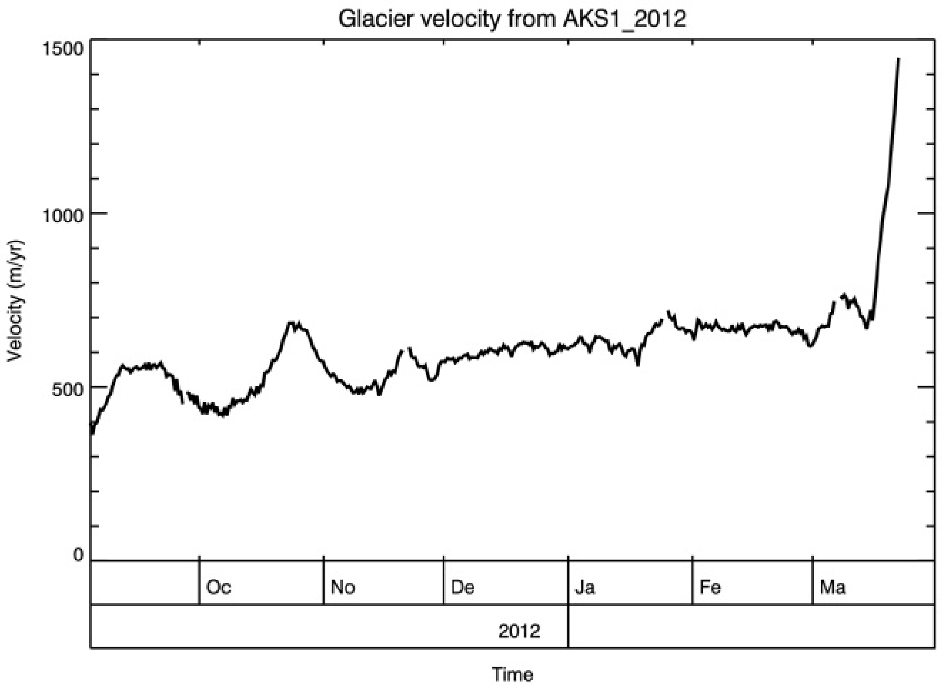

Figure 28. *The velocity record following AKS1_2011 is showing a similar build-up in velocity, but terminates in March 2013, possibly due to overturning of the instrument (crevasse opening or wind are candidates).*

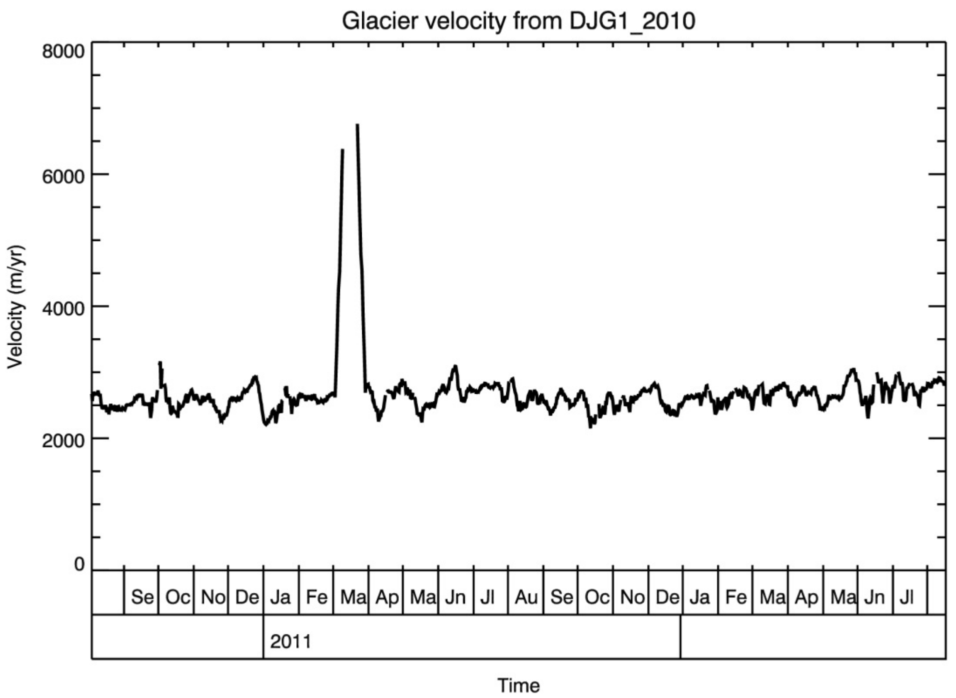

Figure 29. *Velocity record from Daugaard-Jensen Glacier in the northwestern part of Scoresby Sund, central East Greenland. The March 2011 peak is due to a failure not particular to the instrument as it is seen in all the DJG-records as well as the record from Helheim Glacier for the same period. The remaining variability is up to 500 m/yr, corresponding to roughly 20% of the average velocity. No clear annual cycle is visible.*

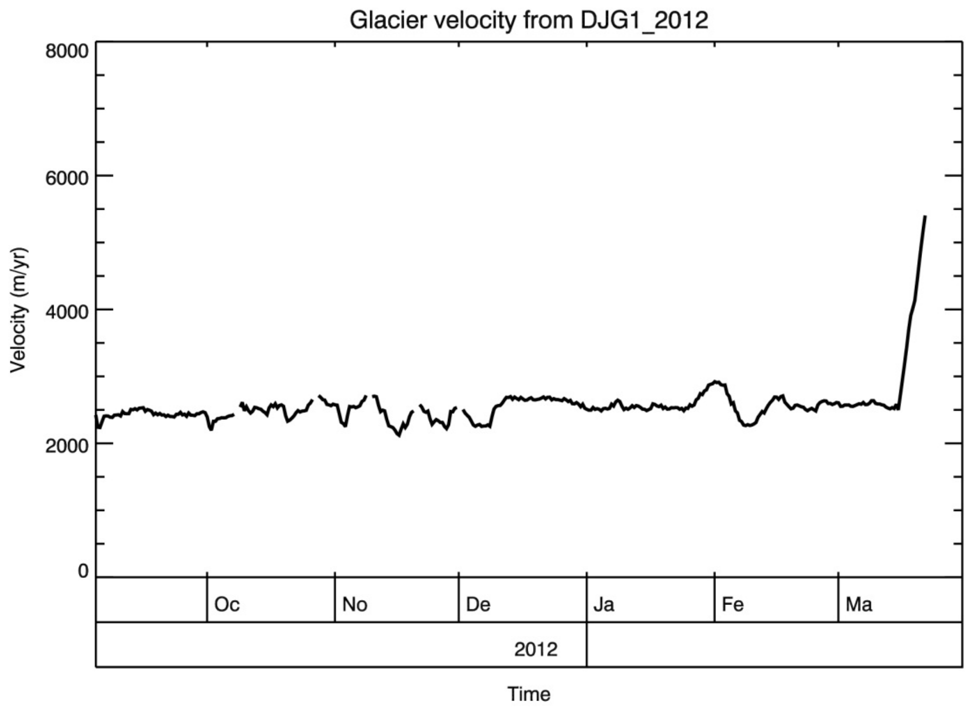

Figure 30. *Extension of the DJG_2010 record. The speed-up at the end is probably not real.*

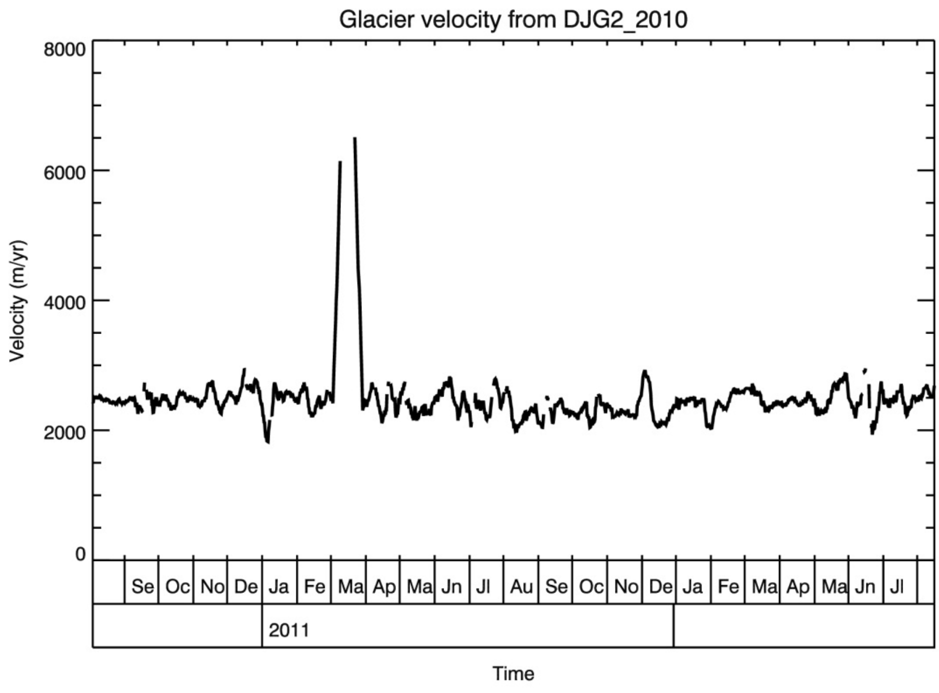

Figure 31. *Velocity record from DJG2_2010, a site higher up-glacier than DJG1, with very little change in the velocity, resembling the DJG1_2010 record.*

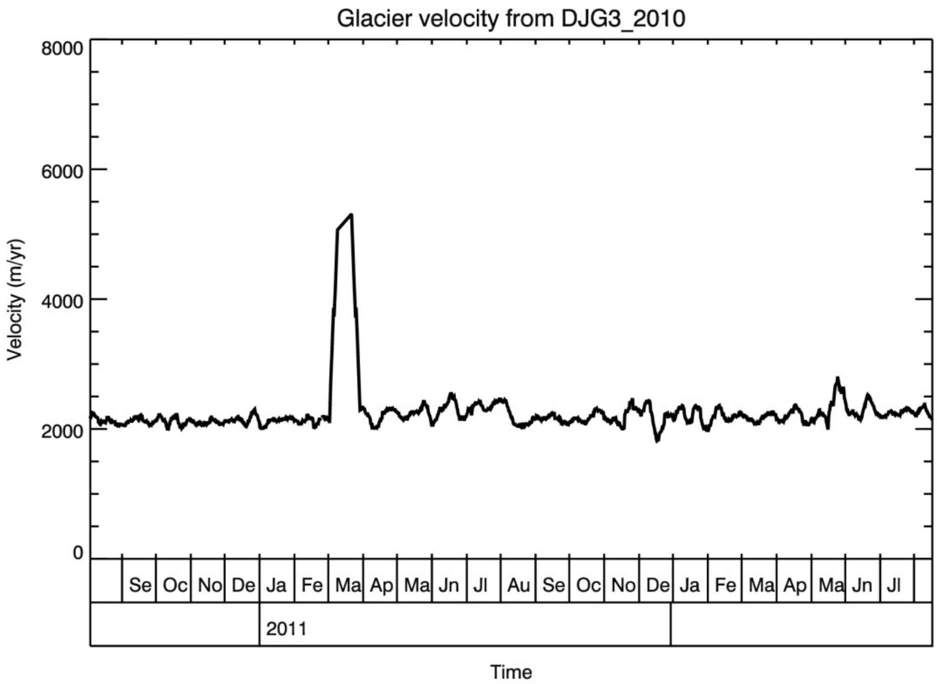

Figure 32. *Velocity record from the uppermost site in the DJG campaign – again very similar to DJG2-2010.*

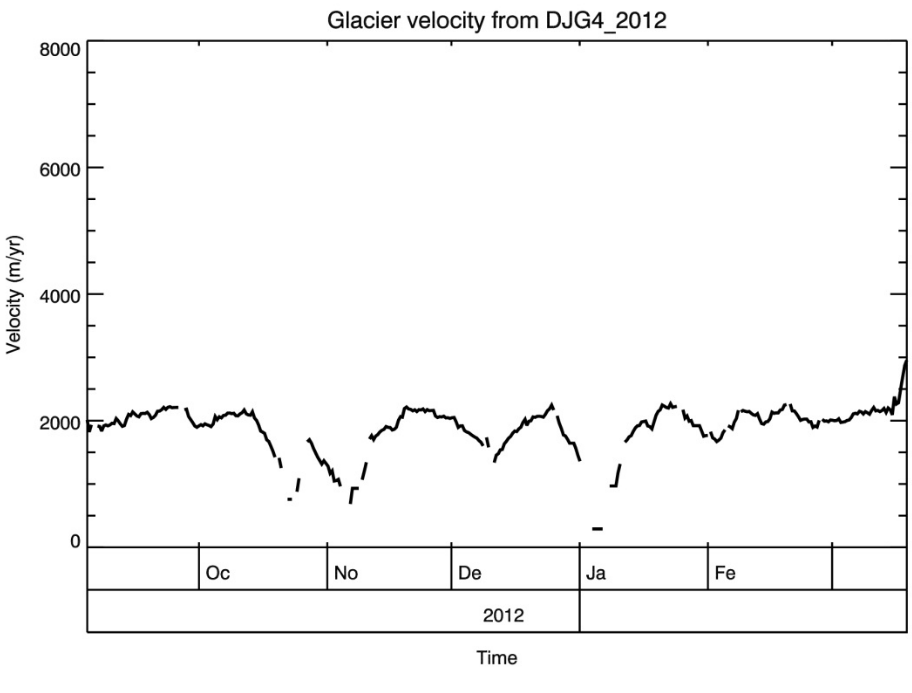

Figure 33. *DJG4-2012 was positioned as a reoccupation of the original deployment site of DJG3_2010 shown in Fig. 32. Transmissions from this tracker needs further processing as it has experienced unwanted periods of high frequency sampling yielding unreliable velocities.*

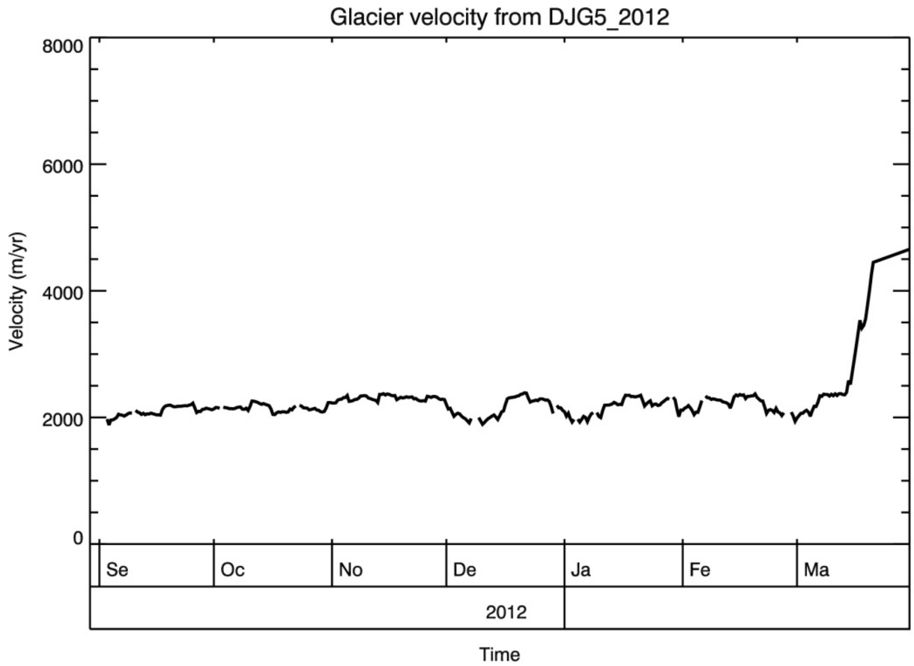

Figure 34. *DJG5-2012 was positioned as a reoccupation of the original deployment site of DJG2_2010 shown in Fig. 31. The increased velocity in March, 2013 is an artifact.*

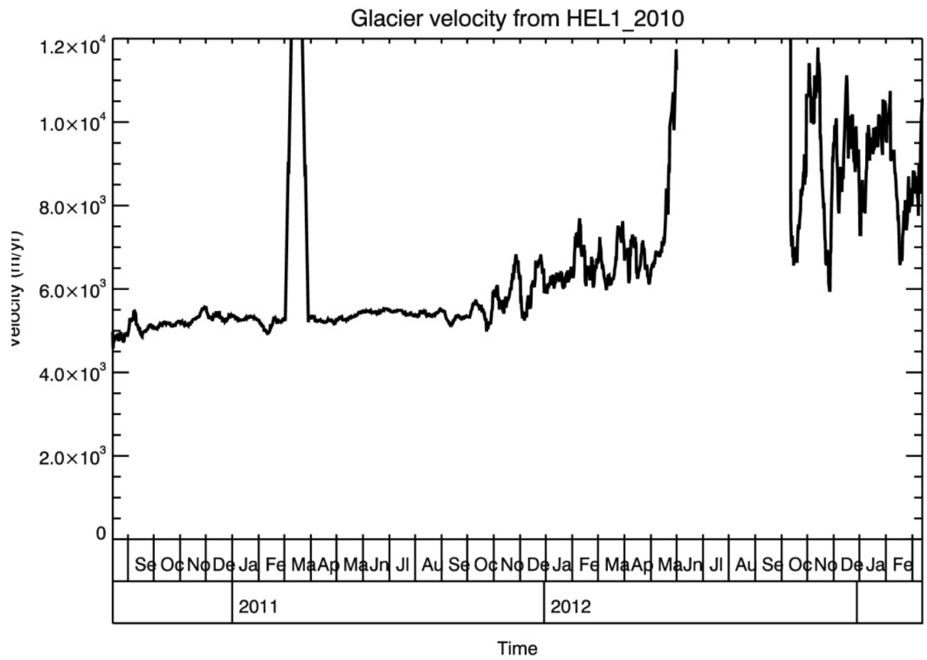

Figure 35. *The tracker on Helheim Glacier exhibits the same artifact in March 2011 as all the DJG-records further north (conf. Fig. 21). In late 2011, the tracker most likely moved into a region of crevasse formation closer to the front and was considered gone by summer 2012, before suddenly reappearing in late 2012 exhibiting strongly fluctuating, yet on average realistic velocities until early 2013 where it was finally lost.*

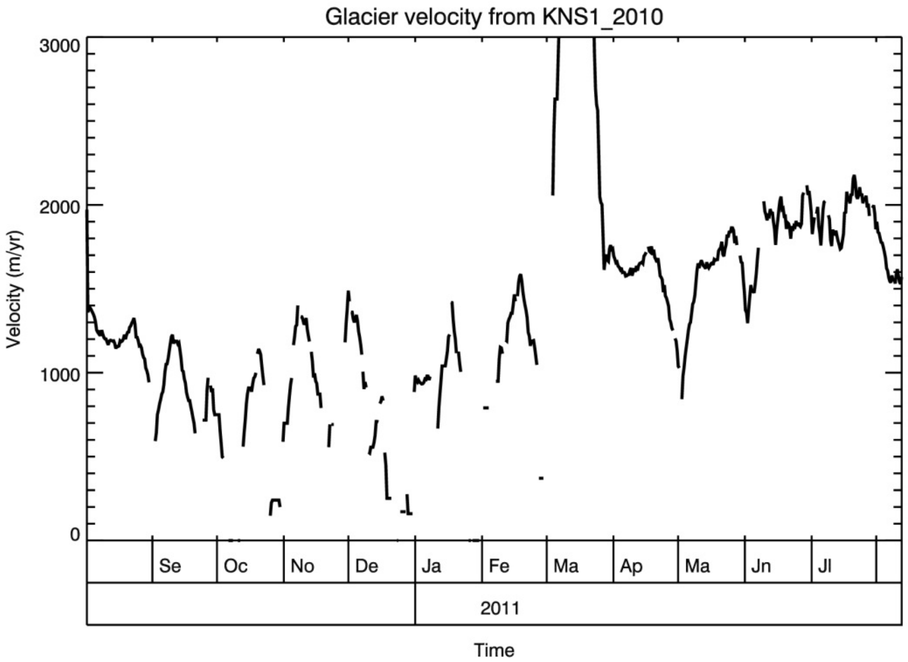

Figure 36. *The tracker on Kangiata Nunata Sermia is the same unit later placed on Daugaard-Jensen glacier as DJG4-2012 in Fig. 33 and suffered from the same high frequency sampling (and transmission) problem. It is likely that further re-processing may yield more reliable velocities.*

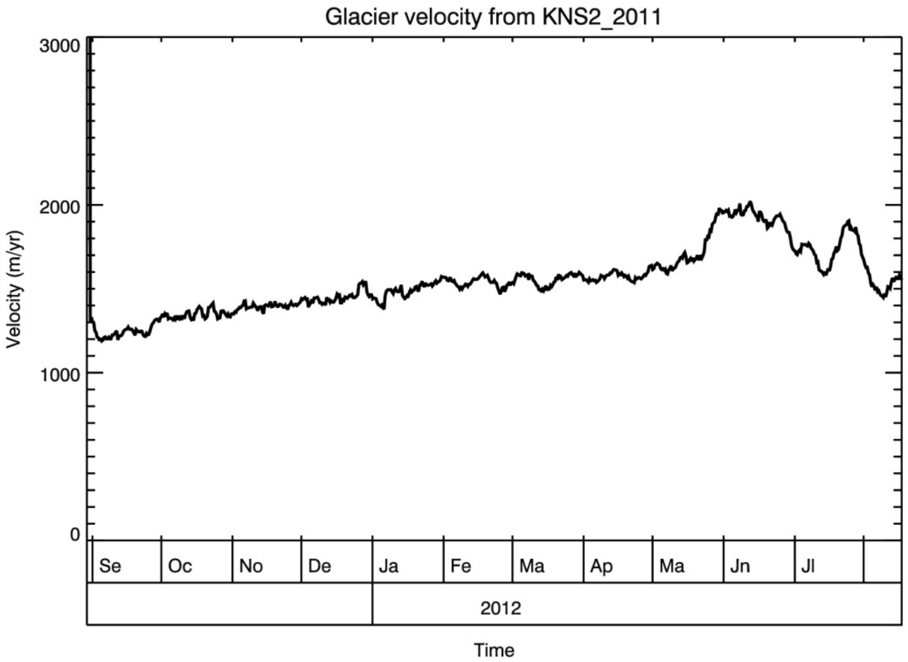

Figure 37*. The tracker deployed on KNS in 2011 shows a characteristic slow acceleration over the entire winter, abruptly accelerating at the onset of the melt season, before rapidly decelerating to a late summer minimum also reported in Ahlstrøm et al. (in press).*

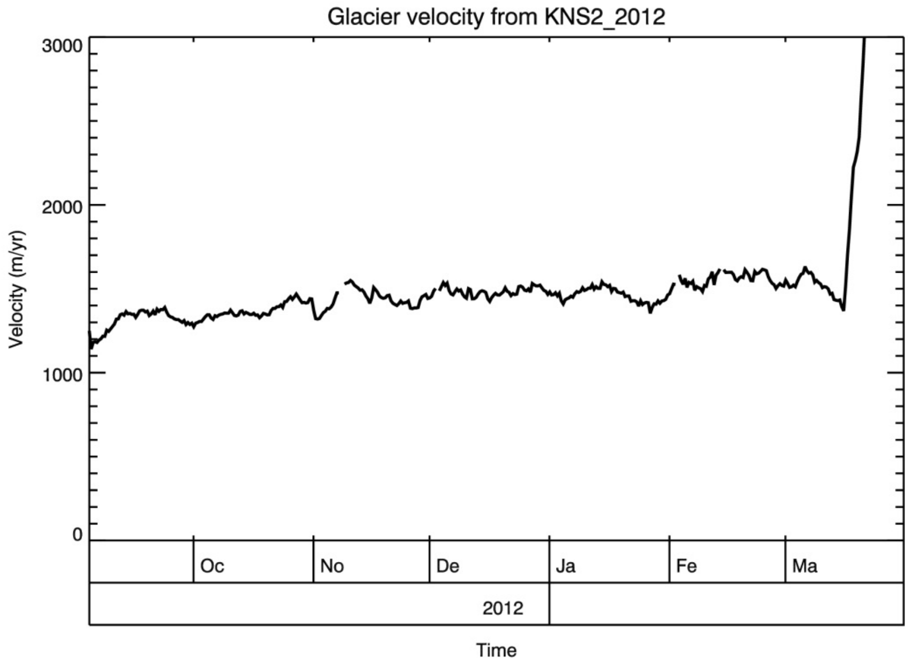

Figure 38. *The KNS2-2012 record is a re-occupation of the deployment site for the KNS2-2011 and follows the same pattern of slow acceleration over the winter. The last, extreme part of the record is an artifact.*

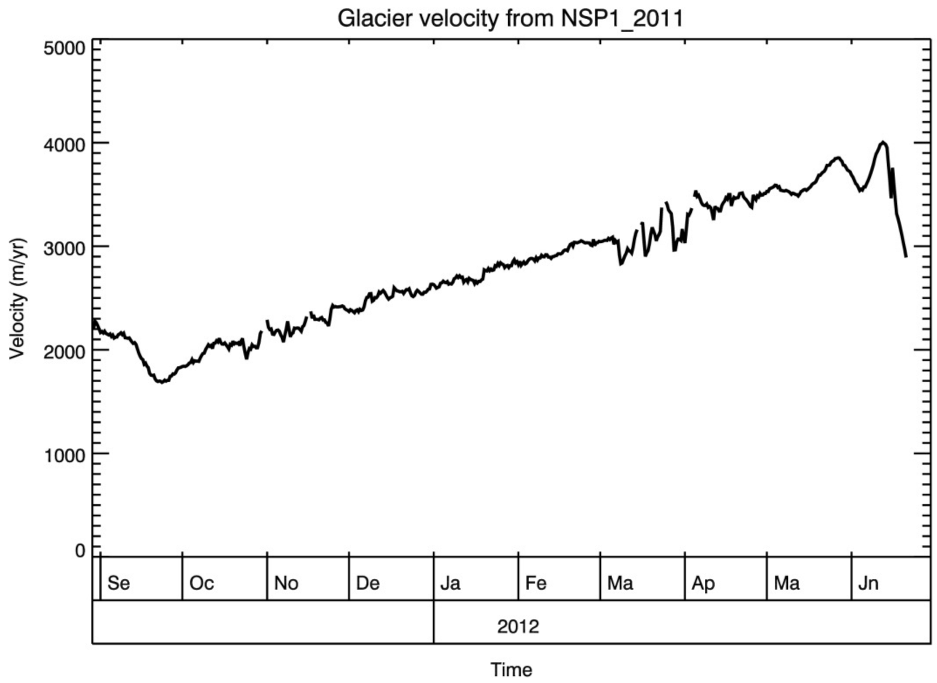

Figure 39. *Velocity record from Narsap Sermia, a large outlet glacier in the Godthaabsfjord. This record is different because the recent emptying of a large glacier-dammed lake and the subsequent break-up of the floating tongue dramatically changed the flow regime of this glacier.*

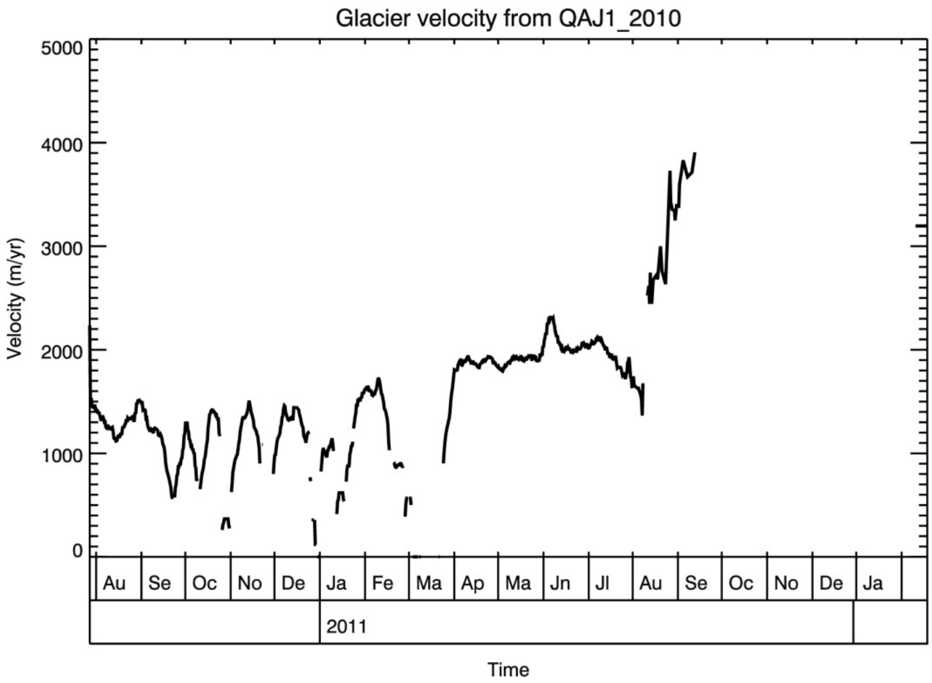

Figure 40. *Velocity record from Qajuutap Sermia (QAJ in Fig. 21). The rise at the end of the record is most likely an artifact from the data processing. This record also exhibits the high frequency sampling problem of KNS1/DJG4.*

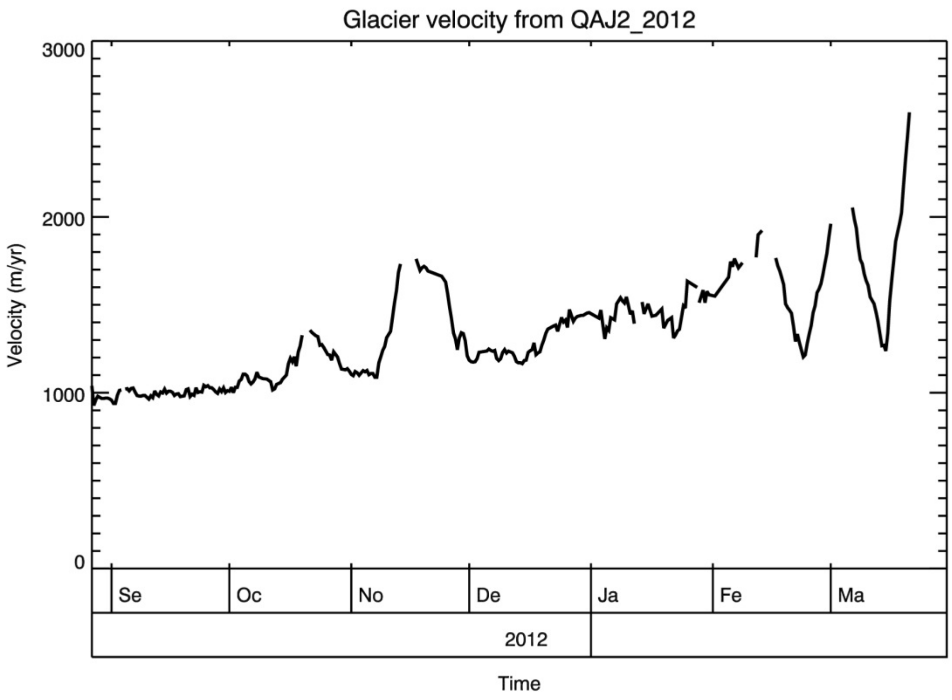

Figure 41. *Velocity record continued from QAJ1_2010, probably documenting the loss of an instrument into a crevasse.*

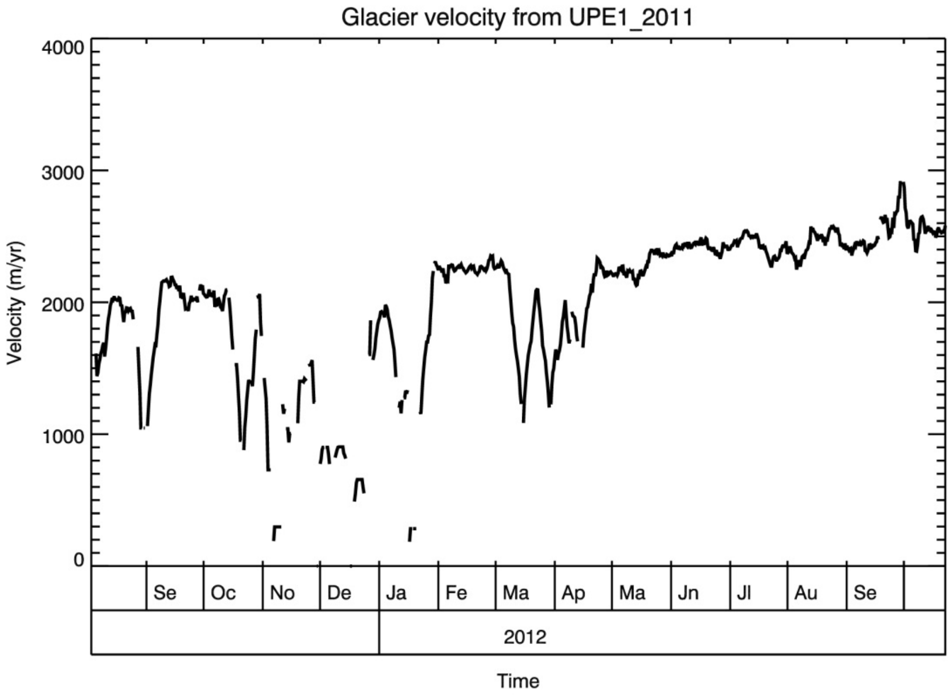

Figure 42. *Velocity record from Upernavik Glacier (no. 3 from southern end). The record shows numerous gaps and some less satisfying errors (sudden slow velocities). Datasets like this might be cleaned when evaluated carefully.*

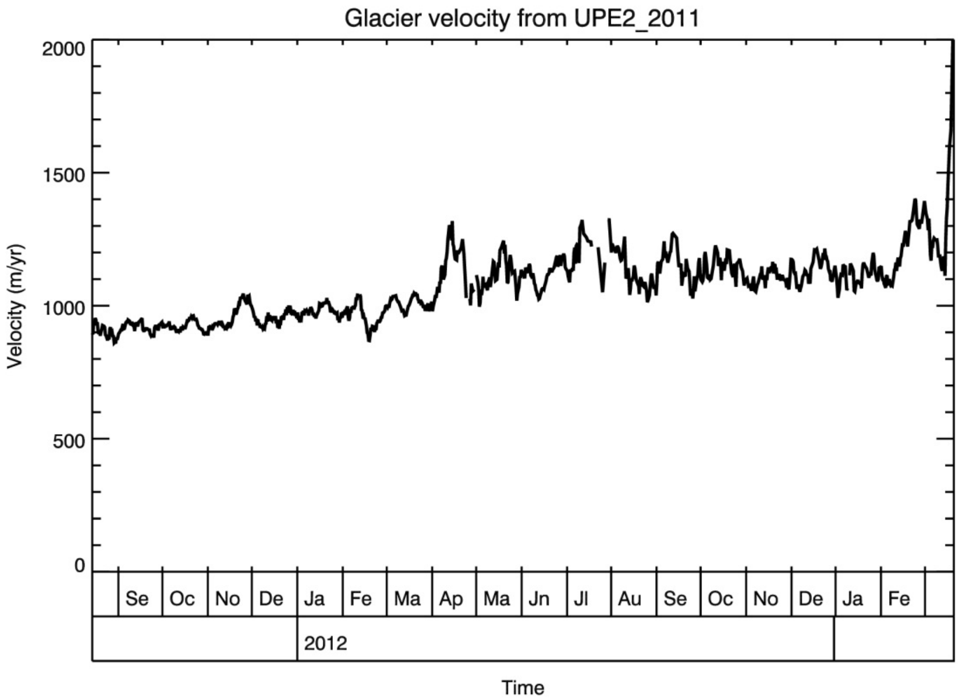

Figure 43. *Velocity record on the southernmost of the four glaciers in the Upernavik Glacier complex. The record shows a slight increase with some extremes in the summer melt period.*

Extreme Ice Survey cameras

The IVEL project was established in 2010 in collaboration with Dr. Jason Box at Byrd Polar Research Center at The Ohio State University. Coincidentally, after a year long transition, Jason is now Professor in Glaciology at GEUS. Through this collaboration, PROMICE has joined the Extreme Ice Survey (EIS) project[1], directed by photographer James Balog. The idea was to combine the GPS-derived velocity at the instruments with a velocity field derived from single-look time lapse photography (Ahn & Box, 2010). Unfortunately, a proposal submitted by our U.S. partners to strengthen their participation in IVEL was not funded and operations had to be adjusted accordingly. Among other things, delay in the transfer of camera systems prevented camera deployment that year at 3 of 4 sites. The Daugaard-Jensen Glacier site was installed

The Helheim installation turned out to have a faulty component and was not fully installed until 2012. So far, a 2684 images have been retrieved from Daugaard-Jensen Glacier, covering from July 2010 to September 2012 with a gap in summer 2011. The DJG EIS cam is currently operating. The Upernavik site has not been visited since deployment in 2011, but is on the field plan to be visited in August 2013. From the EIS camera at Kangiata Nunata Sermia, we have so far retrieved 3779 images and plan to acquire more in the 2013 field work.

Figure 44. *Photo from the EIS camera at Daugaard-Jensen Glacier. Note that the camera has been positioned to capture the main trunk of the glacier (rather than e.g. the spectacular calving front) with rock outcrops at both the top and bottom of the glaciers and a high viewing angle, all to maximise its use for calculating the velocity field directly from the image.*

[1] http://extremeicesurvey.org/team-eis/

Figure 45. *A look inside the EIS camera box. Photo Dirk van As © GEUS.*

Figure 46. *Maintenance and data retrieval from EIS camera at Daugaard-Jensen Glacier (DJG in Fig. 21). Photo: Søren Nielsen © GEUS.*

Figure 47. *Maintenance of EIS camera at Kangiata Nunata Sermia (KNS in Fig. XXMAP). Photo: Horst Machguth © GEUS.*

The future of the Extreme Ice Survey (EIS) in Greenland

Despite the fact that no scientific publications have been submitted using EIS data since Ahn and Box (2010) and that the GEUS EIS installations so far have had limited success in deployment and maintenance, the following points build the case to maintain EIS equipment in 2013 and beyond.
J. Box is now (since 1 Jan 2013) at GEUS in the never before filled Professor of Glaciology. The Chasing Ice debut in Copenhagen 19 May, 2013 was a powerful reminder to Prof. Box to follow through with his commitment to PROMICE and EIS.

EIS director James Balog's field assistant Matt Kennedy is delivering to Copenhagen 16 June 2013 four of the following camera components valued at 25,877 Dkr. to support continued image acquisition.

- Nikon D3200[2]. The D3200 has twice the image resolution than the D200 24.2 Mpixel, 6,016 × 4,000 image resolution compared with the existing D200 camera bodies that have 3,872 × 2,592 (10.2 Mpixel)[3]. Value $2200
- New Timer + Cables. Value $1000
- SanDisk SDXC 64 GB SD Card. Value $1000
- Hardware to replace MBD200 camera base. Value $400

55 students attended the 6 June, 2013, "Frokostmøde med Professor Jason Box"[4] arranged students J.A. Antoft and J.A. Kristensen of Geografisk Institut, Københavns Universitet. At this meeting, Prof. Box made a passionate plea to develop a student team to help analyze EIS Greenland photos. Prof. Box posted the vision on his web site[5]. The strategy with student engagement is to build a "team" to help process the many images EIS has produced in Greenland. Prof. Box outlined a theory with which to connect what we learn about glacier dynamics with surface climate. As of the afternoon of the next day, 4 students have contacted Prof. Box. He will coordinate a meeting the following week.
GEUS Photogrammetry Lab Manager Max Nykjaer Strunck attended the Frokostmøde and announced to the students that he "would love" to see students in his lab using the very expensive software licenses they had to develop 3D time lapse. The 3D time lapse project is an attractive gateway to other data products form the EIS photos such as velocity determination through time.

Discussion and outlook

The continuous GPS-derived velocity data sets acquired from a significant number of marine-terminating outlet glaciers in Greenland represent a number of possibilities. As already documented in Ahlstrøm et al. (2013), the velocity data is ideal for validation of the satellite-derived velocity maps. These are in turn invaluable for the calculation of the ice discharge

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[2] http://en.wikipedia.org/wiki/Nikon_D3200
[3] http://en.wikipedia.org/wiki/Nikon_D200
[4] https://www.facebook.com/events/372302862875169/
[5] https://sites.google.com/site/jboxgreenland/eis-comes-to-geografisk-institut/eiscomestogeografiskinstitutkoebenhavnsuniversitet

to the ocean. The GPS velocity data may subsequently be used to work out the error from assuming constant velocities over the season, when calculating ice loss from discharge. A SVALI PhD-study on modelling outlet glacier mass loss utilizing the velocity data retrieved here has just been advertised at GEUS in order to improve on the dynamic mass loss calculations performed in PROMICE (Andersen et al., presentation 2013).
The GPS records also support work done in related projects, such as the ESA CCI Ice Sheets where the Danish contribution is greatly enhanced through the strong validation potential represented by these instruments.

Work is still to be commenced on the EIS images already in-house. However, four cameras are now in position and hopefully collecting images of Daugaard-Jensen Glacier, Helheim Glacier, Kangiata Nunata Sermia and Upernavik Glacier. Currently, a team of students is being put together for the processing of the first seasons of EIS photos, to retrieve distributed near-field velocity maps. With the main collaborator from the U.S., Dr. Jason Box, now filling the position as Professor in Glaciology at GEUS, there is an improved platform to take this work further.

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List of acronyms

ASIAQ	Greenland Survey
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AWS	Automatic weather station
DMI	Danish Meteorological Institute
DTU-S	Datnish Technical University – Space
ESA	European Spece Agency
ESA CCI	European Space Agency Climate Change Initiative
GCRC	Greenland Climate Research Center
GLIMS	Global Land Ice Measurements from Space
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GrIS	Greenland ice sheet
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NSIDC	National Snow and Ice Data Centre
SAR	Synthetic Aperture Radar
SEB	Surface energy budget
SMB	Surface mass balance
SUSIE	Scripts and Utilities for SAR Ice-motion Estimation
WGMS	World Glacier Monitoring Service
WMO	World Meteorological Organization

Appendix A: PROMICE publication list

This appendix details the scientific results produced by PROMICE team members with relation to their activities in PROMICE. This means that commercial activities apart from that dealing with the climate change-hydropower relationship have not been listed. The appendix is divided in three, showing 55 peer-reviewed scientific publications, 98 scientific conference contributions and 9 reports.

Scientific publications

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Programme for Monitoring of the Greenland Ice Sheet

No 2 • 2012

TRACKING THE LOST ICE

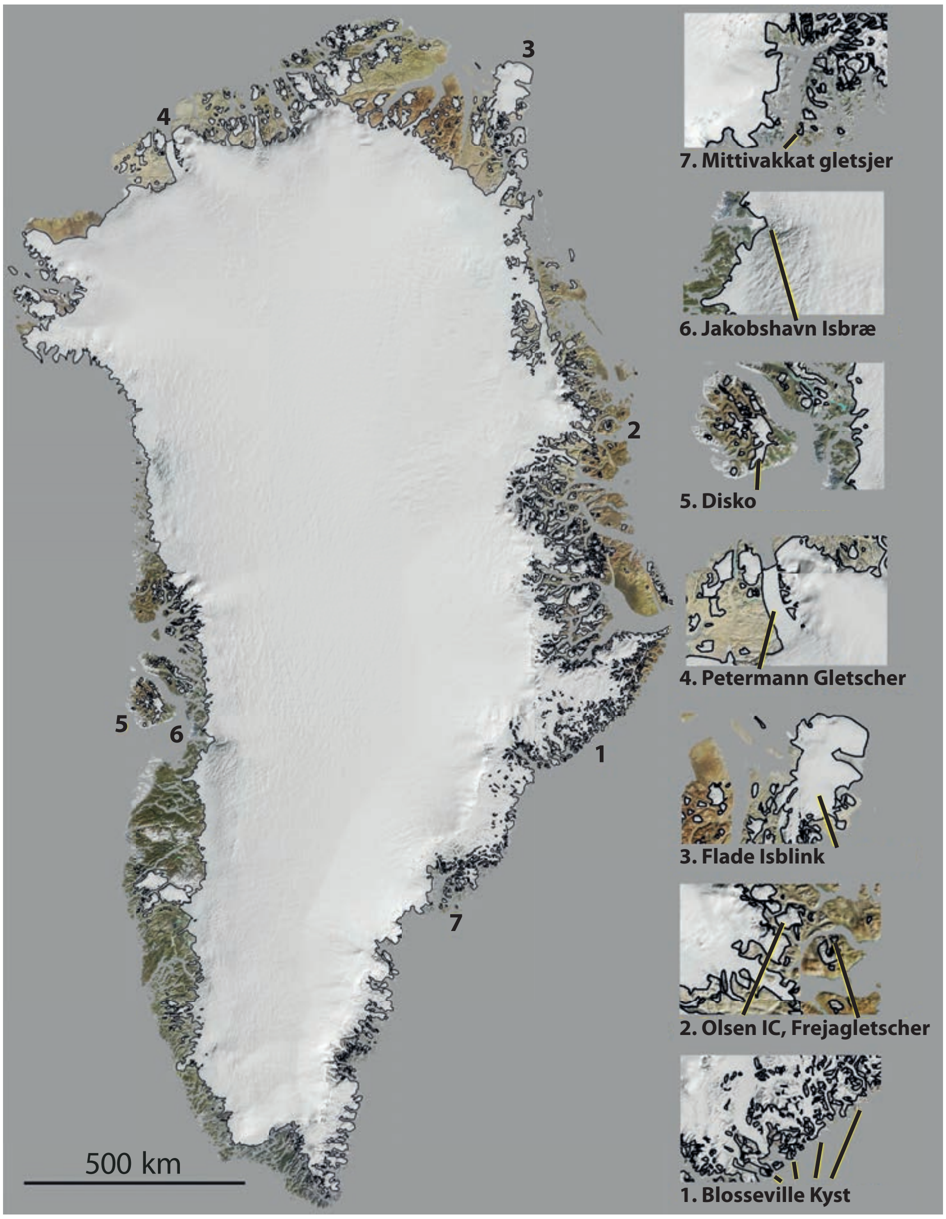
'In just 12 years, the Greenland ice sheet has shrunk with a seventh of its total area, corresponding to 300,000 km²'. This is what a press release from the publishers of the Times Comprehensive Atlas of the World, HarperCollins, stated on 15 September 2011.

The news was released just before the publication of the new 13th edition of the Times Atlas. The press release described the drastic changes that the cartographers had observed since the last revision of the map of Greenland in 1999. Picked up first by the Guardian in England, the news travelled around the world in no time. It made the headlines as the most striking proof of Climate Change, so far. From Europe to the USA and Asia, people woke up to this alarming news, which immediately was sent into orbit in the blogosphere and the social media.

But the real news was that the freshly printed atlas included a grave mistake, made by the otherwise well-reputed publishers of the world's perhaps most well-respected Atlas.

A few hours after the misleading news had begun its world tour, the scientific community was on the alert. The 'news' reached the PROMICE team at the Geological Survey of Denmark and Greenland (GEUS) via Cryolist.org, a global list server, used by glaciologists to share information. At GEUS, the scientists' immediate reaction was to shake their heads in disbelief. As responsible for Denmark's and Greenland's official monitoring programme, the team had for a long time worked on an accurate estimate of the changes in the mass balance of the Greenland ice sheet, so HarperCollins' statements were so far-fetched that, at first, it was assumed that they would be quickly dismissed as an obvious mistake. Any schoolgirl or boy could access Google Earth and see for her- or himself that the alleged loss of ice was set way too high.

But there were no alert schoolboys or girls that day, so instead of being dismissed, the news grew by the hour, potentially harming the communication of the actual evidences of Climate Change.



The new ice-margin data from PROMICE are shown as black lines, which have been placed over a mosaic compiled from cloud-free satellite images from 2009¬ to 2011 (see the reference on the back of this newsletter). The insets are enlargements of some of the areas, shown on the big map, where the glaciologists work at the moment.

Through Cryolist.org, glaciologists now started to work methodically to organise a coordinated reply. The glaciologists reacted fast and unanimously, taught by experience from the devastating Himalaya-gate story, in which a simple mix-up of digits in a year had made it unnoticed into the authoritative IPCC's climate report, playing havoc with the communication of climate research. An official letter from Scott Polar Research Institute contradicting the statements was published in the Guardian. Likewise, glaciologists all over the world approached the major media, such as CNN, New York Times and BBC. The quick response paid off: before the end of the second day, the news had changed from being an erroneous reporting that the Greenland ice sheet had lost 15% of its ice mass into being the scientists' contradiction of the original statement from no other than the Times Comprehensive Atlas of the World.

Five days later, HarperCollins openly backtracked their dramatic statement, and two days after that they went all the way to acknowledge their mistake, promising to correct the atlas in cooperation with relevant scientists. Together with an international team of glaciologists, the PROMICE team had contacted HarperCollins offering to assist in the correction, and sent their newest map data, seen on the front of this newsletter. This process resulted in the publication in January 2012 of a very detailed supplementary map of Greenland, which is now attached to all editions of the atlas, with an in-depth explanation of the mistake and a note on how the ice-margin changes are detected from satellite photos.

On the new map from the Times Atlas, it now says: "Ice extent data: © Geological Survey of Denmark and Greenland (GEUS). Ice margins produced by PROMICE – Programme for Monitoring of the Greenland Ice Sheet, updated to 2011 based on MODIS imagery from NASA". In the text box on the map sheet, it says: "This map uses data supplied by the Geological Survey of Denmark and Greenland, who track the changes in the ice extent using the latest satellite imagery."

The complete high-resolution dataset from PROMICE of the Greenland ice margin will soon be published. And what emerged from the scientists' input and the publishers' corrections can be seen in the links in the box below.

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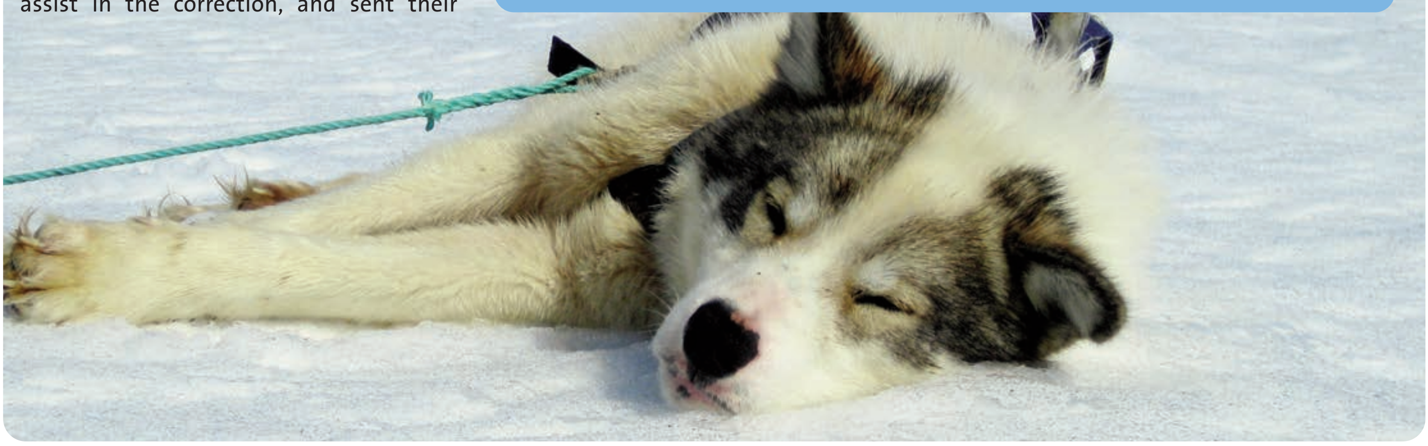

PROMICE

PROMICE is financed by the Ministry of Climate, Energy and Building through the climate support programme DANCEA (Danish Cooperation for Environment in the Arctic), which is managed by the Danish Energy Agency.

- The purpose of PROMICE is to monitor the mass loss of the Greenland ice sheet, both the melting on the surface and the volume of icebergs calved.
- PROMICE is headed by GEUS in cooperation with DTU Space and Asiaq. Furthermore the programme collaborates with the Danish Meteorological Institute and foreign universities and authorities.
- Read more about PROMICE on *www.promice.dk*, where you can find photos and videos, get direct access to measuring data from the ice sheet and the PROMICE outreach material. On the website you can also subscribe to our newsletter.

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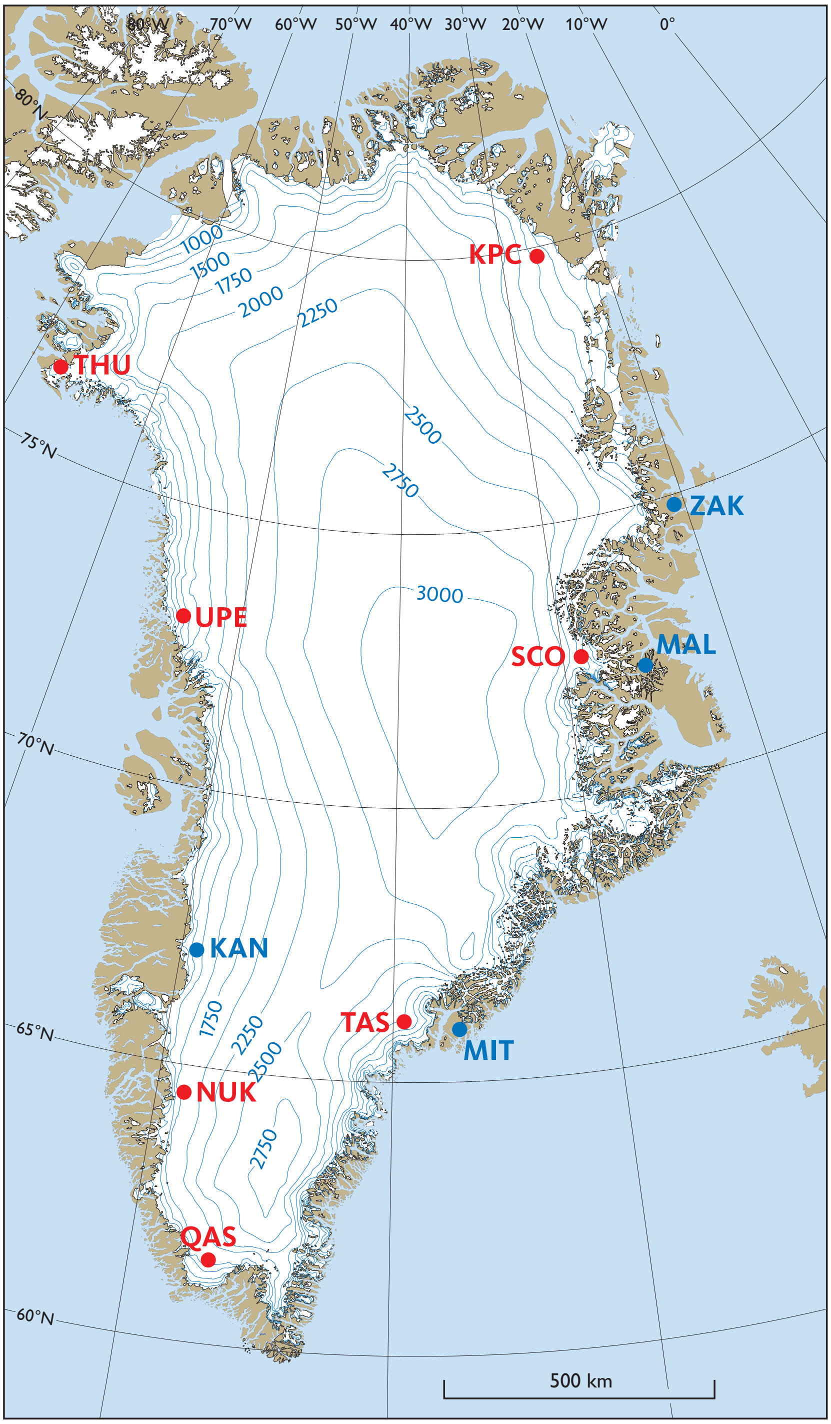
Programme for Monitoring of the Greenland Ice Sheet

No 3 • 2012

SECOND-HIGHEST ICE MELTING

In the summer of 2012, an unusually strong heat wave rolled over most of Greenland, causing extreme temperatures and melting conditions. Ice-core records show that events like these are rare, occurring only once every 150 years on average, with the last event from 1889 being the only of its kind for a period of seven centuries.

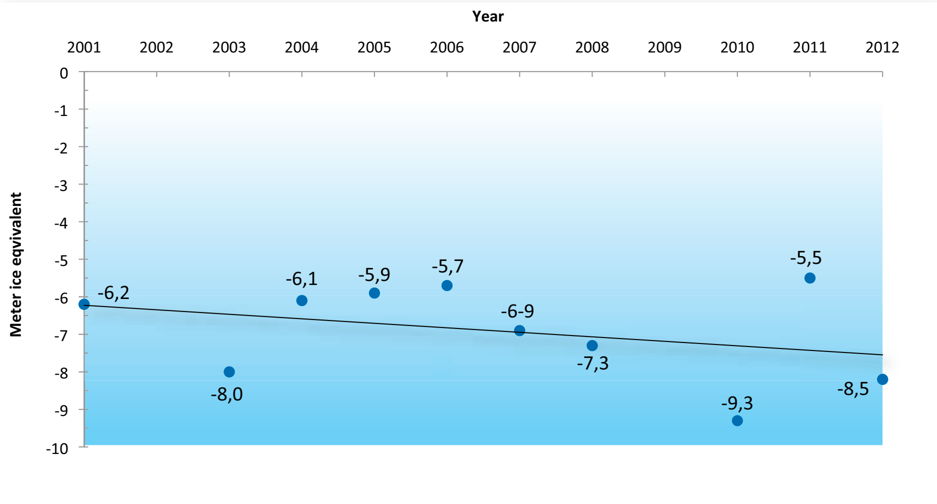
During the summer of 2012 the PROMICE automatic weather station (AWS) network (see the map) measured extremely high temperatures in most areas, and on 12 July 2012, satellite observations from NASA even revealed signs of melting across virtually the entire surface (over 98%) of the Greenland ice sheet. This event coincided with the anomalous heat present over most of Greenland, but especially the south and south-western part. The remote sensing shows that the event of July 2012 is unique for the satellite era (1979 to date) and it lasted for a few days. The event was also recorded by the PROMICE AWS network, which gives insight in the exact climatic conditions leading to the extreme melt extent. On 11 July, the lower QAS station measured an air temperature of 12.1°C while the lower NUK station reached an unprecedented 17.1°C – in a place where temperatures above 5°C are rare. Only a few weeks later on 27 July, these temperature observations were matched (13.1°C and 17.0°C, respectively). Even at the



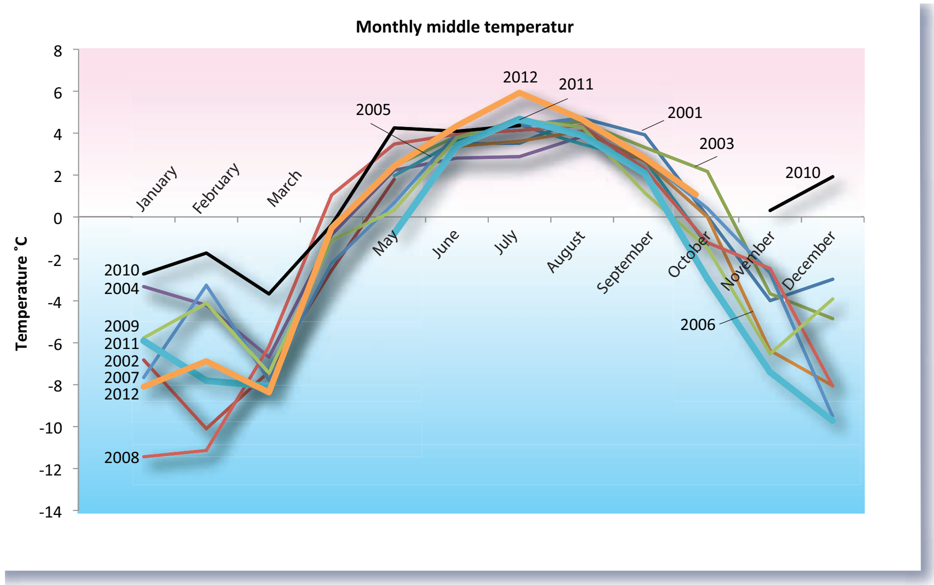
The eight areas on the Greenland ice sheet where the PROMICE-operated weather stations are located. Two or three stations are placed in each area at different levels above the sea. In QAS in South Greenland there are three stations. The QAS_L station, mentioned in the text, is placed on the ice at a height of 310 m.

highest point of the ice sheet, at the Summit research station, snow started melting as temperatures crept above the freezing point on 11 and 27 July. Although 2012 saw the highest air temperatures in the history of PROMICE, in most places more melt was recorded in the warm year 2010 (especially in South and South-West Greenland) as seen in the figure to the top right. To date, more than 60 annual melt estimates have been derived from the 19 AWS of the PROMICE network situated on the ice sheet illustrated on the PROMICE webpage.

Several extreme melt years have already been observed, of which particularly the years 2010 and 2012 stand out. Analysis of the AWS data from the PROMICE network shows that this was due to unusually little snow in the winter/spring of 2010 and a subsequent long melt season, whereas the winter/spring of 2012 was very cold (e.g. -31.6°C at the lower NUK station on 8 March) with a normal amount of winter snow to delay melting of the underlying ice in spring. PROMICE observations such as temperature thus not only quantify melt from the satellite-derived indicators, but can also be used to establish the underlying causal relationship. The figure to the bottom right illustrates how 2012 had a very warm summer and a cold spring, while the melt-record year 2010 was very warm in the winter, spring and autumn but with a normal mean temperature during the summer months. The PROMICE melt measurements and climate data offer a unique insight into the climate–ice-sheet interaction on the full spatial scale, see for yourself at *www.promice.dk*.



The ice melting in metres per year from 2001 to 2012 at station QAS_L placed at a height of 310 m on the ice sheet in South Greenland.



More ordinary meteorological parameters are also measured by the weather stations, such as the mean monthly air temperature. 2012 had a very warm summer and a cold spring, while the melt-record year 2010 was very warm in the winter, spring and autumn but with a normal mean temperature during the summer months.

Follow the measurements transmitted from the Greenland ice sheet on the PROMICE database website:

http://jupiter.geus.dk/promiceWWW/home.seam

PROMICE

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