SVALI

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Top-level Research Initiative

Interim report of current rates of changes of land ice in the Arctic and North-Atlantic region

Stability and Variations of Arctic Land Ice

2012

What is SVALI

SVALI is a Nordic Centre of Excellence bringing together researchers from 17 Nordic institutes. It has been formed to study basic glaciological processes using remote sensing, airborne and in-situ measurements and carry out advanced Earth Systems Modelling with focus on land ice in the Arctic and North Atlantic area. The NCoE SVALI constitutes a platform for joint process studies, analyses, sharing of methods, researcher training, outreach activities and for reporting of scientific results regarding the impact of climate change on terrestrial ice.

SVALI is a part of the Top-level Research Initiative, which is a major Nordic collaborative venture for studies of climate, energy and the environment. The SVALI NCoE is together with NCoE's DEFROST and CRAICC within the TRI sub-programme "Interaction between Climate Change and the Cryosphere" (ICCC), which aims to improve our understanding of stability, variations and dynamics of the cryosphere.

Funding for SVALI

Funding for SVALI is provided by the Nordic Top Level Research Initiative which was initiated by the Nordic prime ministers in 2008 and is supported by Nordic institutions in particular those financing research and innovation. SVALI comprises participants from 17 Nordic institutions and is headed by the University of Oslo.

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Introduction

Louise Sandberg Sørensen, Signe Bech Andersen, Jon Ove Hagen

This is the first Interim report of current rates of changes of land ice in the Arctic and North-Atlantic region from the Nordic Centre of Excellence 'Stability and Variations of Arctic Land Ice' (SVALI). SVALI is one of three Nordic Centres of Excellence within the Nordic Top Research Initiative sub-programme 'Interaction between Climate Change and the Cryosphere'. The report (Deliverable D.1.1-7 in the project) is written by the partners in Theme 1 "Observing the present – baseline and changes".

The report is a step towards answering one of the key questions to be addressed within SVALI:

How fast is land-ice volume in the Arctic and North-Atlantic area changing?

The recent warming of the Earth has led to rapid changes in the cryosphere with increased flux of meltwater and icebergs from glaciers which have contributed significantly to global sea-level rise. The Arctic and North-Atlantic region contains a substantial part of the world's terrestrial ice masses including the Greenland Ice Sheet (GrIS) as well as Glaciers and Ice Caps (GICs) and a significant fraction of global glacial runoff originates in these areas. Thus, the answer to the above question has important societal implications with regard to e.g. coastal changes, natural resources, hydropower and water management.

This report includes a short overview of the current state of the land ice in the Arctic and North-Atlantic region based on published literature together with an overview of existing monitoring activities. The main focus of this first interim report is on airborne LiDAR measurements of ice-covered areas in the region, and on surface-elevation changes derived from these measurements. Repeated LiDAR surveying of glaciers is on-going in several Nordic areas, and data obtained in recent years have not all been interpreted so far in terms of ice-volume changes. The picture of ice-volume changes given by LiDAR measurements is therefore being refined every year. This report describes work in progress and more detailed results will soon be available.

The reason for the special focus on LiDAR mapping is the long tradition for such measurements within the Nordic national research institutes, and a need for a combined overview and assessment based on these data. It is important to combine all available data to obtain reliable information about the current changes of land ice masses.

A strong basis of observational data is crucial for improving the understanding of the physical processes driving these changes, and for improving models used to predict the state of the cryosphere in the future.

Current state of the land ice in the Arctic and North-Atlantic region

Tómas Jóhannesson and Signe Bech Andersen

There are on-going efforts to monitor changes in land ice by all Nordic countries. In combination with international efforts and remote sensing, uncertainties about the magnitude of the changes in the North-Atlantic region have been dramatically reduced in recent years, particularly for Greenland. Quantitative estimates of the recent net rate of ice loss are shown in Figure 1 and Table 1.

By far the largest contribution, equivalent to ~20% of the current global rate of sea-level rise, comes from the Greenland Ice Sheet, including outlet glaciers and detached ice caps in the coastal areas, which are estimated to account for at least 0.08 mm/yr sea-level rise. Although small in comparison with Greenland, the contributions from glaciers in Iceland, Svalbard and Scandinavia are important, not only due to the immediate societal impacts, but also because of the potential for rapid changes. For the Earth as a whole, the current contribution of glaciers and ice caps to rising sea level, including the coastal glaciers surrounding the polar ice sheets, is larger than the contribution of either the Greenland or the Antarctica Ice Sheet (IPCC 2007; Meier et al., 2007; Church et al., 2011).

	Loss of ice (Gt/yr)	Sea level rise (mm/yr)	Period	Reference
Greenland	234 ± 20	0.65	2003–2011	Barletta et al., 2012
Scandinavia	~2	0.006	2002–2010	Estimate based on Kjøllmoen et al., 2011
Iceland	9.5 ± 1.5	0.03	1995–2010	Björnsson et al., 2012
Svalbard	4.3 ± 1.4	0.012	2003–2008	Moholdt et al., 2010

Table 1. Observations of the rate of net loss of ice and the corresponding contribution to global sea-level rise.

For the Nordic Region, direct in-situ observations of the rate of ice loss from mass-balance and ice- surface measurements are more extensive than for many other areas on Earth. Such measurements are valuable for calibrating and validating remote-sensing observations that are important for estimating ice loss in other areas on Earth with less exten-

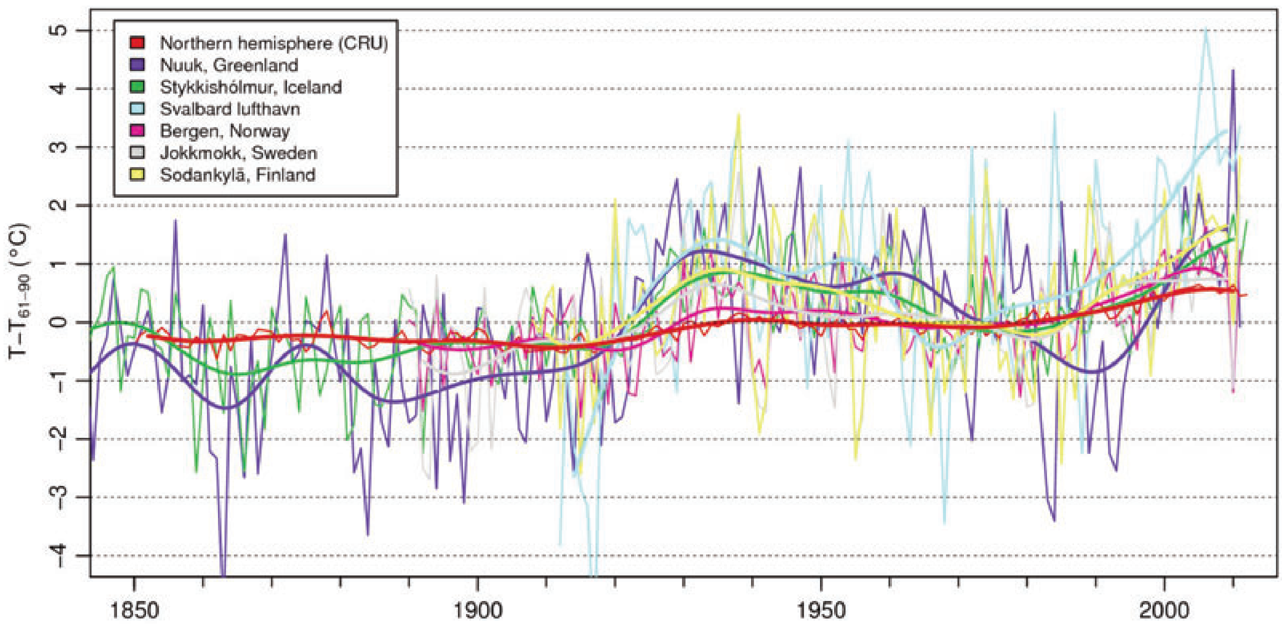


Figure 2. Mean annual temperature deviation from the 1961–1990 average as well as a 10-year weighted Gaussian running average for six weather stations in the Nordic countries together with an estimate of the mean annual temperature of the Northern Hemisphere (Jones et al. 2012). (Data sources: Nuuk: Vinther et al., 2006 and the Danish Meteorological Institute; Stykkishólmur: the Icelandic Meteorological Office; Bergen, Svalbard airport: the Norwegian Meteorological Institute (eklima.no); Jokkmokk, Sodankylä: the U.K. Met. Office, the Swedish Meteorological and Hydrological Institute).

sive mass-balance and ice surface measurements. SVALI and the study of the Nordic GICs are therefore very much of global importance. The rate of ice loss from GICs in the North Atlantic region has intensified dramatically since the latter part of the 20th century (Krabill et al., 2004; Moholdt et al., 2010; Barletta et al., 2012; Björnsson et al., 2012; Jacobs et al., 2012; Jóhannesson et al., 2012b; Sasgen et al., 2012) in response to rapid warming in the area (Figure 2).

The warming in many Arctic and sub-Arctic areas in the last several decades has been much more rapid than the global or hemispheric average. Figure 2 shows that this is indeed the case for Greenland, Iceland and Svalbard and to a lesser degree for the Scandinavian stations shown. The figure also shows great differences in climate development between regions and a large magnitude of the natural climate variability. When viewed over a 10-year timescale, the recent rapid warming appears to have started in ~1970 when the Northern Hemisphere temperature is considered, in ~1985 in Iceland and Scandinavia, and in ~1995 in Greenland, whereas the climate in Svalbard started warming rapidly before 1970, and the warming slowed down around 1980 and intensified after ~1990. Although the warming in the last decades in the North Atlantic region has been dramatic, the climate history of the last one and a half century shows decadal variations in temperature of almost the same magnitude. Such decadal variations will undoubtedly be very important for the climate development in the North Atlantic region during the next decades, as they have been in the past, indicating that large variations in the rate of ice loss in the area are to be expected in the future.

The Greenland ice sheet

Louise Sandberg Sørensen, René Forsberg and Signe Bech Andersen

The Greenland ice sheet (GrIS) stores a total of 2.85 million km^3 (2.6 million Gt) of ice and covers 1.71 million km^2, corresponding to approximately 80% of the surface area of Greenland. If totally melted, it would raise global sea level by 7.3 m. The mass balance of Greenland is affected by both meteorological and dynamic processes, with some 400–500 Gt of new snow deposited on the Greenland Ice Sheet every year, and mass lost by melting and iceberg calving. The mass balance of the GrIS is currently negative, meaning the ice sheet is losing mass.

Figure 1. Observations of the rate of net loss of ice and the corresponding contribution to global sea-level rise, given as mean yearly values.

Within the last decade, the mass loss has been accelerating, with a yearly average mass loss of around 240 Gt/yr. In recent years, especially 2007, 2010 and 2012, record-high surface temperatures over the ice sheet (Box et al., 2010, Nghiem et al., 2012) have resulted in record ice-sheet-melt extent (Fettweis et al., 2011), with a mass loss up to 400 Gt/yr. In addition to accelerating sea-level rise, the mass loss is associated with an increased production of icebergs through larger ice velocities (Joughin et al., 2010), a major concern for shipping and especially hydrocarbon exploration.

Many changes have been documented by remote sensing, such as mass changes derived from gravity- change measurements by the GRACE mission (Velicogna and Wahr, 2005; Lutsche et al., 2006; Forsberg and Reeh, 2007; Jacobs et al., 2011; Sasgen et al., 2012; Barletta et al., 2012), velocity changes from Synthetic Aperture Radar Interferometry (InSAR) (Rignot and Kanagaratnam, 2006; Joughin et al., 2010), and surface-elevation changes derived from laser and radar satellite and airborne measurements (e.g. Krabill et al., 2004; Sørensen et al., 2011).

The different remote-sensing methods for estimating the mass loss of the GrIS rely on different assumptions and error modelling, and until recently estimates of overall mass loss could, in extreme cases, differ by 50–100% between different research groups and instruments used.

A primary method for mass-loss measurement is inversion of GRACE gravity changes (Tapley et al., 2004); however, lack of resolution, difference between different data-processing centres, and errors in Glacial Isostatic Adjustment (GIA) models can give large discrepancies. Methods relying on measuring height changes by radar or laser using satellites such as ICESat or EnviSat/CryoSat rely on assumptions on snow and ice density, firn compaction and radar penetration for modelling mass changes. A third main method – the mass-budget method – is based on velocity determination by SAR interferometry combined with ice-thickness measurements through "gates" at ice margins and outlet glaciers, using models of accumulation and melt for estimating the difference between input and output of mass through the surface of the ice sheet upstream of the grounding line and the "gates".

To settle the difference between the major methods, ESA and NASA in 2011 commissioned a study – IMBIE (International Mass Balance Intercomparison Experiment; Shepherd et al., 2012) – where a common period and rigorous comparison were used for an improved independent intercomparison. Results of IMBIE, where SVALI scientists were key participants, have led to revised estimates of the mass balance, now with good agreement between methods, giving an overall mass loss of Greenland for the period 2000–2011 of −223 ± 37 Gt/yr for the combined methods. Similar consistencies in results derived by different methods have been reported in e.g. Sørensen et al. (2011) and Sasgen et al. (2012).

The consistency between the different methods also applies to basin-level studies (Sasgen et al., 2012; Shepherd et al., 2012). Figure 4 shows the subdivision of the GrIS into

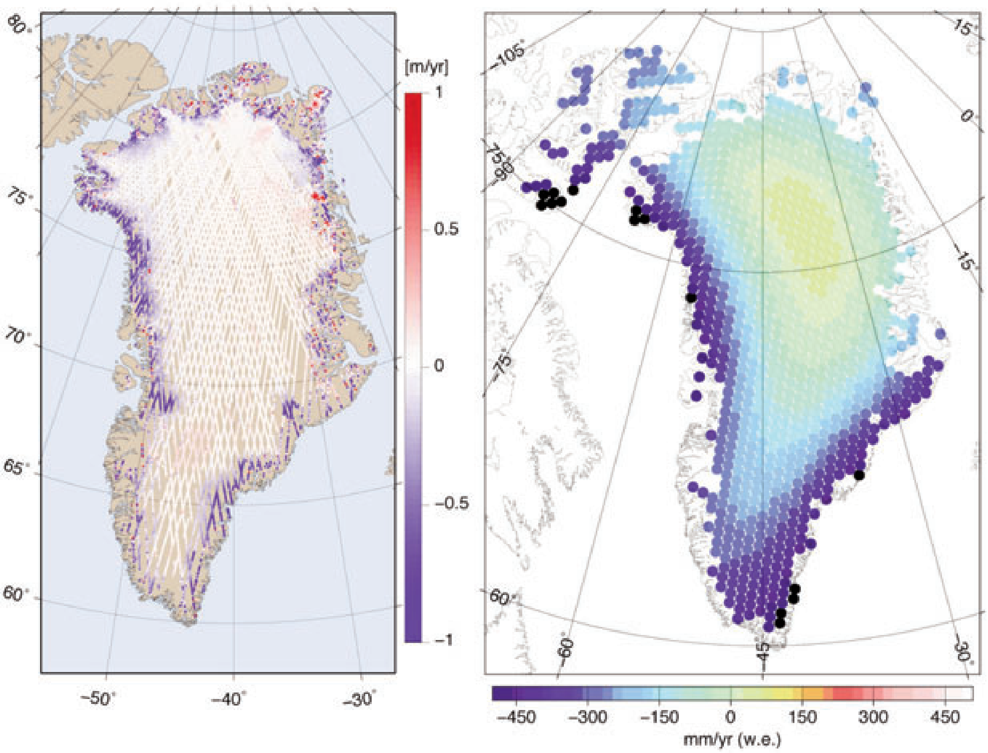


Figure 3. Changes of the Greenland ice sheet showing two different remote sensing techniques: Left: height changes from ICESat laser measurements 2003-9 (Sørensen et al., 2011); right: mass loss from GRACE, expressed as equivalent water loss (Barletta et al., 2012).

seven major drainage basins to assess regional differences in mass changes. The mass-balance estimates for each of these for the period 2003–2009 (based on gravity changes from the GRACE satellite) are listed in Table 2, and examples from two rapidly changing regions are shown in Figure 4.

The mass loss has led to a decrease in the areal extent of the ice sheet, especially in the regions of the major outlet glaciers. The retreat of the ice margin is in some areas more than 10 km, but in many other areas the ice margin is nearly unchanged. Recently, three new data sets on ice extent have become available (Rastner et al., 2012; Howat and Negrete, in prep., showing ice extent around year 2000; and Citterio and Ahlstrøm, in review, based on mid-1980s aerial photography). These data, combined with new 2011 estimates (Kargel et al., 2012), show that Greenland lost at least a 2.6 x 103 km² area between the 1980s and the present, which is about 0.2% of the total area.

Measurements carried out on or near the ice sheet are essential to validate and constrain the satellite observations and models. Such activities include unmanned climate and mass-balance stations from GEUS (in the Programme for Monitoring of the Greenland Ice Sheet (PROMICE)), as well as Greenland-wide networks of GPS stations, measuring the uplift rates caused by the reduced load of the ice sheet (the NSF GNET project). Many of the SVALI partner institutes are involved in these activities in Greenland. In recent years, the ICEBridge project, initiated by NASA to bridge the gap between the ICESat and ICESat-2, has acquired annual LiDAR measurements of many outlet glaciers in Greenland. This effort, together with DTU Space airborne measurement campaigns over the GrIS, provides important additional details of the changes at many of the fastest changing locations. These measurements are further described in section 3.1.

Basin	1	2	3	4	5	6	7	Total
Mass Balance (Gt/yr)	–19	–10	–37	–36	–23	–65	–45	–234

Table 2. Example of basin-scale, mass-balance estimates for the GrIS for the period 2003–2009 (based on gravity changes from the GRACE satellite, Barletta et al., 2012).

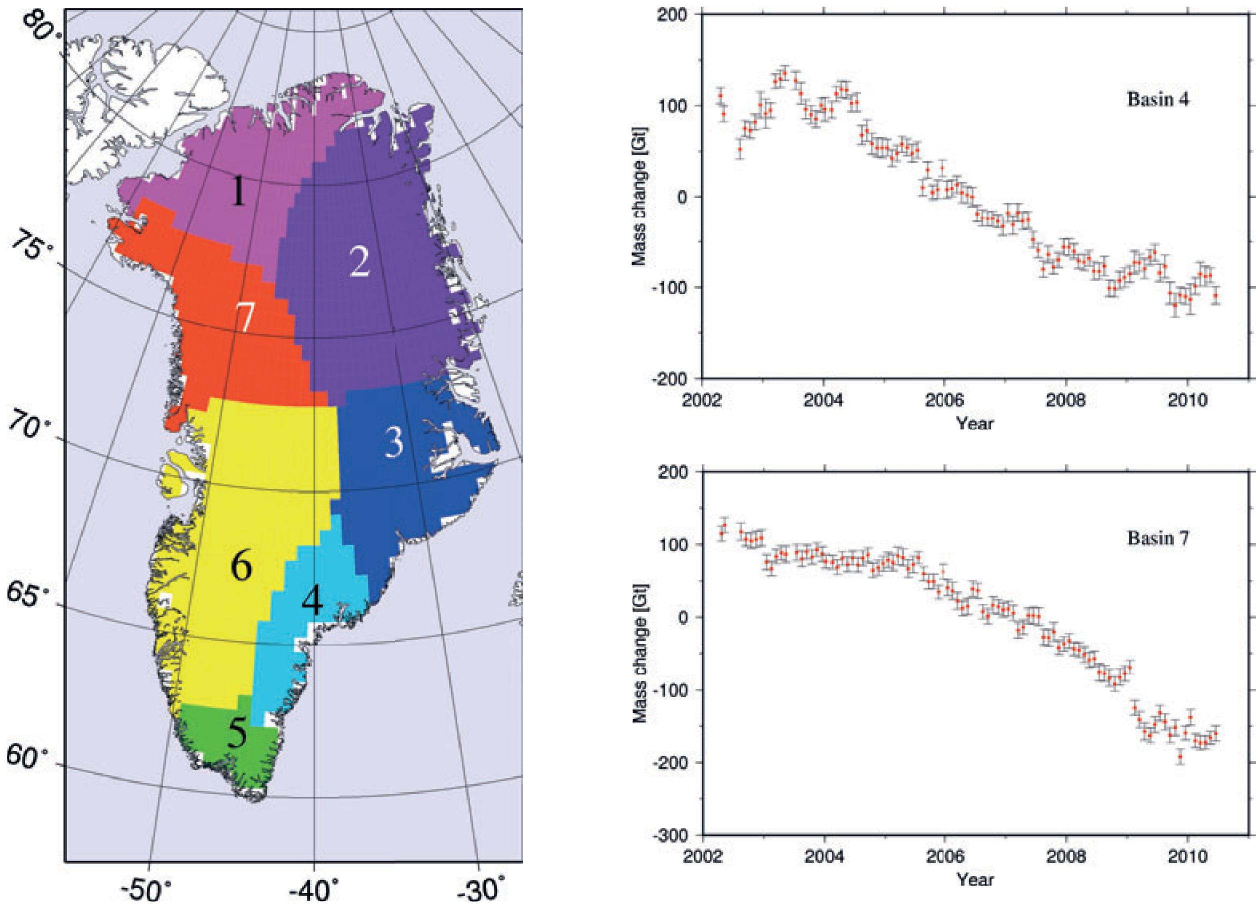


Figure 4. Left: Basin definition of the GrIS (Hardy et al., 2000). Right: examples of time series of GRACE mass-loss estimates for the rapidly changing NW and SE regions (Barletta et al., 2012, SVALI/Ice2Sea mass change studies).

Small glaciers and ice caps

Tómas Jóhannesson, Liss M. Andreassen, Jon Ove Hagen, Horst Machguth and Michele Citterio

Small glaciers and ice caps cover an area of approximately 720 × 10³ km² worldwide including coastal areas in Greenland and Antarctica (Arendt et al., 2012; Huss and Farinotti, 2012). The ice volume stored in these glaciers is still not well known and published estimates vary between 160–290 × 10³ km³ of ice, corresponding to ~0.35–0.72 m of sea-level rise, if all these glaciers were to melt completely (IPCC 2007; Radić and Hock, 2010; Cogley, 2012; Grinsted, 2012; Huss and Farinotti, 2012; the range reflects the spread of published estimates which include small glaciers in Greenland and Antarctica to a varying degree). Of this area, small glaciers and ice caps in the Arctic, including the coastal areas of Greenland, cover approximately 400 × 10³ km² and contain ~150 × 10³ km³ of ice, corresponding to ~0.4 m sea-level rise (AMAP, 2011). Although the total ice volume contained in small glaciers and ice caps is much smaller than in the large Greenland ice sheet (7.3 m sea-level equivalent (sle)) and Antarctica (56.6 msle), the small glaciers are believed to be responsible for more than half of the current contribution of land ice to rising sea level (1.0 mm/yr of 1.8 mm/yr for the period 1996 to 2006 (Meier et al., 2007) or even more (1–1.4 mm/yr for the period 2001–2005 according to Cogley (2009)), see also the review by Steffen et al. (2010).

Scandinavia

Glaciers in Norway cover an area of 2700 km² (Andreassen and Winsvold, 2012), 0.7% of the area of mainland Norway. Glaciers in Sweden cover 240 km². Mass-balance observations from Scandinavia from the second half of the twentieth century reveal cumulative mass surplus at the maritime glaciers since the 1960s, whereas the more continental glaciers had mass deficits (Andreassen et al., 2005; Holmlund et al., 2005, Zemp et al., 2010). All glaciers in Norway, except Langfjordjøkelen, had a transient mass surplus in the period 1989 to 1995, mainly as a consequence of increased winter accumulation (Andreassen et al., 2005). Since 2001, all monitored glaciers in Scandinavia have experienced an overall mass deficit. The rate has changed from mass surplus to mass deficit at the coastal glaciers, whereas the decrease of the continental glaciers has accelerated. The mass balance for the period 2001–2010 ranges from −0.1 $m_{w.e.}$/yr (w.e.= water equivalent) for Nigardsbreen to −0.8 $m_{w.e.}$/yr for continental glaciers in Jotunheimen (Storbreeen, Hellstugubreen and Gråsubreen). For the glaciers in the Swedish mass-balance programme, all semi-continental, the mass balance ranges from −0.47 $m_{w.e.}$/yr for Storglaciären to −1.15 $m_{w.e.}$/yr for the rapidly wasting ice cap Riukojietna. At Langfjordjøkelen in the northernmost part of mainland Norway, the mass balance is −1.3 $m_{w.e.}$/yr. In addition to the field observations, aerial photographs have been taken at about decadal intervals and are used for comparison of the glaciological and the so-called geodetic mass balance, derived for whole glaciers or ice-flow basins from the total ice-volume change indicated by the maps (e.g., Andreassen et al., 2002; Haug et al., 2009; Zemp et al., 2010). In several cases, this comparison has revealed a significant difference between the glaciological and geodetic mass balances and, overall, geodetic methods show more a negative balance or less mass surplus than the glaciological mass balances suggest.

Iceland

Glaciers in Iceland store a total of 3600 km³ of ice and cover 11 000 km², corresponding to approximately 11% of the area of the country, and they are retreating and thinning rapidly at present (Björnsson and Pálsson, 2008). Mass-balance measurements and measurements of changes in the ice-surface elevation on the three largest ice caps, Vatnajökull, Hofsjökull and Langjökull, indicate a consistently negative mass balance since the middle of the 1990s, −1.3 $m_{w.e.}$/yr for the period 1997–2009 for Langjökull (Pálsson et al., 2012), −1.3 $m_{w.e.}$/yr for the period 1999–2008 for Hofsjökull (Jóhannesson et al., 2012b) and −0.8 $m_{w.e.}$/yr for the period 1995–2010 for Vatnajökull (Björnsson et al., submittet). The average for all the glaciers in Iceland for the period 1995–2010 has been estimated to approximately −0.9 $m_{w.e.}$/yr corresponding to a total melting of 9.5 Gt/yr. The mass balance of the Drangajökull ice cap in north-western Iceland is estimated to be less negative than for the main ice caps, −0.5 $m_{w.e.}$/yr for the period 1999–2011 (Jóhannesson et al., 2012b), whereas the mass balance of several smaller ice caps in southern Iceland has been found to be even more negative (Guðmundsson et al., 2011; Jóhannesson et al., 2012b). The downwasting of the glaciers is projected to intensify during the coming decades, leading to their almost complete disappearance within the next 150–200 years (Aðalgeirsdóttir et al., 2011; Jóhannesson et al., 2012a;). Total melting of all glaciers in Iceland would lead to ~1 cm rise in global sea level.

Svalbard

The archipelago of Svalbard has a glaciated area of ca. 35 000 km² with an estimated volume of ca. 9000 km³ (Hagen et al., 1993). Glaciers range from small cirque glaciers of a few km² to large areas of contiguous ice fields and ice caps, the largest being Austfonna of ca. 8000 km².

There are over 1500 glaciers that are larger than 1 km² on Svalbard. While a glacier inventory was first compiled by Hagen et al. (1993), there has not been a readily available digital inventory. Work on a new digital glacier database is about to be completed and will be available through an Norweigian Polar Institute (NPI) web site as well the GLIMS project (König et al., in press). Glacier outlines have been created for the years 1936, 1966–71, 1990, and 2007/8. For most glaciers, outlines are available for more than one of these years. For the 20th century, data of glacier outlines were created from cartographic data in the original NPI topographic map series of Svalbard. The 2007/8 glacier outlines are derived from ortho-rectified satellite images acquired from the SPOT-5 and ASTER satellite sensors. In areas where three images or more are available, the overwhelming majority of the glaciers are observed to be in sustained retreat over the period from 1936 to 2008.

Mass-balance monitoring of glaciers on Svalbard started by the NPI in 1967 on Austre Brøggerbreen (~5 km^2) and in 1968 on Midtre Lovénbreen (~5 km^2) in Kongsfjorden in North-West Spitsbergen, the largest island on Svalbard. Measurements on Kongsvegen (~100 km^2) were started in 1987; and on the combined glacier system Kronebreen and Holtedahlfonna (~500 km^2) in 2003. The mass-balance time series are among the longest continuous data series from the Arctic. However, they cover only a small fraction (~2%) of the total glaciated area and are all from the same region of Svalbard. The time series show no clear trend. The two smaller, low-lying glaciers have had a steady negative mass balance, but no recent increased melt-rate can be clearly detected. The larger glaciers are in general more positive, since their accumulation areas are both higher and larger than for the two smaller glaciers. On all four glaciers, summer ablation is more variable than winter accumulation, so that summer temperatures provide most of the control on variations in the annual balance.

Coastal areas in Greenland

Glaciers and ice caps near the coast in Greenland are expected to respond more rapidly to climate change than the main ice sheet and their mass-balance characteristics and dynamic response are more akin to the glaciers in Scandinavia, Iceland and Svalbard. They, and similar glaciers in Antarctica, are therefore often grouped together with other small glaciers and ice caps on Earth when the response of the cryosphere to climate changes is analysed. It should, however, be noted that for some analyses, such as interpretation of gravity measurements, these glaciers must be treated as a part of the neighbouring ice sheet, whereas in other contexts, such as interpretation of mass-balance measurements or ice-flow modelling, it is more appropriate to consider them as part of small glaciers and ice caps.

Until recently, relatively little was known about the glaciers and ice caps near the coast of Greenland. Recently, three data sets have become available: the first glacier inventory representing all glacierised areas of Greenland (Rastner et al., 2012) and the GIMP ice cover grid (Howat and Negrete in prep.), both document glacier extent ca. year 2000; the third is the PROMICE aero-photogrammetric map of all ice masses in Greenland from ca. mid-1980's (Citterio and Ahlstrøm).

The Rastner et al. (2012) inventory separates the ice sheet and local ice bodies in to categories by assigning a connectivity level (CL) to each glacier:

- CL0: no connection to the ice sheet
- CL1: weakly connected and clearly separable, dynamically independent
- CL2: strongly connected but dynamically still largely independent

The CL0 glaciers cover an area of 65 000km^2, CL0 and CL1 in combination cover 89 000 km^2 and glaciers of all three connectivity levels amount to 130 000 km^2. While the status of CL2 glaciers is debatable, CL0 and CL1 glaciers are clearly to be considered as local glaciers. Thus the area of glaciers and ice caps on Greenland is considerably larger than previous estimates (e.g. 48 600 km^2, Weng, 1995, or 54 000 km^2, Radic and Hock, 2011), even when only CL0 glaciers are included. However, based on ice-thickness measurements, total sea-level equivalent (SLE) of Greenland's small glaciers and ice caps (SGICs) might not differ much from previous estimates. Taking only CL0 and CL1 glaciers into account, Bolch et al. (subm. 2012) calculate a mass loss of 30 $\pm$ 6 Gt/yr, corresponding to 0.08$\pm$0.02 mm/yr SLE between 2003 and 2008. Considering SGICs, the involved uncertainties make quantitatively assessing of glacier change rates difficult on the decadal scale (Kargel et al., 2012). In West Greenland, on the longer timescale from the Little Ice Age (LIA) to 2001, the mean area change of SGICs was −28%, −20% and −23% on the Disko island and the Nuussuaq and Svartenhuk peninsulas, respectively (Citterio et al., 2009). The most pronounced mass changes occur in the south and south-east while mass loss is minimal in the north and north-east. It is worth noting, finally, that the rate of per area-unit mass loss of Greenland's SGICs is approximately 2.5 times larger than for the ice sheet itself, confirming the assumption that local ice bodies are more sensitive to climatic change than the large polar ice sheets (Bolch et al., subm. 2012).

LiDAR observations

Tómas Jóhannesson

Airborne LiDAR surveying has been proven to be an accurate method for measuring ice-surface elevations independently of surface texture, snow properties near the surface and external light sources (Arnold et al., 2006). Traditional photographic methods often fail in the accumulation area of glaciers due to lack of contrast and the signal from radar surveying of the same areas penetrates the snowpack to a varying degree depending on snow density and liquid water content in the snow, leading to an uncertainty in estimates of ice volume changes from repeated measurements (Rignot et al., 2001).

The high-resolution LiDAR DEMs may also reliably be used to assess glacier area and analyse periglacial features (Abermann et al., 2010) and accurate ground-control points extracted from the LiDAR measurements can be used to aid the photogrammetric processing of existing stereo imagery (Barrand et al., 2009).

Traditional mass-balance measurements at stake locations are carried out annually on a number of glaciers in the Nordic countries and elsewhere in the world and provide an important indication of variations in the mass budget of the glaciers. These measurements can be biased when the stakes values are integrated to calculate mass-balance estimates over whole ice-flow basins (Østrem and Haakensen, 1999). Repeated surveying of the ice-surface elevation of the glaciers with several year intervals make it possible to correct for the bias in the mass-balance measurements and improve the mass-budget estimate considerably (Jóhannesson et al., 2012b).

Changes in ice surface elevations on glaciers tend to be concentrated in narrow regions along glacier margins, in heavily crevassed areas on ice streams and near calving ice fronts. These areas are often hard to map accurately by remote sensing using space-borne sensors because of the steep terrain and rough surface characteristics. LiDAR mapping of these areas complements the available satellite data and also provides important validation data for the satellite measurements.

Airborne LiDAR surveying is typically conducted from an altitude of 0.5–4 km above ground, point densities are in the order of 0.1–10 per m², the swath width ranges from several hundred metres to 2 km and the vertical accuracy of the resulting digital elevation models (DEMs) is 0.1–0.5 m (Arnold et al., 2006). The typical speed of the aircraft is 200 km/h and it is possible to survey hundreds of km² on a good cloud-free day. The irregular point measurements are usually averaged to create DEMs on regular 5 × 5 to 100 × 100 m² grids for further analysis and comparison with other ice-surface measurements.

Greenland

Rene Forsberg, Louise Sandberg Sørensen, Sine M. Hvidegaard

Greenland has been measured primarily by US airborne trackwise laser scanning during the PARCA and later IceBridge initiatives. Also DTU-Space has measured large parts of the ice sheet as part of the PROMICE and ESA-CryoSat validation experiments. Due to the large size of the Greenland Ice Sheet, it is not possible to map the entire area by LiDAR as has been done for smaller ice caps and glaciers in e.g. Norway or Iceland. Therefore, the focus has generally

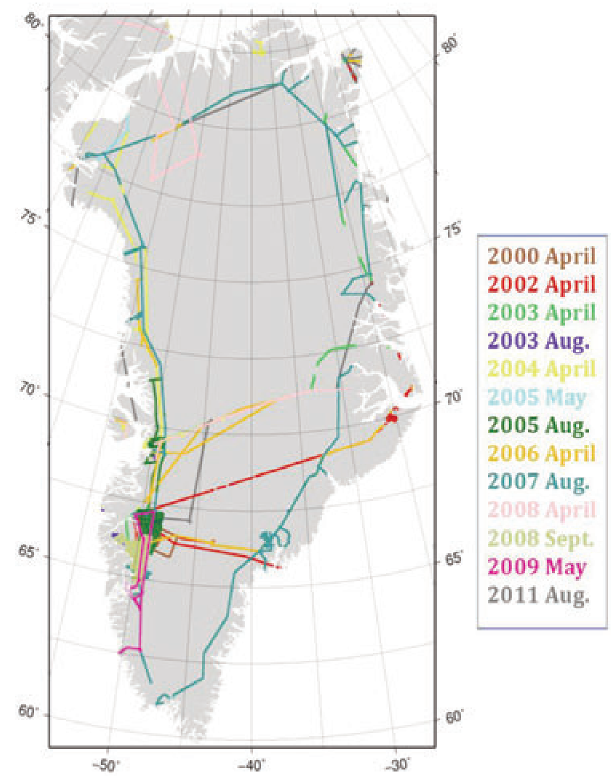


Figure 5. Flight lines of LiDAR campaigns in Greenland carried out by DTU-Space since 2001. The 2007 and 2011 campaigns were part of PROMICE, and especially designed for monitoring changes along a perimeter 'fence' of the Greenland ice sheet.

been on monitoring the ice-sheet margin where the largest changes take place. To determine the overall mass balance of the GrIS from LiDAR, it is therefore necessary to combine the measurements of elevation by LiDAR with other observations, such as e.g. observations of ice velocities.

The Operation IceBridge mission led by NASA, initiated in 2009, collects airborne remote-sensing measurements including laser altimetry to bridge the gap between NASA's Ice, Cloud and Land Elevation Satellite (ICESat) mission and the upcoming ICESat-2 mission. These data supplement earlier less dense laser-altimetry data collected during the NASA PARCA project (1993–2008). Nearly all the flights have been done by a very large NASA P-3 aircraft, at great costs. The DTU-Space measurements were carried out using smaller Twin-Otter aircraft. The accuracy of the LiDAR measurements is typically 10–30 cm range, with swath widths up to 500 m (where details of the ice surface are resolved at metre level).

Figure 5 provides an overview of the LiDAR campaigns carried out by DTU-Space since 2001, and Figure 6 shows an overview of the IceBridge data. So far, overall mass-balance estimates based on the IceBridge airborne data alone have not been published, but data are collected on an 'infrastructure' basis by NASA, and made openly available after a nominal 6-month period. The airborne data have proven themselves immensely useful for understanding the detailed nature of the ice elevation changes, for process studies and also for providing additional data, especially for complementing radar thickness data, of prime importance both for applications of the mass-budget (InSAR) method, as well as for glaciological flow modelling.

For the mass-budget method, information on ice thickness is required in order to translate changes in ice velocity into changes in the mass of ice lost by calving of icebergs. Airborne laser and radar surveys of the entire ice-sheet margin were performed by DTU-Space in 2007 and 2011 as a part of PROMICE (Figure 7) and will be used particularly to calculate the ice loss by calving.

Scandinavia

Liss M. Andreassen and Peter Jansson

Introduction

Norway

The glacier monitoring programme in Norway in 2012 includes direct mass-balance investigations of 16 glaciers. Accurate maps of glaciers are essential for the processing of the mass- balance measurements and for other calculations. Previously, glacier maps have typically been constructed from aerial photos. Poor optical contrast of snow-covered parts of the glacier surfaces can cause large uncertainties in derived elevations. Data derived from laser-scanning (LiDAR) are very accurate on snow-covered surfaces with low roughness. The first laser-scanning campaigns of Norwegian glaciers were conducted in 2001–2003 when Engabreen was mapped several times (Geist et al., 2005).

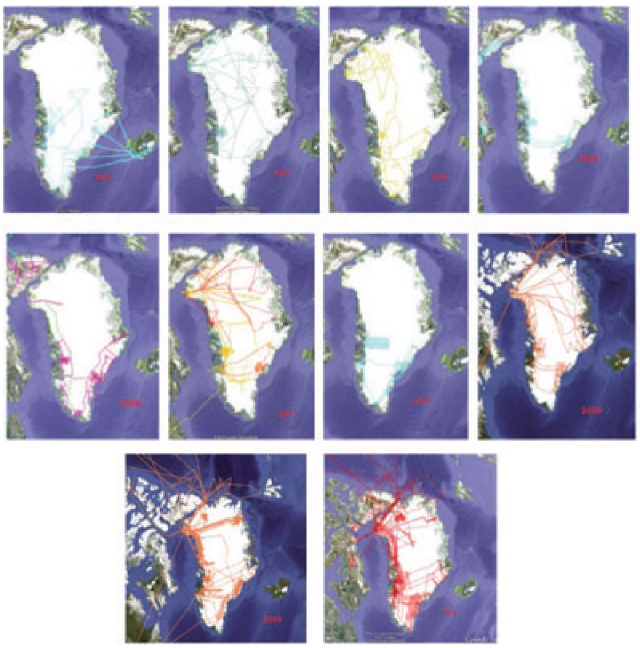


Figure 6. Flight lines of LiDAR campaigns in Greenland carried out by the PARCA and ICEBridge projects since 2001.

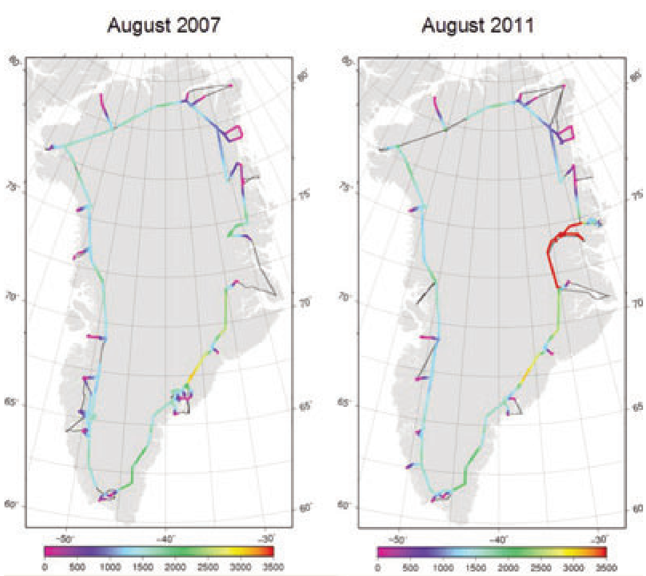


Figure 7. Flight paths and ice-surface elevations of LiDAR campaigns in Greenland performed within PROMICE.

Since 2007, annual LIDAR campaigns have been conducted on a selection of glaciers in mainland Norway. The goals of the surveys are to:

- produce high quality digital terrain models (DEMs)
- document the present state of the glaciers
- assess mass changes since previous mappings of the glaciers.

Sweden

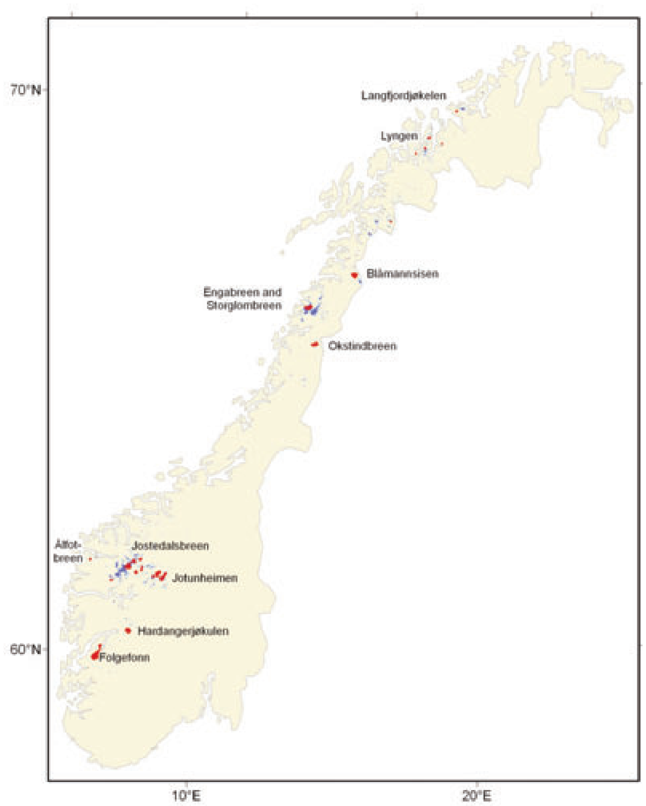
The mass-balance monitoring programme run by Stockholm University and its Tarfala Research Station in Sweden comprises five glaciers. Direct mass-balance measurements are made on Storglaciären (1945/46–), Rabots Glaciär (1981/82–), Riukojeitna (1985/86–), Mårmaglaciären (1987/88–), and Tarfalaglaciären (1985/86–1991/92, 2003/04–). In addition, direct mass-balance measurements have been carried out on Sydöstra Kaskasatjåkkoglaciären, Stuor Raåtaglaciären, Kårsaglaciären, Pårtejekna, Salajekna and Mikkaglaciären for shorter periods. In addition, terminus measurements are made regularly at 22 glaciers, including those in the direct mass-balance programme.

Glacier maps have been made from aerial photographs for many glaciers although most of the material is still unpublished. Storglaciären is well covered by decadal maps from 1949, 1959, 1969, 1980, 1990, 1999 and 2011 (Holmlund, 1987, 1996; Koblet et al., 2010). The 2011 map was made by surveying with land-based techniques (dGPS and total station measurements). Published maps also exist from Riukojietna (Rosqvist and Östrem, 1989), Tarfalaglaciären (Holmlund, 1987), and Salajekna (Klingbjer et al., 2005). The accuracy of the maps is discussed by Koblet et al. (2010) and the necessity of re-analysing the aerial photographs with a uniform methodology has become evident.

To date no LiDAR measurements have been made in Sweden despite many attempts to find funding. The Swedish Land Survey is currently running a programme for scanning the entire country for a new terrain database. The mountain region has unfortunately been postponed as a low priority area. The Swedish glaciers will thus eventually be surveyed by LiDAR but to date the timing and other details about such measurements have not been decided.

LiDAR surveys Norway

The Norwegian LIDAR surveys cover ~800 km² glacier area during the period 2007–2011 (Figure 8, Table 3), more than 30% of the glacier area in Norway. All glaciers included in the current mass-balance program are now mapped with LIDAR scanning (see example of campaigns in Figure 9). The laser scanning and raw data processing were done by commercial companies. Each year the Norweigian water resources and energy directorate (NVE) has sent out invitations to tender



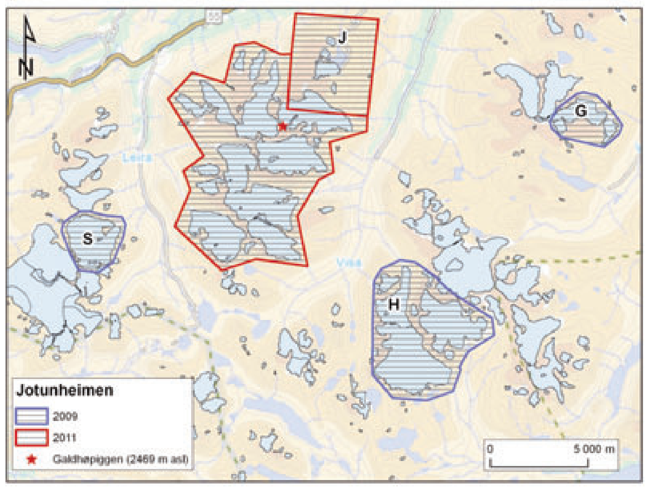


Figure 9. Example of LiDAR campaigns in Jotunheimen, southern Norway. In 2009, several glaciers included in the mass-balance programme (S, H and G) were mapped. In 2011, a selection of glaciers along the Galdhøpiggen (highest peak in Norway) massif was mapped. A subset of the area was mapped with higher resolution covering Juvfonne (J) – an ice patch with many artefact recoveries.

Figure 8. Map of Norway showing laser-scanned glaciers in red – other glaciers shaded in blue.

to potential firms before choosing the company to do the survey. Since 2009, simultaneous air photos have also been taken in addition to the LiDAR measurements and heve been used to produce orthophotos of the glaciers.

Results

The collected LIDAR data have been used to calculate changes in area and volume by comparing to older topographic maps. The geodetic mass balance is calculated by using estimates of ice density and is then compared with values from the direct mass balance method in areas where such measurements are available. Preliminary results reveal discrepancies between the methods for some glaciers, whereas others have good agreement. Recent published analyses of Langfjordjøkelen, a small ice cap in northern Norway, used topographic maps from 1966 and 1994 and LIDAR data from 2008. Results revealed a strong decrease in mass, area and volume. For the period 1994–2008 the geodetic and direct mass balance estimates were −17.7 $m_{w.e.}$ and −14.5 $m_{w.e.}$, respectively, a difference of approximately 20% (Andreassen et al., 2012). Although there are uncertainties in both methods at Langfjordjøkelen as well as at other glaciers, the difference may call for a revision of the published direct mass balance values.

Conclusions

Over the period 2007–2011 laser scanning campaigns have been conducted on selected glaciers in mainland Norway providing new accurate DEMs and orthophotos. The surveys cover nearly 1/3 of the glacier area in Norway and include all glaciers in the present mass-balance program. The new LIDAR data combined with old maps have been used to calculate geodetic mass balance. Geodetic results have been compared with mass balance measured by the direct method, where available, for an independent check of the direct method. The DEMs and orthophotos provide an accurate baseline for future repeated mapping and glacier-change detection.

Year	Glacier	Area (km^2)
2007	Folgefonn	219
2008	Langfjordjøkelen	10
	Engabreen, Storglombreen	68
2009	Nigardsbreen, Austdalsbreen	59
	Storbreen, Gråsubreen, Veobreen	16
	Hellstugubreen, Memurubreen v, a	19
2010	Harbardsbreen	36
	Hardangerjøkulen	73
	Ålfotbreen	17
	Storsteinsfjellbreen	12
	Lyngen glaciers	31
2011	Jostefonn, Spørteggbreen, Sekkebreen	63
	Galdhøpiggmassif	40
	Blåmannsisen	85
	Okstindbreen	50
	Total	798

Table 3. Laser-scanned glaciers in mainland Norway 2007–2011.

Outlook

Further LIDAR campaigns are planned for 2013. In 2012, NVE planned to survey the Folgefonna ice cap and two outlets from Jostedalsbreen: Nigardsbreen and Tunsbergdalsbreen, but this campaign had to be postponed due to adverse weather conditions. The campaigns in 2013 will depend on available funding and are not planned yet apart from the work that was delayed from 2012. Work on calculating geodetic mass balance from these data will be continued in 2012 and 2013 with the goal to publish an overview paper on the geodetic mass balance of Norweigian glaciers. The work on comparing geodetic and direct mass-balance data will also continue and direct mass-balance series will be revised, where necessary.

Iceland

Tómas Jóhannesson, Helgi Björnsson, Sverrir Guðmundsson and Finnur Pálsson

Introduction

Glaciers in Iceland store a total of 3600 km^3 of ice and cover 11 000 km^2, corresponding to approximately 11% of the area of the country, and they are retreating and thinning rapidly at present (Björnsson and Pálsson, 2008). The downwasting of the glaciers is projected to intensify during the coming decades, leading to their almost complete disappearance within the next 150–200 years (Aðalgeirsdóttir et al., 2011; Jóhannesson et al., 2012a). Total melting of all glaciers in Iceland would lead to ~1 cm rise in global sea level.

During the International Polar Year (IPY) 2007 to 2009, an effort was initiated to produce accurate Digital Elevation Models (DEMs) of the main glaciers in Iceland using airborne LiDAR (Jóhannesson et al., 2012b). The purpose was to obtain a good estimate of the current rate of change in glacier geometry and to establish an accurate baseline for monitoring of future changes. In 2012, almost all glacier-covered areas in Iceland had been mapped in this effort, and the total surveyed area was in excess of 15 000 km^2, including proglacial areas and repeated mapping of some areas with rapid changes due to subglacial eruptions and emptying of subglacial water bodies.

Figure 10. Location map of Icelandic glaciers showing the status of the LiDAR mapping at the end of the 2012 survey effort. Glacier outlines delineated from ortho-corrected SPOT5 and Landsat 7 images and aerial photographs from the period 1999–2004 are shown as red curves. Hatched areas on S and SW Vatnajökull with an area of approximately 2200 km² were surveyed in 2012. 60% of the Langjökull ice cap was surveyed by the Scott Polar Research Institute (SPRI) in 2007.

Survey areas

The LiDAR survey areas and the year of surveying of each glacier are shown in Figure 10. Together with earlier LiDAR survey efforts, the survey area includes all glaciers and ice caps in Iceland larger than 10 km² and some smaller glaciers, but glaciers in Tröllaskagi in northern Iceland (more than 150 individual glaciers, ~150 km² in area in total) and some other comparatively small glaciers in other parts of the country are not covered. 60% of the Langjökull ice cap was mapped with LiDAR in 2007 by Scott Polar Research Institute (SPRI) (Pope et al., 2012) and it was possible to create an accurate DEM of the entire ice cap using SPOT5 data from 2004 for gap filling (Pálsson et al., 2012). Table 4 provides an overview over the surveyed glaciers. In addition to the LiDAR DEMs, accurate DEMs derived from InSAR (Magnússon et al, 2005), and SPOT5 HRG or HRS images have been produced for most of the ice caps at different dates in the period from 2003 to 2011 (i.e. Korona, 2009; Guðmundsson et al., 2011). These SPOT5 DEMs have provided useful comparison with the more recent LiDAR DEMs.

Example from Hofsjökull

The Hofsjökull ice cap in central Iceland was surveyed in September 2008 (most of the ice cap) and in July 2010 (the north eastern flank of the ice cap). The results from the 2010 survey were corrected for the changes that had taken place since 2008 and combined with the earlier results to produce a DEM of the entire ice cap representing its late summer geometry in 2008. Comparison of this DEM, which is shown in Figure 11, with an earlier ice surface map from 1999 indicates an average lowering of the ice cap of 1.4 m_{ice} per year in the time period 1999–2008.

Ice-volume changes and mass balance

The LiDAR DEMs have been compared with available DEMs based on aerial photographs and remote sensing since ~1980 for seven ice caps and glaciers to derive spatial and temporal patterns of ice- volume changes in different regions of Iceland (Aðalgeirsdóttir et al., 2011; Jóhannesson et al., 2011,

Glacier	Survey year(s)	Area (km²)
Langjökull (60%, SPRI)	2007	900
Snæfellsjökull	2008	10
Eiríksjökull	2008	20
Hofsjökull	2008, 2010	852
Eyjafjallajökull	2010	70
Mýrdalsjökull	2010	543
Vatnajökull	2010, 2011, 2012	8100[1]
Drangajökull	2011	142
Tungnafellsjökull	2011	33
Tindfjallajökull	2011	13
Torfajökull	2011	9
Kaldaklofsjökull	2011	2
Glaciers in Flateyjardalsheiði	2011	~6[1]
Þrándarjökull	2012	17[1]
Hofsjökull eystri	2012	5[1]
Glaciers in Kerlingarfjöll	2012	5[1]
Glaciers on Snæfell	2012	4[1]

[1] Area in year ~2000, other areas are delineated from the LiDAR DEMs.

Table 4. Glaciers in Iceland surveyed by LiDAR 2007–2012.

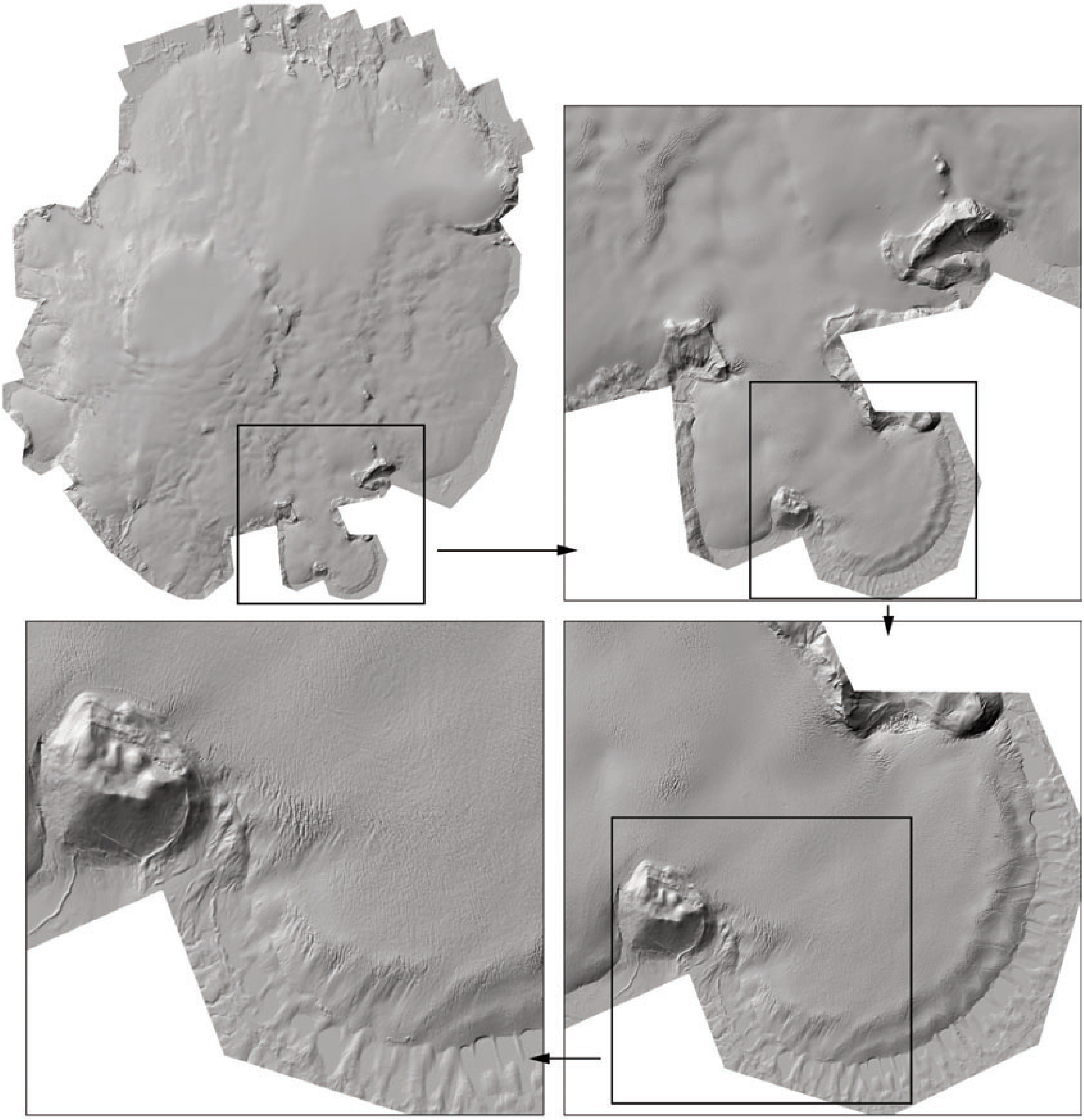


Figure 11: Hillshades from the 2008/2010 LiDAR DEM of Hofsjökull (area 852 km² in 2008), central Iceland. The sequence of four hillshades zooms in on the Múlajökull outlet glacier in the SE part of the ice cap. The high resolution DEMs show glaciological and geomorphological features such as ice- surface undulations, crevasse fields, melt channels incised into the ice, side moraines, end moraines and drumlins.

Glacier	Period	Mass balance ($m_{w.e.}$/yr)
Hofsjökull	1999–2008	−1.3
Langjökull	1999–2007	−1.3
Snæfellsjökull	1999–2008	−1.4
Drangajökull	~1999–2011	−0.5
Eyjafjallajökull	1998–2010	−1.2
Torfajökull	1998–2011	−1.9
Tindfjallajökull	1998–2011	−1.3
Hoffellsjökull	2001–2010	−1.2

Table 5: Changes in ice volume and the average, annual mass balance for eight Icelandic glaciers derived from a comparison of LiDAR measurements with older ice-surface maps based on aerial photographs and remote sensing (Jóhannesson et al., 2011, 2012b; Aðalgeirsdóttir et al., 2011; Pálsson et al., 2012). All changes are calculated directly from the DEMs without correction to take into account slightly different times of surveying within the mass balance year. The mass balance is calculated from the mean change in the ice-surface altitude using a fixed density equal to the density of ice (Sorge's law, Paterson, 1994).

2012b; Pálsson et al., 2012). Table 5 summarises estimates of volume changes and mass balance for these glaciers and the results for Hofsjökull are shown in Figure 12. The maps of the ice loss for Hofsjökull show a typical spatial pattern of such changes for non-surging glaciers, with the greatest surface lowering concentrated along the glacier margin and much smaller changes at intermediate and high elevations.

Geodetic mass-balance estimates for Hofsjökull derived from the LiDAR maps and available older DEMs (Jóhannesson et al., 2012b) indicate a substantial bias of ~0.4 $m_{w.e.}$/yr in the traditional mass-balance measurements that have been conducted on the ice cap since 1987. This value is in the order of one half of the average, negative mass balance, indicated by the traditional mass-balance measurements during the period 1999–2008. The bias is similar for all three ice-flow basins covered by the mass-balance measurements and appears to be relatively independent of time period. The bias is not greater than published estimates of the uncertainty of the traditional mass-balance data, but as it tends to be similar year after year, it can lead to serious biases in mass-balance modelling and dynamic simulations of the ice cap where mass-balance measurements are used for model calibration. In other cases, such as on Langjökull (Pálsson et al., 2012) and Hoffellsjökull (Aðalgeirsdóttir et al., 2011) much smaller biases have been found.

Conclusions and future outlook

The LiDAR DEMs of Icelandic glaciers show their state at the onset of the on-going downwasting of the glaciers. They have been used to assess the rate of change of the glaciers during the last several decades and they will be valuable as a reference for future assessments of glacier changes. Comparison of the LiDAR maps with available older ice-surface maps based on aerial photographs and remote sensing indicate that glaciers in Iceland have been losing mass at a rate of 0.5–2.0 $m_{w.e}$./yr on average since the middle of the 1990s (Jóhannesson et al., 2011, 2012b), confirming the rapid volume changes of the Icelandic ice caps that have been shown by mass-balance measurements since 1995/1996 (Björnsson and Pálsson, 2008). The area-weighted average rate of ice loss has been estimated to be 0.9 ± 0.1 $m_{w.e.}$/yr or 9.5 ± 1.5 Gt/yr for this time period, corresponding to approximately a

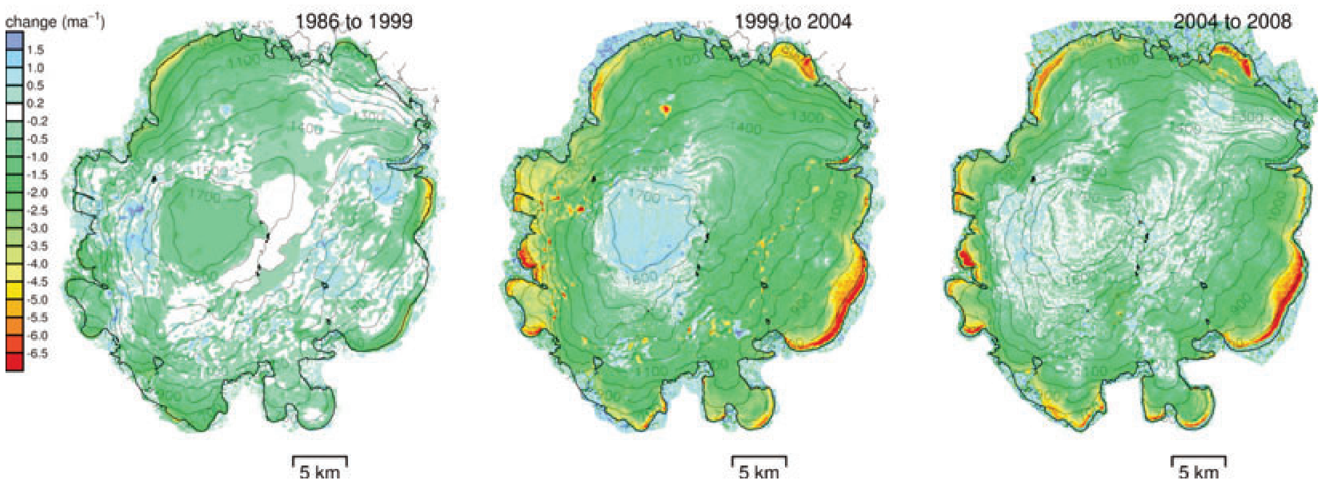


Figure 12: Annual average change in ice-surface elevation of Hofsjökull from 1986–1999/2001, 1999/2001–2004 and 2004–2008. The figures show elevation contours based on the 2008 LiDAR map and the outline of the ice cap in 1999. The DEM from 1986 is based on aerial photographs. The 1999/2001 DEM is based on aerial photographs from 1999 in the ablation area, GPS-measurements from 2001 near the summit and interpolation based on the altitude distribution of previous and later elevation changes at intermediate altitudes. The DEM from 2004 is derived from SPOT5/HRS optical satellite images obtained from the SPIRIT project (Korona, 2009).

0.03 mm /yr rise in sea level (unpublished data from IES and IMO; Björnsson et al., submitted). The DEMs are being used in several glaciological and geomorphological research projects of subglacial eruptions, jökulhlaups and hazard assessments for settlements near the glaciers and they will be useful in research of glacier dynamics such as studies of surges, calving, subglacial water flow and ice flow over bedrock topography. The very high resolution and good relative accuracy also make LiDAR maps useful for mapping crevasses and the creation of various special purpose maps of the glaciers, including maps to improve the safety of travel and search and rescue operations on the glaciers.

Svalbard

Jack Kohler, Jon Ove Hagen

Introduction

Geodetic mass balance based on older maps, airborne and satellite-borne sensors has been used to obtain spatially distributed measurements of mass changes of glaciers in Svalbard.

The geodetic mass-balance of Svalbard has mainly been obtained by analysing ICESat data from 2003–2008 (Moholdt et al., 2010a). Most glacier regions in Svalbard have experienced low-elevation thinning combined with high-elevation balance or thickening during this period. During that same period the geodetic mass balance (excluding calving front retreat or advance) of Svalbard's glaciers is estimated to be −4.3 ± 1.4 Gt/yr, corresponding to an area-averaged water equivalent (w.e.) balance of −0.12 ± 0.04 $m_{w.e.}$/yr. The largest ice losses have occurred in the west and south, while northeastern Spitsbergen and the Austfonna ice cap have gained mass. Winter and summer elevation changes derived from the same methods indicate that the spatial gradient in mass balance is mainly due to a larger summer season thinning in the west and the south than in the north-east.

However, the volume change over the past 40 years for Svalbard, excluding Austfonna and Kvitøya, is estimated to be more negative, or −9.71 ± 0.55 Gt/yr or −0.36 ± 0.02 $m_{w.e.}$/yr, corresponding to an annual contribution to global sea-level rise of 0.026 mm/yr SLE (Nuth et al., 2010). This result was based on satellite altimetry from ICESat (2003–2007) compared with older topographic maps and digital elevation models (1965–1990).

LiDAR

Only a few limited campaigns over Svalbard have involved LiDAR. Early missions collected elevation data along profiles: repeating the measurements along the same tracks allowed elevation changes to be calculated along the profiles. In principle, total glacier mass changes can be calculated by assuming a spatial distribution of the measured elevation change, but the more preferred technique is to make a detailed surface map of the entire glacier surface. A further advantage of this method, for areas with sufficient bedrock exposures, is that older photogrammetric campaigns can be reanalysed using the new high accuracy DEMs to increase the number of possible control points in the digital photogrammetry (e.g. James et al., 2006). However, significantly more air time is required to obtain complete coverage of an area. Later LiDAR campaigns have made complete maps of individual glaciers, but none are larger than 130 km². In the following, the available LiDAR data we are briefly summarised.

Data

Three different LiDAR campaigns have been flown over Svalbard.

The first LiDAR ice-surface elevations were acquired by NASA in 1996 and 2002 using the Airborne Topographic Mapper 3. Elevations were measured along a limited number of profiles, which followed more or less centre-lines of some of the larger glaciers on Svalbard. Seventeen glaciers in Spitsbergen and Nordaustlandet were surveyed (Figure 13). The technical details of the ATM3 are described by Krabill et al. (2000), and vertical accuracies are estimated to 0.1 m or better (Bamber et al., 2005). Results have been reported in Bamber et al. (2004, 2005) and Kohler et al. (2007).

Glacier	Survey year(s)	Area (km²)
Samarinbreen	1996, 2002	81
Muhlbacherbreen	1996, 2002	56.6
Rechercherbreen	1996, 2002	146
Antoniabreen	1996, 2002	29.3
Sveabreen	1996, 2002	165
Kongsvegen	1996, 2002	108.2
Nordenskiöldbreen	1996, 2002	206.2
Lomonosovfonna	1996, 2002	>1000
Hochstatterbreen	1996, 2002	594.6
Oslobreen	1996, 2002	330.8
Åsgardfonna	1996, 2002	>1000
Dunerbreen	1996, 2002	184.6
Vegafonna	1996, 2002	25.1
Vestfonna	1996, 2002	>1000
Austfonna	1996, 2002	>1000
Sør Franklinbreen	1996, 2002	117.4
Fridtjovbreen	1996, 2002, 2005	50.4
Slakbreen	2003	36.1
Midtre Lovénbreen	2003, 2005	5.2
Grønfjordsbreen	2005	38.3
Austre Bøggerbreen	2005	9.8
Albrechtbreen	2005	66.5
Gullfaksebreen	2005	127.3

Table 6: Svalbard glaciers for which there are published LiDAR measurements. Glacier area either from Hagen et al. (1993) or from NPI glacier database (König et al., in press).

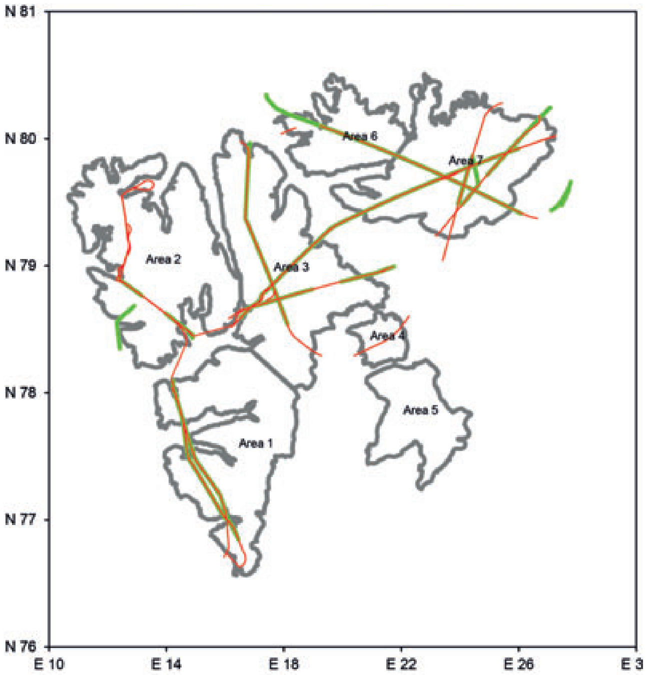


Figure 13. Svalbard, divided into seven regions. NASA LiDAR flight-lines are indicated, green showing the flight-lines from 1996, red from 2002.

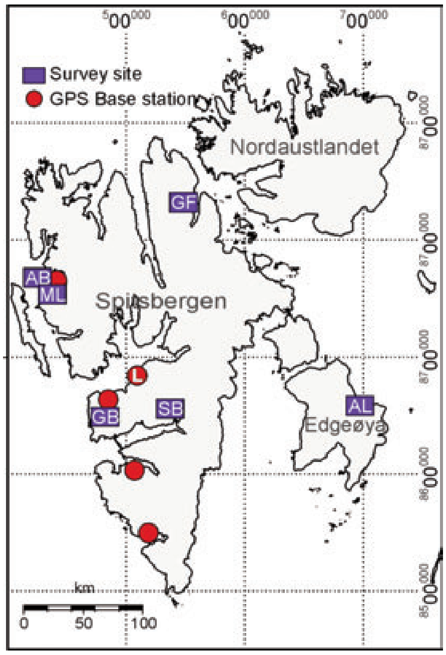


Figure 14. Map showing where whole glacier LiDAR DEMs have been obtained by NERC-ARSF. From James et al. (2012).

The U.K. Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) used an Optech Airborne Laser Terrain Mapper (ALTM) 3033 system to map a number of glaciers in 2003 and 2005 (Table 6). Results have been reported in Kohler et al. (2007), Barrand et al. (2010), James et al. (2012) and Murray et al. (in press).

In connection with the CryoSat CalVal activity, several LiDAR flight campaigns were carried out along profiles over the Austfonna ice cap. Data are available for 2004, 2007, 2011 and 2012. However, the data are not yet published.

Results

The repeated NASA flight lines from 1996 and 2002, using NASA's Airborne Topographic Mapper (ATM), were done on seventeen ice caps and glaciers in the Svalbard archipelago. The results were used to obtain the elevation changes along the flight lines but not to estimate overall mass balance.

Elevation changes were obtained for twelve glaciers and four ice caps over a six-year period between 1996 and 2002. Lower elevation, southerly located glaciers show the largest thinning rates of ~0.5 m/yr, while some of the higher, more northerly ice caps appear to be close to balance. Thus, there appears to be a strong and significant latitudinal gradient in mass balance, with most negative mean elevation change (dh/dt) values in southern Spitsbergen, and less negative values moving northward (Bamber et al., 2005).

The NASA data from the Austfonna ice cap in Nordaustlandet in north-east Svalbard (area 7 in Figure 13) indicate an anomalous, positive ice-surface elevation change for the central accumulation area. The central part of the ice cap showed a thickening of close to 0.5 m/yr. This was explained by a possible increase in precipitation that coincides with the loss of perennial sea ice in the adjacent Barents Sea (Bamber et al., 2004). The thickening of the central parts of Austfonna was later confirmed by ground-base GPS profiles and by satellite data from ICESat giving a similar rate of thickening for the period 2002–2008, with a pronounced interior thickening of up to 0.5 m/yr, at the same time as the margins were thinning at a rate of 1–3 m/yr. Moholdt et al. (2010a) calculated the geodetic surface mass balance of Austfonna to be −1.3 ± 0.5 Gt/yr (or −0.16 ± 0.06 $m_{w.e.}$/yr). The interpretation of the elevation changes was, however, different, as Moholdt et al. (2010a) indicated large dynamic instability in the ice cap as the cause for the elevation changes.

The NERC LiDAR flights in 2003 and 2005 covered several glaciers as shown in Figure 14.The results were quite variable in the different areas, but the overall picture is a clear, thinning of all observed glaciers. Using a combination of maps, DEMs, and LiDAR profiles, Kohler et al. (2007) demonstrated that the average rate of of glacier thinning in western Svalbard has increased during the past decades. An increase in thinning rates implies that the rate of mass loss is increas-

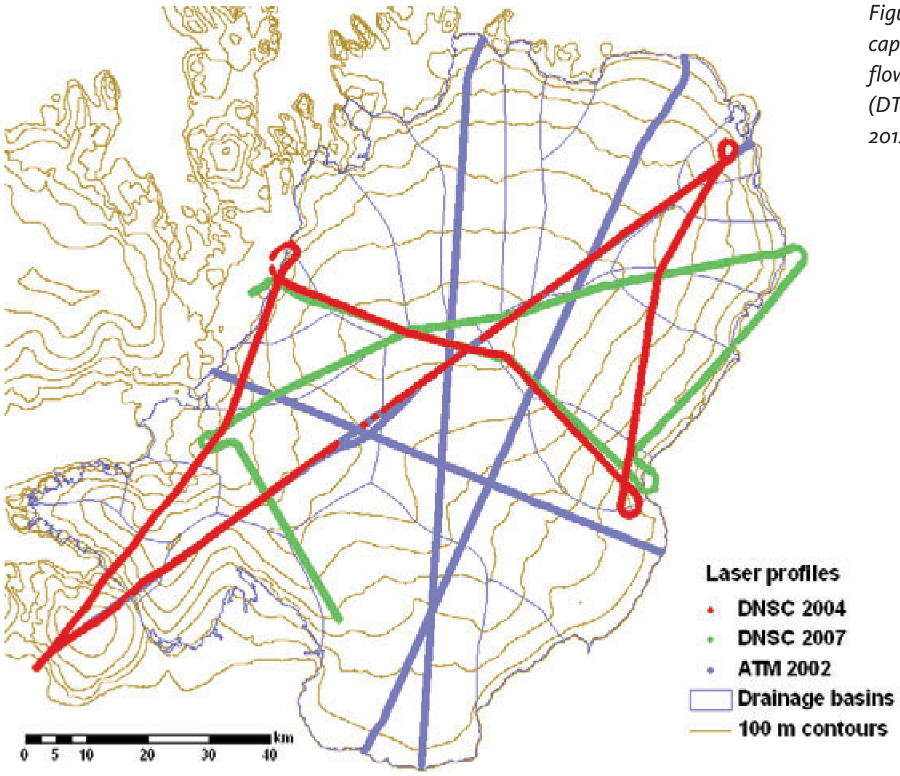


Figure 15. Airborne LiDAR on the Austfonna ice cap (8000 km²). ATM (NASA) 2002 was also flown in 1996 (Bamber et al. 2004). DNSC (DTU) flight lines were repeated in 2011 and 2012.

ing. They focused mainly on two glaciers where data from several periods were available and showed that there has been a clear trend with increasing rate of elevation change since the 1960s. The increased glacier thinning is consistent with climate trends on Svalbard. The thinning rates appear to have increased most significantly on the upper parts of the studied glaciers.

James et al. (2012) analysed the NERC ALTM LiDAR data on all the surveyed glaciers shown in Figure 14. They made time-series of high-resolution glacier DEMs derived from existing aerial photographs and LiDAR data. This revealed a significant increase in the thinning of the Svalbard glaciers from the period 1961–1990 to the period 1990–2005, with a notable increase in thinning rates in the glaciers' upper parts of similar magnitude to that measured at the glaciers' termini, thus confirming the conclusions from Kohler at al. (2007). They also extrapolated the average thinning rates to the archipelago, excluding Nordaustlandet and Kvitøya, by applying the average elevation-change altitude curves to the hypsometry of all Svalbard glaciers and calculated a mass balance of −0.46 ± 0.03 $m_{w.e.}$/yr over the whole time series (1961–2005) with balances before and after 1990 of −0.37 ± 0.07 $m_{w.e.}$/yr and −0.61 ± 0.07 $m_{w.e.}$/yr, respectively. This is more negative than other estimates and may be caused by a bias because the studied glaciers and the mass-balance gradient derived thereof may not be representative of the much larger study area. Nuth et al. (2010) found that the total volume change for Svalbard glaciers (excluding Austfonna and Kvitøya ice caps) over the past 15–40 years before 2007 was −9.71 ± 0.53 Gt/yr or −0.36 ± 0.02 $m_{w.e.}$/yr.

Winter and summer elevation changes derived from geodetic methods both by Moholdt et al. (2010b) and Nuth et al. (2010) indicate that the spatial gradient in mass balance is mainly due to a larger summer season thinning in the west and the south than in the north-east. This result confirms the pattern of change derived from the LiDAR from the NASA ATM and the NERC ALTM.

Conclusions

Jon Ove Hagen, Rene Forsberg and Tómas Jóhannesson

The ice sheets, ice caps and glaciers of the North Atlantic region show large changes. The total ice-mass changes are by far the largest in Greenland, and currently estimated to be 234 ± 20 Gt/yr, corresponding to a global sea-level rise of approximately 0.6 mm/yr. This is more than 3 times the estimated mass loss from Antarctica, but still far from explaining the observed global sea-level rise of about 3 mm/yr, which is dominated by the contributions from smaller ice caps and glaciers, as well as the thermal expansion of the ocean.

The net mass loss of Greenland shows a large interannual variability, with higher mass loss in anomalously warm years, such as 2007, 2010 and 2012. Compared to earlier investigations, new coordinated studies, combining different methods, have narrowed the error estimates of such interannual values for mass loss, and for the first time given potential for a reliable Greenland-wide monitoring of mass loss. At the same time, large-scale airborne laser surveys (NASA's operation IceBridge) provide detailed data on the specific areas of change, notably the large outlet-glacier regions.

For the ice caps and glaciers of the North Atlantic region, although losing mass at a much lower absolute rate (approximately 9.5 Gt/yr for Iceland and 5 Gt/yr for Svalbard), the loss relative to the glacier area is large, and locally of great socio-economic importance, e.g. for hydropower in Norway and Iceland. The smaller ice caps and glaciers are more difficult to monitor from space, especially after the loss of the ICESat laser mission in 2009, although the ESA CryoSat mission should have a potential for monitoring such ice masses (this is currently being investigated, partly in SVALI).

Airborne LiDAR surveying is the preferred tool to obtain high-resolution data of glacier and ice-cap geometry and changes. LiDAR-derived DEMs obtained by repeated flights can accurately monitor volume changes. However, flights collecting data are costly so only limited glacier regions are currently well covered by such data. In Iceland and in some parts of Norway, LiDAR surveys of whole glaciers and ice caps have been carried out, and sometimes even repeated, while in Svalbard and Greenland, repeated surveys are only available on selected profiles. In Norway, the surveys in the period 2007–2011 cover ~800 km² of glaciers, more than 30% of the total glacier area in mainland Norway. In Iceland, almost all the ~11 000 km² of glaciers have been mapped, but repeated LiDAR flights have only been carried out for limited areas.

Mass balances determined from the LiDAR maps and available older glacier surface maps based on aerial photographs and other sources have revealed substantial biases in the traditional mass-balance measurements on several glaciers and ice caps in Iceland and Norway. This indicates that bias correction based on estimated ice-volume changes over extended periods should be an integral part of long-term mass-balance monitoring programmes. Methodologies for incorporating bias correction from geodetic mass-balance estimates into the current mass-balance programmes in Iceland and Norway are being developed. This is particularly important in the cases where glacier-mass balance estimates are used for the design of infrastructures such as hydropower plants, roads or bridges.

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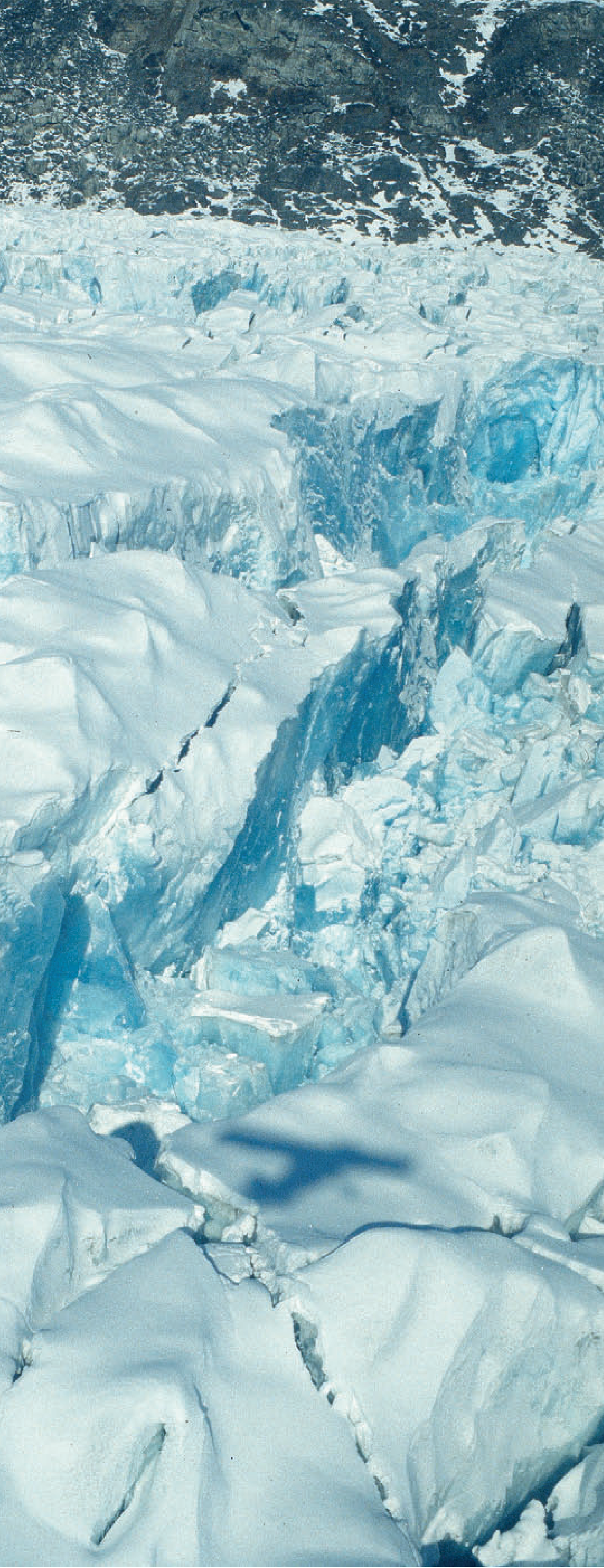

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