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Observations of widespread accelerated thinning in the upper reaches of Svalbard glaciers

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Abstract

The measured rise in eustatic sea level over the 20th century was dominated by mass loss from the world's mountain glaciers and ice caps, and predictions suggest that these fresh water reservoirs will remain significant into the 21st century. However, estimates of this mass transfer to the ocean are based on a limited number of observations extrapolated to represent not only regional changes but often changes across individual glaciers. Combining high resolution elevation data from contemporary laser-altimetry surveys and archived aerial photography makes it possible to measure historical changes across a glacier's entire surface. Here we present a high spatial resolution time-series for six Arctic glaciers in the Svalbard Archipelago spanning 1961 to 2005. We find increasing thinning rates before and after 1990 with elevation losses occurring most notably in the glaciers' upper reaches. In the absence of a clear meteorological driver, we recommend further investigation into a possible albedo amplification of prevailing meteorological trends to explain these higher elevation changes, which could have important consequences on the region's mass balance due to the sensitivity of its hypsometric distribution. However, the strong influence of decadal-scale variability, while explaining lower rates of mass loss reported in earlier studies, highlights that caution must be exercised when interpreting thinning rates when averaged over long periods.

1 Introduction

Reconstructions of global sea level between 1870 and 2004 indicate a 20th century rise of $1.7 \pm 0.3\,\mathrm{mm\,a^{-1}}$ including a $0.013 \pm 0.006\,\mathrm{mm\,a^{-2}}$ acceleration (Church and White, 2006). The most significant contribution from the cryosphere to this rise in sea level has come from the world's mountain glaciers and ice caps (Kaser et al., 2006; Lemke et al., 2007; Cazenave et al., 2009; Berthier et al., 2010). While the significance of these ice masses as a source of future sea level rise is expected to continue into the

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21st century, the complex drivers of glacier behaviour and thus mass balance are still not entirely understood (Meier et al., 2007).

A compilation of global mass balance records of glaciers and ice caps excluding those associated with the Greenland and Antarctic ice sheets reveal sea level contributions of $0.43 \pm 0.19\,\mathrm{mm\,a^{-1}}$ sea level equivalent (SLE) in the last 50 yr with rates of $0.33 \pm 0.17\,\mathrm{mm\,a^{-1}}$ SLE from 1961 to 1990 and $0.77 \pm 0.15\,\mathrm{mm\,a^{-1}}$ SLE from 2001 to 2004 (Kaser et al., 2006). Similar estimates for the period 2001 to 2005 are as high as $1.12 \pm 0.14\,\mathrm{mm\,a^{-1}}$ SLE (Cogley, 2009). The timing of this increased rate of cryospheric mass loss agrees well with observed changes in sea level rise (Merrifield et al., 2009). However, there remains a high degree of uncertainty in mass change estimates and therefore in future sea level predictions due largely to a shortage of long-term glacier mass balance records. Records that do exist often rely on the extrapolation of sparse point or profile measurements to the glaciers and regions they are meant to represent, which is especially problematic in mountainous, coastal regions with strong climatic gradients like the Svalbard archipelago.

The glaciers and ice caps of Svalbard are considered to be an early indicator of Arctic cryospheric response to climate change due to their position at the northern extent of the warm North Atlantic currents and consequent sensitivity to climatic trends (Fleming et al., 1997; Lefauconnier et al., 1999). Thus, there have been a number of important investigations into the mass balance of the archipelago's ice. Early reports of stake and pit records dating back to the 1950s found that several Svalbard glaciers were in negative balance and the authors hypothesized that this had probably been the case since their Little Ice Age maximum in the early 20th century (Hagen and Liestøl, 1990; Lefauconnier et al., 1999). The consistent negative balance suggested that Svalbard glaciers were not in balance with current climatic conditions. However, the lack of significant trend in the rates of mass loss indicated no response to climatic warming. A pan-Arctic study of mass balance also reported high rates of mass loss in Svalbard at three glaciers between 1945 and 1995 (-0.55 m water equivalent (w.e.) $\mathrm{a^{-1}}$) but again without any signal of anthropogenic warming suggesting any such signal could be lost

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in the high annual variability (Dowdeswell et al., 1997). In contrast, more recent studies reported accelerated rates of thinning up to 2005 at three sites in western Svalbard, which were consistent with local climate records (Kohler et al., 2007).

The difficulty in generalising volume or mass balance changes to the archipelago from point, profile or a small number of sites is that it does not account for the ice hypsometric distribution or the strong climatic gradients that prevail in Svalbard (Førland and Hanssen-Bauer, 2003). The importance of these parameters were recognized by Hagen et al. (2003) who applied average net balance/altitude curves derived from direct mass balance measurements, ice cores and ground penetrating radar (GPR) in 13 identified regions around the archipelago. Using data that covered the period 1969 to 1999, they measured a "slightly negative" net balance (-0.014 ± 0.003 m w.e. a^{-1}) with the majority of loss coming from smaller mountain glaciers with the higher elevation ice caps closer to balance. Advances in airborne and spaceborne surveying have significantly improved the distribution of mass balance measurements to better capture regional variability. Centreline airborne laser surveys in 1996 and 2002 over 16 ice caps and glaciers revealed a complex pattern of elevation change with mean changes of -0.19 m w.e. a^{-1} (Bamber et al., 2005). A historical context was provided using old topographic maps and aerial photographs which gave estimated mass changes of -0.30 m w.e. a^{-1} from the mid 1930s to 1990 in the west and southwest regions (Nuth et al., 2007) and -0.36 ± 0.02 m w.e. a^{-1} for the period when 1960s data was compared to the early 2000s laser surveys (Nuth et al., 2010).

The mass balance results of the studies cited above vary considerably and comparison is difficult due to differences in methodology, study area and temporal coverage. However, there is general agreement that the ice of the Svalbard archipelago is significantly losing mass. While reports based on data from the 1990s and earlier found no strong evidence of climatic warming, more recent research suggests that rates of mass loss are increasing and that this is likely attributable to local climate trends. However, these mass balance studies are hampered by a variety of limitations including short time series, low spatial resolution and/or poor distribution of sample sites. Recent evidence suggests that sparse direct or indirect mass balance data are not necessarily representative of regional-scale or even glacier-wide mass changes (Barrand et al., 2010; Berthier et al., 2010). As yet no study of Svalbard mass balance has been able to provide: (i) a distributed sample of study sites; (ii) long-term time series (up to 44 yr); (iii) over several epochs; (iv) using high resolution, full-area topographic data that does not rely on extrapolation.

In this paper we combine historical aerial photographs and contemporary airborne laser altimetry (lidar) surveys to produce a minimum of three epochs of high resolution DEMs for six sites around Svalbard. The resulting volume change measurements are produced from tens of thousands of individual change measurements for each site that cover the full glacier width without extrapolation. This approach enables the resolution of spatially variable changes that are not necessarily represented by centreline profiles and therefore will provide improved understanding of glacier mass balance in the Svalbard Archipelago.

2 Data and methods

2.1 Topographic modelling

We targeted a number of potential sites around the Svalbard archipelago for topographic modelling. Site selection was based on a number of factors including spatial distribution, elevation range, aspect, and suitability for photogrammetry. Since photogrammetry is dependent on stable surfaces from which ground control points (GCP) can be measured in photographs, potential sites were limited to those whose geometry provided a sufficient distribution of exposed bedrock and stable depositional features. Aerial photographic coverage of Svalbard has been frequent but incomplete with only the 1990 campaign offering near complete coverage of the archipelago. Thus, during the site selection process we identified glaciers where at least two epochs of photographic coverage were available. However, because of the difficulty of processing and typically poor image quality, we opted to exclude the high-oblique photographs from the 1930s. Since the methods employed here cannot account for mass losses from tidewater calving or surging glacier dynamics we limited sites to land-terminating, non-surge-type glaciers. Therefore, the results presented below do not account for any dynamically-driven changes in glacier volume in Svalbard although like Nuth et al. (2007) we assume these to be small compared to elevation changes (Paterson, 1994).

Of the sites selected, high resolution lidar surveys were successfully undertaken for 6 glaciers (Fig. 1 and Table 1). These glaciers included Austre Brøggerbreen (AB), Albrechtbreen (AL), Grønfjordbreen (GB), Gullfaksebreen (GF), Midtre Lovénbreen (ML) and Slakbreen (SB). Surveys were undertaken during summer 2003 and 2005 by the Airborne Research and Survey Facility (ARSF) of the U.K.'s Natural Environment Research Council (NERC) using an Optech ALTM 3033 laser scanner that recorded first and last laser return and accompanying 8-bit laser return intensity. Post-processing of lidar data required coincident, high quality global positioning system (GPS) data from base stations within ∼50 km of the aircraft, which we installed and operated during the field campaigns (Fig. 1). While AL and GF were both beyond this range, comparison with lidar processed using advanced long-baseline GPS processing produced only negligible improvement in data quality. All lidar post-processing, when laser data are combined with GPS and onboard navigation data, was carried out at the Unit for Landscape Modelling, University of Cambridge.

As an initial data quality control, lidar data points with low laser return intensity were checked for errors since lidar elevation quality are highly dependent on signal-to-noise ratio (Wehr and Lohr, 1999) and thus are more likely to represent erroneous elevation measurements. However, it is important to check lidar data quality independently, typically against differential GPS (dGPS), for systematic errors. The ARSF lidar were compared to on-ice dGPS at two sites in NW Svalbard (Barrand et al., 2009, 2010) where differences between the surfaces were found to average ±0.16 m. However, these data were collected over a 6 day period around the date of lidar acquisition and

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thus were influenced by the changing ice surface. Lidar data quality was more appropriately assessed at the local airport runway (L, Fig. 1) whose surface had been surveyed with dGPS. The comparison confirmed that the error of the lidar data were within the manufacturers specifications of ±0.10 m which we adopt for this study.

Historical DEMs were generated using archived stereo aerial photography held by the Norwegian Polar Institute (Table 1), which were processed in the SOCET SET digital photogrammetry suite. The use of a calibrated metric camera during each historic mission meant that internal camera errors could be modelled and removed to improve DEM quality. GCPs were extracted from lidar DEMs on stable land surfaces around each site with the aid of image enhancement techniques like relief-shading and contrast stretching. To compensate for the lower quality of lidar-derived GCPs compared to traditional survey-quality ground control, we collected a larger number of GCPs (40 to 80 points) and tie points (>100 points) than would traditionally be used in photogrammetric processing in order to increase the measurement redundancy in the adjustment of the block of photographs (James et al., 2006; Barrand et al., 2009). DEMs were extracted automatically from the adjusted photographs on a 10 m grid where image contrast permitted good autocorrelation between images. In areas of poor contrast (i.e. where surfaces were snow covered or in dark shadow) DEM points were measured manually where possible using the software's 3D-editing capabilities.

Since glacier surfaces are not stable over time, the assessment of photogrammetric DEM quality was not straightforward. Typically, DEM quality is measured in terms of: (i) the fit of the measured points and camera calibration parameters to the block adjustment solution given in root mean square error (RMSE) of X, Y and Z coordinates; and (ii) the comparison of the DEM to an independent check data set (Wolf and Dewitt, 2000). It was not possible to collect a temporally coincident DEM over reasonable timeframe using ground based methods due to the remoteness of the glaciers and the speed with which their surface can change. Therefore, we assessed the DEM quality by comparing the lidar DEM at an off-ice test site characterised as topographically stable and with similar textural and relief characteristics to the ice. The photogrammetric block

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adjustment suggested a good fit of the measured parameters to the block solution with average RMSE of the ground control in X, Y and Z of 1.33, 1.50 and 0.43 m, respectively. The comparison of the photogrammetric DEMs to the lidar using the test site yielded errors ranging from ±0.25 m in good contrast areas to ±1.5 m in poor contrast areas. Since there is a degree of spatial autocorrelation of elevation errors in the differenced DEMs (Rolstad et al., 2009), we conservatively adopted the latter for the photogrammetric DEM error in the following analysis.

2.2 Sequential DEM analysis

Two periods of elevation and volume change were measured across our sample glaciers using sequential DEM analysis approximately covering the periods 1961–1990 and 1990–2005 (Table 1). These epochs, which were available at all six sites, were the main focus of this study. However, an photographs from 1977 was also available at AB, ML and SB providing an intermediate period over which to measure elevation and volume changes.

Differencing DEMs for volume change measurement, known as the geodetic method, is the most accurate method over long periods (Cox and March, 2004) and provides measurement of elevation and volume changes across a glacier's full width. This approach eliminates the need for extrapolation of point or profile measurements, which is especially important in the glaciers' higher reaches where shadowing and drifting snow can make surface elevation changes more variable at a given elevation. It is ideal for application in Svalbard where climate-driven elevation changes are large compared to ice fluxes and density changes (Kohler et al., 2007).

2.3 Svalbard hypsometry

To put our results in the context of the area-altitude distribution of the archipelago's ice, we measured Svalbard's hypsometry for each drainage basin using digitized drainage basins from Hagen et al. (1993) and the Norwegian Polar Institute 100 m Svalbard

DEM. Drainage basins were geocoded using map grid intersections and converted to binary masks which were applied to the DEM using only on-ice points. From this ice-DEM, hypsometry curves were produced for each drainage basin.

3 Results

Our sequential DEM analysis revealed changes in frontal position and elevation consistent with glaciers adjusting to a warming climate with thinning greatest at the retreating termini and decreasing up-glacier (Fig. 2). Terminus position data in Table 2 show that all six of the glaciers experienced significant retreat over the period of observation.

Elevation change statistics (Table 3) show maximum elevation changes (Δh_{max}) between 1961–2005 were recorded at SL and GB, which both lost more than 90 m of elevation over the study period at their 2003 and 2005 termini, respectively. Even the northeast site (GF), in an area thought to be closer to balance (Nuth et al., 2010), experienced elevation losses of over 50 m. The site with the highest mean annual elevation change ($\overline{\dot{\Delta h}}$), was low-lying AL on the eastern island of Edgeøya, which lost an average of $1.00 \pm 0.03\,\text{m}\,\text{a}^{-1}$ over its surface. Elevation changes across all our sites averaged $-0.59 \pm 0.04\,\text{m}\,\text{a}^{-1}$ between 1961–2005. The terminal retreat and elevation losses we observe suggest that all six of our sites have been in significant negative mass balance over the period of observation.

Pre- and post-1990 $\overline{\dot{\Delta h}}$ for each site are given in Table 4 and reveal a significant increase of thinning between these periods. Average $\overline{\dot{\Delta h}}$ increased from $-0.52 \pm 0.09\,\text{m}\,\text{a}^{-1}$ before 1990 to $-0.76 \pm 0.10\,\text{m}\,\text{a}^{-1}$ after 1990 representing a 46 % increase in thinning rates between the two periods. Increases in thinning rates over these periods of similar magnitude were previously reported for parts of western Svalbard (Kohler et al., 2007). However, the inclusion of an intermediate epoch of photographs flown in 1977 at AB, ML and SB illustrates the difficulty of interpreting elevation changes between two discrete points in time especially when separated by long

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periods. The rates of elevation change from Table 4 for AB, ML and SB imply a uniform annual thinning rate before 1990 that is significantly lower than after 1990. However, Fig. 3 shows that the lower thinning rates of the earlier epoch at AB (and to some extent ML) are the result of lower thinning rates during the period 1977–1990. Conversely, SB experienced a fairly constant increase in thinning over the whole period.

The most important finding from our analysis is that some of the greatest increases in $\overline{\Delta \dot{h}}$ occurred in the higher reaches of the glaciers in areas of former snow accumulation. These findings were possible because of the high resolution, full-width DEMs which provided a detailed analysis of elevation changes by altitude without the need for extrapolation. As expected, elevation changes were greatest at lower altitudes with maximum changes reaching almost $-2.5\,\mathrm{m\,a^{-1}}$ at SB (Fig. 4). Plotting these changes in $\overline{\Delta \dot{h}}$ against elevation for each site emphasises how the glaciers' upper reaches are consistently experiencing similar or indeed greater increases in thinning rates than at their termini (Fig. 5).

4 Discussion

4.1 Meteorological context

A strong link between net mass balance and both summer temperatures and winter precipitation has been demonstrated in Svalbard (Hagen and Liestøl, 1990; Lefauconnier et al., 1999) and thus we interpreted our results in the context of the local meteorology using data from the Longyearbyen meteorological station (L, Fig. 1). Between 1961 and 2005, annual mean temperature at Longyearbyen increased by 1.8 °C. However, high interannual and decadal variability means long-term trends must be large in order to be statistically significant (Førland and Hanssen-Bauer, 2003). Alternatively, the June, July, August (JJA) mean temperature at Longyearbyen increased significantly (with 95 % confidence) by $0.02\,^{\circ}\mathrm{C\,a^{-1}}$ between 1961–2005 (Fig. 6). No significant

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trend was measured during 1961–1990 but JJA temperatures after 1990 increased significantly by 0.07 °C a^{-1}. These warming temperature trends are likely driving the acceleration of thinning at low elevations but they cannot independently account for the increased rates of change we see at higher elevation.

To explain the intermediate period of lower thinning rates, we calculated the average annual positive degree day (PDD) for each period and compared them to the mean PDD for the whole time series (Fig. 6). This comparison revealed that the 1980s was indeed a period of significantly cooler summer temperatures than either the preceding or following period. While this accounts for the mass loss at AB and ML during this period, this appears to have not occurred further south at SB where there is no evidence of glacier response to this cooler period. Coincidentally, the Svalbard mass balance research published in the 1990s was based on time series that terminated around the end of this cold period, which would explain the lack of trend in rates of mass loss for many of these earlier studies. Clearly these results are indicative of the extreme regionality of Svalbard's climate and the strong sensitivity of glaciers to even decadal meteorological trends. There is clearly a need to interpret geodetic volume and mass changes in the context of the prevailing meteorological conditions at the time of each epoch in the time series.

An analysis of Longyearbyen precipitation data revealed a strong post-1990 negative trend in total precipitation (−4.4 mm a^{-1}) but no significant trend over the whole period. In contrast, solid precipitation decreased significantly since 1961 (−0.9 mm a^{-1}) with a stronger negative trend since 1990 (−3.0 mm a^{-1}). To put this in context, at these rates annual precipitation in 2005 was predicted to be ~45 mm less (750 mm snow equivalent assuming fresh snow density of 60 kg m^{-3}) than it was in 1990 in a region with already relatively low accumulation rates of less than 1 m w.e. a^{-1} (Hagen et al., 2003a).

Clearly, these trends in precipitation and temperature will have a significant effect on the amount and distribution of accumulation and explain some of the thinning observed in the upper reaches of our study sites. However, an additional elevation change curve at Midtre Lovénbreen (ML) for the period 2003–2005 (Fig. 4) displays the same pattern of increased high elevation thinning found elsewhere during two years when the entire glacier surface was essentially snow-free at the time of data acquisition. Therefore, we conclude that increased thinning rates in the glaciers' upper reaches cannot be fully explained by differences in accumulation rate driven by temperature and precipitation trends.

4.2 Role of Albedo

Kohler et al. (2007) suggested an increase in albedo might be responsible for higher thinning rates at higher elevations at ML. The role of surface albedo during the 2010 Greenland melt season was recently demonstrated (Tedesco et al., 2011) and our observations of widespread enhanced thinning at higher elevations are consistent with a decrease in albedo attributable to a loss of summer snow cover from higher summer temperatures and lower winter precipitation. The loss of a reflective and insulating layer of snow amplifies these prevailing meteorological trends and has a significant and immediate impact on albedo since bare ice absorbs about three times as much of the Sun's energy as snow (Paterson, 1994). The so-called albedo feedback is closely interconnected with the balance-altitude feedback, where surface lowering from melt or from decreasing winter accumulation, exposes ice to warmer altitudes thereby enhancing melting. Both were described by Kaser et al. (2006) as two of the most important feedbacks reinforcing the response of glacier mass wastage to post-1970 climate warming. The decreasing albedo from the deposition of fossil-fuel black carbon is thought to be responsible for over two thirds of Arctic warming since the mid-1970s (Shindell and Faluvegi, 2009). Measurements of atmospheric black carbon near Ny Ålesund in northwest Svalbard were lower between 1979–1989 than during both 1990–1992 (Heintzenberg and Leck, 1994) and 1997–2007 (Eleftheriadis et al., 2009) and thus could additionally have contributed to the albedo feedback. However, inconsistencies in measurement approach between the different periods of study make it difficult to attribute this difference conclusively to changes in long term atmospheric black carbon.

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4.3 Hypsometric context and upscaling

Independent of their cause, the changes we have observed have important implications for the mass balance of the archipelago. Critically, Svalbard's ice is especially sensitive to changes in the equilibrium line altitude (ELA) due to its hypsometric distribution which places the bulk ofSvalbard's ice close to the current estimated ELA (Fig. 7). Consequently, even small changes in the ELA will have a large impact on the mass balance of the archipelago (Hagen et al., 2003b). To illustrate, at its estimated average altitude of ∼460 m a.s.l., a 50 m increase in the ELA (or an equivalent surface lowering) would result in a loss of ∼3000 km^2 of accumulation area, which is equal to ∼8 % of Svalbard's ice-covered area and ∼18 % of the accumulation zone according to most recent estimates (Hagen et al., 1993). Additionally, current estimates of Svalbard's ELA and hypsometry are based largely on the 1990 aerial survey and our results show that Svalbard's ice has already undergone significant changes since that time. It is clear from Fig. 7 that in the later period, no accumulation area exists at all elevations included in this study.

Finally, to put our results in context of other Svalbard mass balance studies, we upscaled our average thinning rates to the archipelago, excluding Nordaustlandet and Kvitøya, by applying the average elevation change-altitude curves to our hypsometry in 50 m elevation bins (Fig. 7). Using a ice density of 918 kg m^{-3} and assuming that changes at elevations above our study sites were within the error limits of this analysis, we calculated a mass balance of -0.46 ± 0.03 m w.e. a^{-1} over the whole time series (1961–2005) with balances before and after 1990 of -0.37 ± 0.07 m w.e. a^{-1} and -0.61 ± 0.07 m w.e. a^{-1}, respectively. There is difficultly in comparing the results between different mass balance studies due to the varying time scales and different areas of focus especially given the strong regionality of the area. We expect our upscaled mass balance estimates to overestimate mass contributions due to the necessary omission of the east coast ice caps where rates of mass loss are lower and the high elevation ice caps that are believed to be in positive balance (Moholdt et al.,

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2010). As such, our estimate for the whole study period is higher than that of Nuth et al. (2010), which looked at a similar period but included the large Vestfonna ice cap in north eastern Svalbard. However, our measured increase in mass loss from pre- to post-1990 is similar in magnitude to the increase in sea level contributions from glaciers and ice caps globally reported by Kaser et al. (2006) for similar periods.

For comparison to results from the Gravity Recovery and Climate Experiment (GRACE) satellite mission, we convert our geodetic mass balances using ice area from Nuth et al. (2010) to $-11.1 \pm 0.8\,\mathrm{Gt\,a^{-1}}$ from 1961–2005 and increasing from -9 ± 2 to $-15 \pm 2\,\mathrm{Gt\,a^{-1}}$ before and after 1990, respectively. Our post-1990 mass loss (1990–2005), while significantly higher than the Wouters et al. (2008) calculation of $-8.8 \pm 3\,\mathrm{Gt\,a^{-1}}$ between February 2003 and January 2008, is in agreement with the $-15.5 \pm 2.4\,\mathrm{Gt\,a^{-1}}$ calculated for the period January 2003 to January 2009 using a destriping-filtered GRACE solution (Mémin et al., 2011), which suggests similar rates of mass loss over the two decades. However, our results from the intermediate DEM epoch as well as recent reports of non-linear trends in ice mass change over periods as little as 3 yr from superconducting gravimeter time series (Omang and Kierulf, 2011) warns against comparing mass change rates for different time periods.

5 Conclusions

Our high resolution time series of glacier DEMs derived from archived aerial photographs and lidar reveal a significant increase in thinning of Svalbard glaciers from the period 1961–1990 and 1990–2005 with a notable increase in thinning rates in the glaciers' upper reaches of a similar magnitude to that measured at the glaciers' termini. Analysis of local meteorological data reveal that while a positive trend in summer temperature and a negative trend in winter accumulation are no doubt behind the overall increase in thinning, we find no metrological explanation for this high elevation thinning. However, this trend may be explained by an amplification of recent climatic trends by albedo feedback due to a loss of snow cover, which has been identified as a main

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factor in the Arctic amplification of climate warming (Serreze et al., 2002; Lemke et al., 2007) and recently demonstrated in Greenland (Tedesco et al., 2011). If this is the case, our study provides the first widespread observation of this amplification effect on the geometry and area-altitude distribution of Arctic glaciers. Taken in the context of Svalbard's high sensitivity to changes in the ELA, the net effect will be a loss of a significant proportion of the former snow accumulation area to summer ablation. However, our analysis of elevation changes during a colder period in the 1980s showed that decadal-scale meteorological variability, while having a significant impact on glacier surface changes, might be very local in Svalbard, which complicates the interpretation of changes in glacier geometry and mass results when averaged over long time periods and from only a few records. Our findings highlight a need for continued high resolution monitoring and lend support to conclusions that acceleration in the melt of mountain glaciers and ice caps is partly responsible for post-1990 acceleration in sea level rise (Merrifield et al., 2009) and that albedo feedbacks are reinforcing the glacial response to recent climate warming (Kaser et al., 2006).

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Table 1. Acquisition details of airborne laser altimetry (lidar) and photographic surveys.

		Lidar		Photography	
	Elevation Range (m a.s.l.)	Acquisition Date	# of Points (x 10^6)	Acquisition Date	Scale
Austre Brøggerbreen (AB)	90–650	06-07-2005	31.8	28-07-1966 05-08-1977 20, 25-08-1990	1:50 000 1:50 000 1:50 000
Albrechtbreen (AL)[a]	50–300	14-08-2005	42.0	08-1971[b] 22, 27-07-1990	1:30 000 1:50 000
Grønfjordbreen (GB)	35–700	07-07-2005	54.4	19-08-1969 02-07-1990	1:50 000 1:50 000
Gullfaksebreen (GF)[a]	65–890	09-07-2005	98.7	07, 09-07-1961[c] 30-07-1966 22, 28-07-1990	1:45 000 1:50 000 1:50 000
Midtre Lovénbreen (ML)	75–650	09-08-2003 05-07-2005	23.5	28-07-1966 05-08-1977 20, 25-08-1990	1:50 000 1:50 000 1:50 000
Slakbreen (SB)	180–1000	08-08-2003	46.3	23-25-08-1961 16-08-1977 22-07-1990	1:40 000 1:20 000 1:50 000

[a] Photographic and lidar coverage do not cover the whole catchment area of these glaciers whose highest elevations include featureless ice sheet which is unsuitable for photogrammetry.
[b] Exact acquisition date unknown.
[c] Early epoch coverage was spread over two campaigns. Elevation differences over this period in the area of overlap were within the measurement error and thus the 1961 photographs were merged with the 1966 block of photographs.

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Table 2. Site terminus position relative to earliest epoch along dotted lines shown in Fig. 2.

		Terminus Retreat ($m\,a^{-1}$)		
	Data Coverage	Whole Period	Pre-1990	Post-1990
AB	1966–2005	22	25	35
AL	1971–2005	42	33	64
GB	1969–2005	30	38	29
GF	1966–2005	12	11	19
ML	1966–2005	12	13	10
SB	1961–2003	32	20	59

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Table 3. Glacier elevation and volume change statistics derived from full-coverage DEM differencing over the full period of data coverage.

Site	Study Period	$\overline{A}$ (km^2)	Δh_{max} (m)	$\overline{\Delta h}$ (m)	$\overline{\Delta \dot{h}}$ (ma^{-1})	ΔV (x10^5 m^3)	$\Delta \dot{V}$ (x10^4 m^{3}a^{-1})
AB	1966–2005	10.96 ± 0.04	−67 ± 1	−25 ± 1	−0.64 ± 0.03	−2.73 ± 0.11	−0.70 ± 0.03
AL	1971–2005	28.56 ± 0.09	−73 ± 1	−34 ± 1	−1.00 ± 0.03	−9.71 ± 0.29	−2.86 ± 0.09
GB	1969–2005	35.83 ± 0.12	−94 ± 1	−31 ± 1	−0.87 ± 0.03	−11.3 ± 0.37	−3.13 ± 0.10
GF	1966–2005	42.98 ± 0.14	−53 ± 1	−10 ± 1	−0.25 ± 0.03	−4.17 ± 0.44	−1.07 ± 0.11
ML	1966–2005	5.47 ± 0.02	−66 ± 1	−17 ± 1	−0.44 ± 0.03	−0.94 ± 0.06	−0.24 ± 0.01
SB	1961–2003	40.18 ± 0.13	−102 ± 1	−13 ± 1	−0.32 ± 0.02	−5.34 ± 0.41	−1.27 ± 0.10

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Table 4. Mean annual elevation change rates ($\overline{\Delta \dot{h}}$) for pre-1990, post-1990 and whole period of data coverage.

		$\overline{\Delta \dot{h}}$ (ma^{-1})		
		Whole Period	Pre-1990	Post-1990
AB	1966–2005	−0.64 ± 0.03	−0.62 ± 0.09	−0.74 ± 0.10
AL	1971–2005	−1.00 ± 0.03	−0.95 ± 0.11	−1.21 ± 0.10
GB	1969–2005	−0.87 ± 0.03	−0.74 ± 0.10	−1.17 ± 0.10
GF	1966–2005	−0.25 ± 0.03	−0.23 ± 0.09	−0.28 ± 0.10
ML	1966–2005	−0.44 ± 0.03	−0.38 ± 0.09	−0.58 ± 0.10
SB	1961–2003	−0.32 ± 0.03	−0.22 ± 0.07	−0.55 ± 0.12

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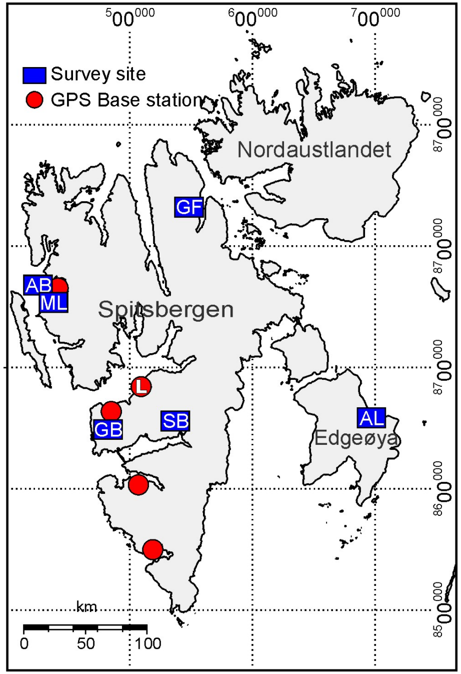

Fig. 1. Sites included in the study are Austre Brøggerbreen (AB); Albrechtbreen (AL); Grønfjordbreen (GB); Gullfaksebreen (GF); Midtre Lovénbreen (ML); and Slakbreen (SB). GPS base station locations are shown by red circles. Meteorological data were collected at Longyearbyen (L). The station at Longyearbyen was relocated ∼6 km from the town site to its current airport site in 1975. Map coordinates for this and all subsequent figures are in meters, UTM Zone 33X.

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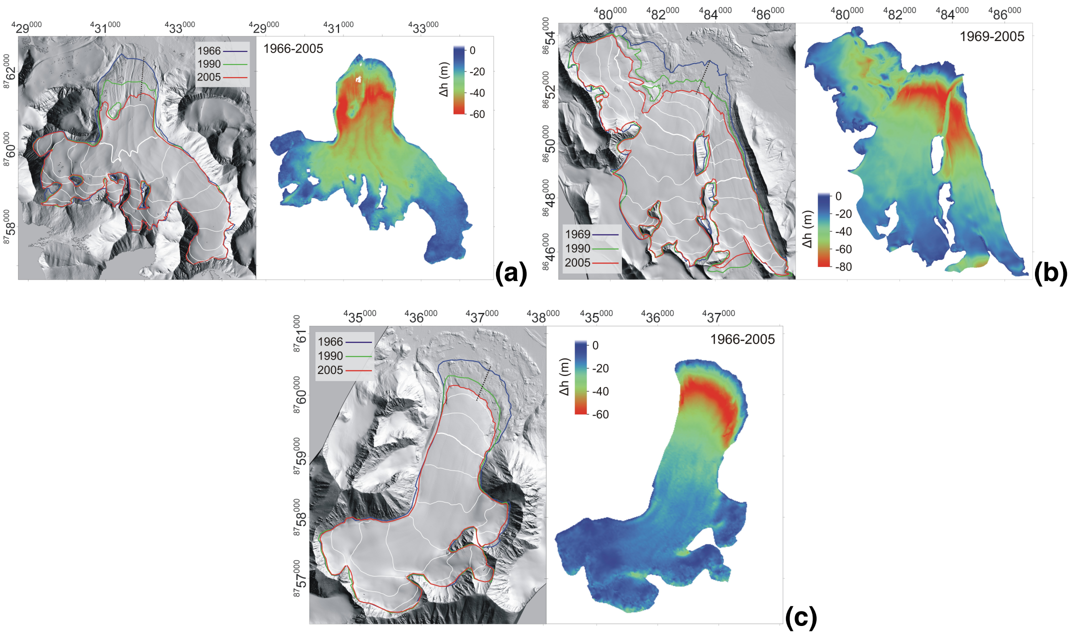

Fig. 2. Contemporary DEMs and sequential DEM analysis results (showing Δh) for: **(a)** Austre Brøggerbreen (AB) **(b)** Grønfjordbreen (GB); **(c)** Midtre Lovénbreen (ML); **(d)** Albrechtbreen (AL); **(e)** Gullfaksebreen (GF); and **(f)** Slakbreen (SB). Top or left-hand panel shows the shaded-relief DEMs of 2005 lidar (2003 for SB) with elevations plotted on a 5 m grid and glacier outline overlays. Contour interval is 50 m with bold contour at 300 m. Elevations in meters above sea level. Bottom or right-hand panel shows accompanying elevation change map on 10 m grid over the full period of data coverage.

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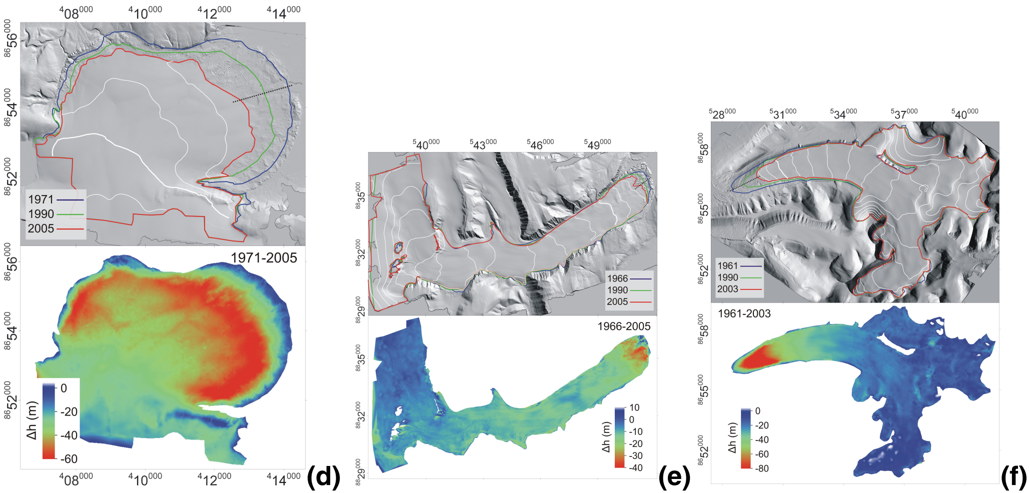

Fig. 2. Continued.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

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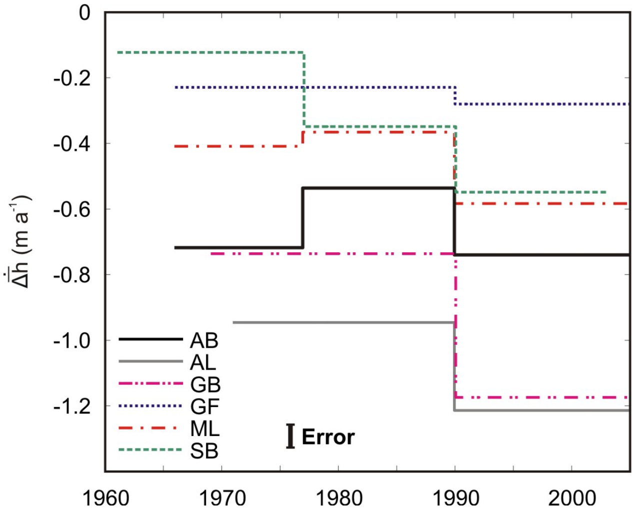

Fig. 3. Average annual elevation change ($\dot{\overline{\Delta h}}$) over all periods including the intermediate epoch at AB, ML and SB.

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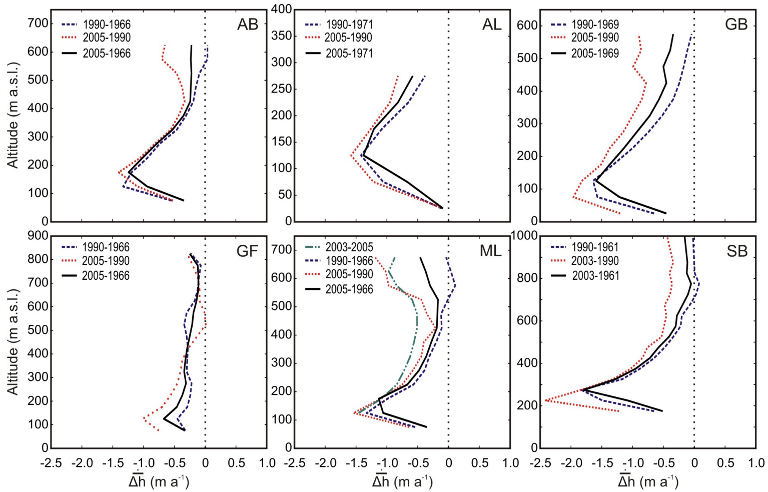

Fig. 4. Elevation change curves for the six survey sites, shown in 50 m altitude bins. Decreased thinning rates at lowest elevations reflect the thinning of the front to zero ice thickness between epochs and thus terminal retreat.

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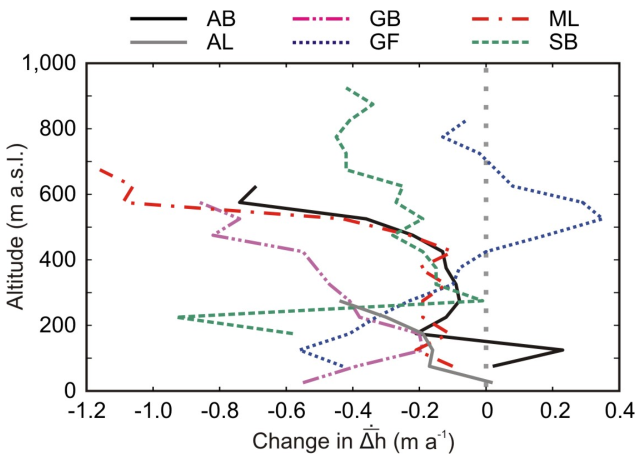

Fig. 5. Differencing elevation change rates from pre-1990 and post-1990 periods by altitude highlights the speedup in thinning is greatest at higher elevations with only GF in the far NE as the exception.

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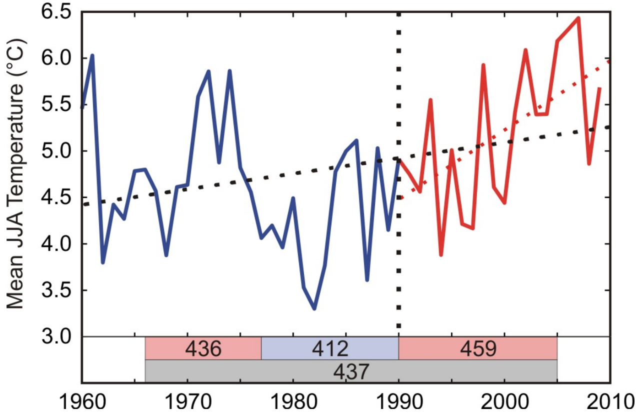

Fig. 6. JJA Temperature data from the Longyearbyen station (L, Fig. 1). Trend for whole period (black dotted line) is 0.02 °C a^{-1} whereas the trend for the post-1990 period was 0.07 °C a^{-1} (at 95 % confidence). No significant trend was measured for the pre-1990 period. Average PDD for each period and for the whole study period at Longyearbyen meteorological station (L, Fig. 1) are given at the bottom of the main panel.

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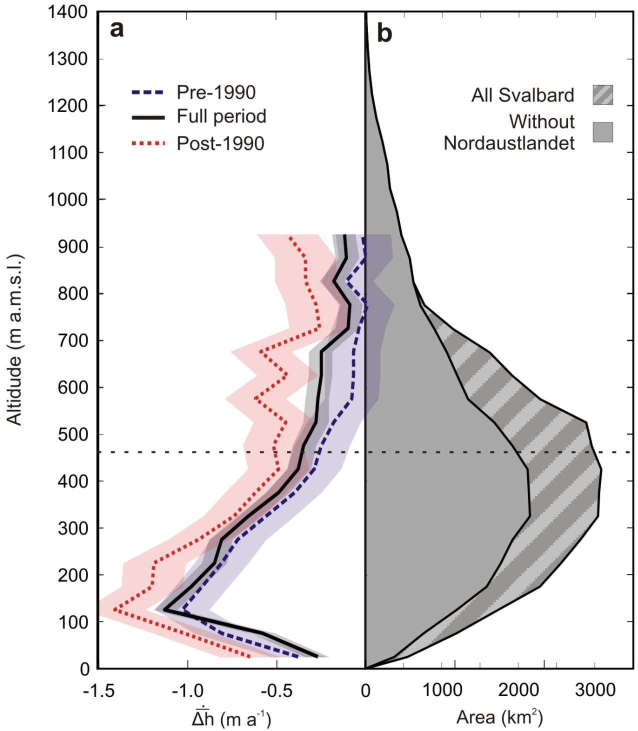

Fig. 7. Hypsometric context of Svalbard elevation changes. **(a)** Elevation change with altitude is plotted to show annual changes before and after 1990 and over the whole period of data coverage. Error estimates are represented by the shading around each curve. The horizontal dashed line is the current estimated average ELA of ~460 m a.s.l. from Hagen et al. (2000b); **(b)** Svalbard's hypsometry plotted inclusive and exclusive of the ice of Nordaustlandet.

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