Geodetiske data til bestemmelse av volumendringer av breis på Jan Mayen

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Cecilie Rolstad Denby: Determination of glacier ice volume changes from geodetic data from Jan Mayen

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An increase in global temperature will lead to glacier volumes changes, and geodetic mass balance measurements are essential for determining the contribution from glaciers to the global sea level. The total area of Jan Mayen is 373 km^2 , and of these are 105 km^2 glaciated. The mapping history of Jan Mayen started in 1620, and in 1949 the Norwegian Polar Institute (NPI) recorded oblique aerial photographs for production of the first modern topographic map. NPI recorded 43 km^2 from vertical aerial photographs in 1975, and the SPOT 5 stereoscopic survey of Polar Ice, SPIRIT, provided newer elevation data in 2008. These available topographic data sets have been assessed for accuracies and ice volume changes. This analysis suggests a relatively stable ice volume in the period. However, together with the newly digitized glacier boundaries in a 2002 Landsat ETM+ image, the analysis also shows that accurate data (e.g. laser scanning) covering the entire glaciated area is needed to utilize the now 63 year old topographic dataset for a complete geodetic glacier mass balance assessment.

Key words: geodetic mass balance, glaciology, topographic mapping

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Introduction

Climatic changes lead to changes in volume of ground based glacier ice, which induce changes in global sea level. The IPCC AR4 2007 reports a 100-year linear trend (1906-2005) of 0.74°C increased global surface temperature. The report also states; 'Global average sea level has risen since 1961 at an average rate of 1.8 [1.3 to 2.3] mm/yr and since 1993 at 3.1 [2.4 to 3.8] mm/yr, with contributions from thermal expansion, melting glaciers and ice caps, and the polar ice sheets'. The volcanic island Jan Mayen (71°N, 8°30'W, area: 373km^2) is situated in the North Atlantic Ocean between Iceland and Svalbard (Fig. 1, A), with a glaciated area of about 105 km^2. Since the mid-1990s a reduction in ice volume has been observed for glaciers on Iceland (Gudmundsson and others, 2011, Pope and others, 2010, Björnsson and Pálsson, 2008), and on the western and southern parts of Svalbard (Nuth and others, 2010). In light of the observed changes in global surface temperature and ice volume at Svalbard and Iceland, it is of interest to determine recent volume changes of the twenty glaciers flowing down from the central Berenberg crater (2277 ma.s.l.).

Ice volume changes, or the so called mass balance of glaciers, can be measured by three methods; 1) the direct glaciological method, where melt and snow accumulation is measured annually on stakes drilled into the ice and by snow probing, 2) geodetic mass balance where repeated elevation data covering complete drainage basins is subtracted to estimate volume changes, or 3) direct measurements of mass changes from gravity measurements. The direct glaciological mass balance of one Jan Mayen glacier, Sørbreen (area: ~15 km^2, Fig. 1 B), was measured in 1972 to 1974, and 1976 to 1977 (Hagen 2004, Orheim 1976), and new measurements were initiated in connection to the third International Polar Year in 2007–2008 (Hulth and others, 2010). However, these sparse surface mass balance data do not give adequate information of possible ice volume changes. Repeated surface elevation data over long time spans are more suited for assessing the mass changes of Jan Mayen glaciers, but the accuracy of the existing topographic datasets must be considered carefully as they are measured using very different photogrammetrical methods. Gravity measurements are available from satellite, however the glaciated area and the mass changes are too small on Jan Mayen to be recorded by these instruments. Some aerial gravity measurements have been conducted from Jan Mayen by the Norwegian Mapping Authority, but they cover mostly the surrounding ocean areas.

Previous observations show variations in the area extent of Jan Mayen glaciers. Maps and sketches of the front position of Sørbreen exist from 1623, and the glacier extended to the sea in 1861 and 1876 (Anda and others, 1985). They report two distinctive Holocene glacier advances, one at 2500 BP and a maximum advance at AD 1850. The smallest extent of the glacier is documented in oblique aerial photographs in 1949, where the front had retreated 1200 m from the coast line. The glacier front advanced a few hundred meters during the 1960s. In 2008 field observations showed that the front position was very close to the 1949 position (Hulth and others, 2010).

With the changes in climate, long term records of geodetic data have become increasingly valuable. In this paper the history of data collection is briefly described, and the accuracy of suited datasets for glacier ice volume changes are assessed, and new measurements are suggested.

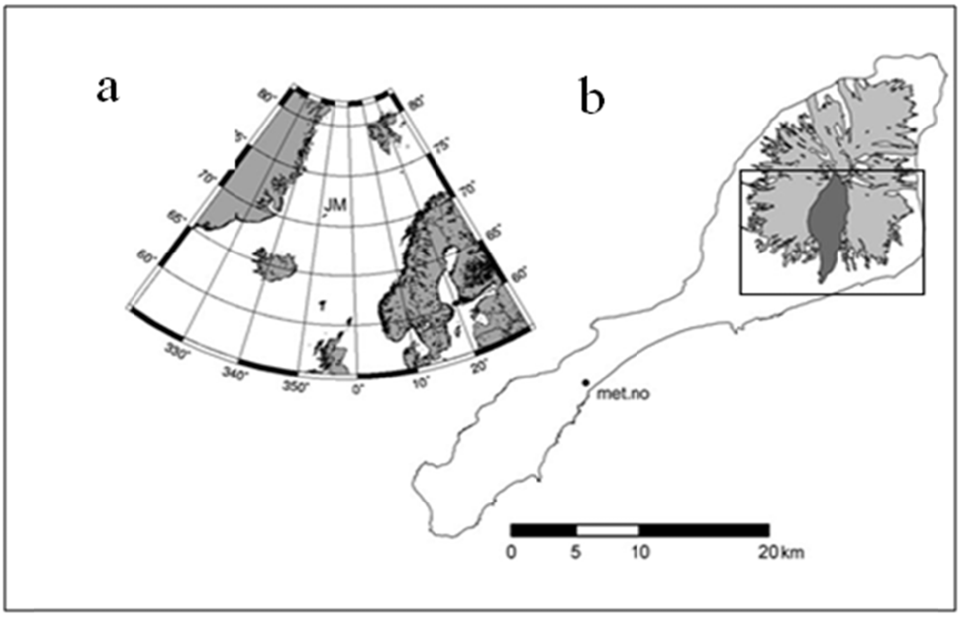

Fig. 1. A: Location of Jan Mayen (JM) 550 km northeast of Iceland. B: Outline of Jan Mayen, the glacierized area on the island (grey) and Sørbreen (dark grey). The black box outlines the area mapped by vertical photogrammetry in 1975. The position of the meteorological station, operated by the Norwegian Meteorological Institute (met.no), is also marked.

Mapping of area and topography of Jan Mayen

The island that today is called Jan Mayen has most probably been known by the vikings, and may have been indicated on early maps such as the Venetian Zeno map from about 1400 (Barr, 1991). An island named Jan Mayen first appeared on Willem Jansz Blaeu 1620 edition map of Europe. Blaeu made a first detailed map of the island, named "Jan Mayen" after the Dutch captain Jan Jacobszoon May, in his famous "Zeespiegel" atlas of 1623 (Barr, 1991, Hacquebord, 2004). Whalers made map sketches of the is-

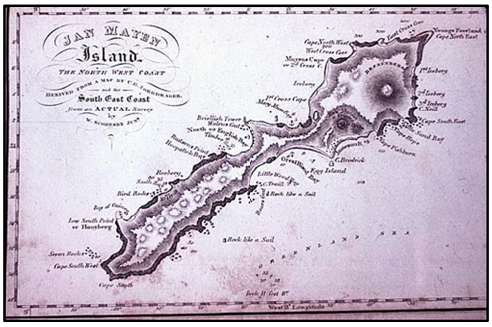

Fig. 2 Parts of Scoresby map from 1817, without topographical elevation contours (Devold, 1928).

land, but the first to report elevation for the Berenberg mountain was William Scoresby in 1817 (Devold, 1928), see illustration of map in Fig. 2. During the first International Polar Year 1882–1883 the Austro-Hungarian Polar Expedition stayed one year at Jan Mayen and performed extensive mapping of the area, also applying magnetic, astronomical and meteorological instruments (Barr, 1991, Corby, G.A), see photograph in Fig.3. The Austro-Hungarian maps (scale 1: 100 000) were of such quality that they were used until the 1950s.

Fig. 3. Boat and anemometer house, some participants (of total 14), and one of the Leonberger dogs; Freja or Lolo, of the Austro-Hungarian Polar Expedition during the International Polar Year 1882–1883.

The first modern topographic map was published in 1958 on two sheets in scale 1: 50 000, from aerial photographs recorded in 1949 and 1955 (Fig. 5 A) by the Norwegian Polar Institute.

Geodetic field work was conducted during 1949 of a group of topographic personnel from NPI, one external astronomer and four assistants. Gunnar Østrem (Fig. 4) was at the time studying in Oslo, but worked as an

Fig. 4. Gunnar Østrem, born 25.03.1922. Foto by Ø.B. Dick , June 2011. G. Østrem was a field assistant during the topographic mapping of Jan Mayen in 1949. At 20.12.2012 he told the author about his experiences on the island. Professor G. Østrem received the Danish 'Hans Egede medal' in 1982 and the Norwegian 'the King's medal of Merit' in gold in 1992 for pioneering glaciological research.

assistant during the summer of 1949 at Jan Mayen. He tells that his task was to assist the astronomer with celestial navigation to determine Jan Mayens exact position, applying a method called longitude by chronometer. Each clear night they measured the passing of stars using a transit telescope mounted on a concrete pillar in the mountain side of the northern middle part of the island. The star passage was timed using a chronometer clock, which was kept continuously near the instrument for stable conditions. The clock was adjusted with a nonius (vernier) scale slide caliper daily at 13.00, according to a radio time signal from Nauen Transmitter Station (established in 1906) in Germany, and these radio signals were even corrected for travel time through air. Based on the summers celestial observations the position of the island was shifted several kilometers in the sea, relative to the position from the Austro-Hungarian map.

Gunnar Østrem also tells that the topographic team placed L-shaped photogrammetrical signals on rocks using 1.5 m wide white fabric. The L-shape was chosen so that the signals could be distinguished from snow piles in the aerial photo-graphs. Positions of the inner corner of the Ls were triangulated, and referred to the local coordinate system.

From the logistic parts of the expedition Østrem tells that the team lived in semicircular corrugated iron Nissen huts, and amongst many things found 5 kg of stale butter and a barrel of biscuits left over from the British Military's stay at the Island a few years earlier during World War II. They also found some dynamite which they used one morning to salute one of the topographers on his 60'th birthday. When the summers work was finished the team was supposed to be picked up by the Norsel ship built for the Norwegian-British-Swedish-Antarctic expedition, also called Maudheim expedition (1949-1952) lead by John Schjeldrup Giæver, with the well known Swedish professor in glaciology Valter Schytt as second in command. Due to time constraints and bad weather this plan was cancelled, and the Norwegian mainland had to be telegraphed, in those days via Bjørnøya to Tromsø. A Royal Norwegian Navy Corvette arrived after several days. As there is no harbor at Jan Mayen a float attached to a rope was launched into the high waves of the rough shore line. The young student Østrem was pleased to reach the warm navy vessel after a cold and wet trip on the float, and what he describes as an unforgettable summer adventure. More of the interesting history of Jan Mayen is described by Susan Barr (1991).

The results of the cleverly conducted geodetic work of the summer 1949 exists today in digital form, as contour lines of 40 m elevation intervals have been digitized by NPI from the analogue map.

A glaciated area of 43 km^2 south of the crater was mapped by NPI from vertical aerial photographs in 1975 (Fig. 1 B and Fig. 5 B, C)). The originally compiled contours on a cartographic film were scanned, the 10 m elevation contour intervals were digitized, and a digital elevation model (DEM) at grid size 40×40 m were generated by Rolstad Denby and Hulth (2011).

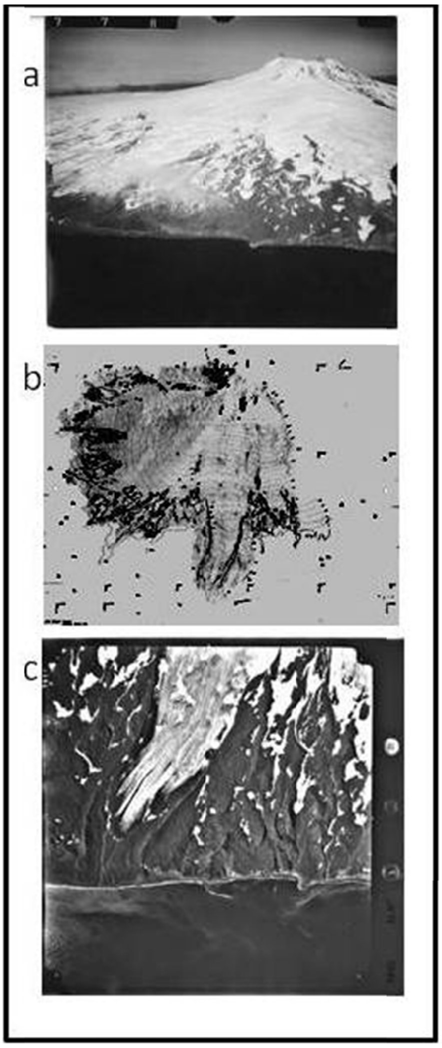

Fig. 5. Optical aerial photogrammetrical data. A: Example of oblique aerial photo late summer 1949, covering thesouthern side of Beerenberg (Norwegian Polar Institute) . B: Scanned cartographic film from vertical aerial photographs, (July 30, 1975) with photogrammetrically compiled contours (Norwegian Polar Institute). C: Vertical aerial photograph (July, 1975) of Sørbreen glacier front (Norwegian Polar Institute).

A digital elevation model is derived from the September 10, 2008 SPOT 5 stereoscopic survey of Polar Ice: reference images and topographies (SPIRIT) by CNES (Korona and others, 2009). The SPOT 5 DEM (40×40 m grid size) covers most of the glaciated area, except for a cloudy area near the eastern glacier edge (Fig. 6, right panel). Areas with poor correlation have interpolated values which are masked out according to Korona and others (2009) recommendations.

Glacier boundaries from Landsat ETM+

A Landsat 7 ETM+ image is geo-located using ground control points along the coast line, and geometrically corrected using the NPI 1949 digital terrain models and ERDAS Imagine software. New glacier boundaries are digitized manually using ArcInfo software, and then compared to the existing maps from 1949. Sørbreen is the only glacier where glaciological studies have been conducted at Jan Mayen, and we therefore note here that Sørbreen has retreated to its 1949 position, see red and yellow lines of glacier boundaries in Fig 6, left panel. This position of the glacier front is also confirmed by field observation in 2008. The Landsat image shows that glaciers have retreated in the north east, which is located in the cloudy area in the SPOT 5, 10 Sept., 2008 image used for topographic mapping, see Fig. 6.

Assessment of differentiated surface elevation data from years 1949, 1975 and 2008 for estimates of ice volume changes at Jan Mayen.

An assessment of the existing elevation data from the oblique and vertical aerial photographs (1949 and 1975), and the SPOT 5 2008 stereoscopic survey has been conducted by Rolstad Denby and Hulth (2011) in order to provide initial information on the current status of the ice volume changes. All DEMs were co-registered, using the SPOT 5 2008 DEM as reference, and horizontally and vertically shifted following a method which involves slope calculations, described by Nuth and Kääb (2011). Details of the data treatment are described in Rolstad Denby and Hulth (2011).

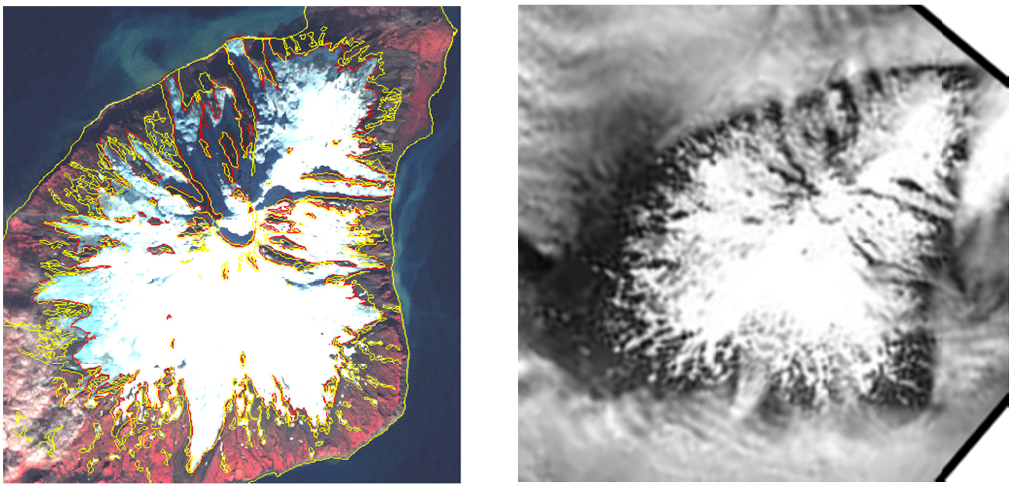

Fig 6. Optical satellite data. Left: Rectified Landsat 7TM+, 13 Sept., 2000. Glacier outlines: yellow lines 1949, red lines 2002. Coastline also in yellow. Right: SPOT 5 image, 10 September 2008.

Error assessment of the differentiated geodetic datasets

Two sets of elevation grids representing the surface types of 1) surrounding rocks, and 2) glaciers, are calculated for each period. The differentiated grids for surrounding rocks are used for estimation of the differentiated elevation uncertainty for each period. The standard error of the off-glacier terrain indicates the uncertainty of the DEM differences at pixel level, but it overestimates the uncertainty when spatially averaging the data for determination of volume changes over an area of several pixels. Non-systematic errors are reduced when spatially averaging, but the reduction will depend on the degree of spatial correlation and on the size of the averaging area (Rolstad and others, 2009). Different measurement methods lead to different correlation scales. Semi-variograms are created from the elevation differences over rocks to identify scales of spatial auto-correlation. From these semi-variogram parameters the uncertainty of the spatially averaged elevation differences are calculated as described in Rolstad and others (2009). In summary the uncertainty in the spatially-averaged elevation difference is estimated by applying the following steps:

1. An elevation difference grid of the bedrock region surrounding the glacier is created.
2. The grid, if necessary, is detrended using a polynomial model to remove systematic bias.
3. The grid is statistically assessed to determine:
   a. the standard deviation of the elevation error derived over the bedrock ($\sigma_{\Delta z}$);
   b. the semi-variogram parameters of nugget, sill and range by fitting a spherical semi-variogram model to the empirically derived semi-variogram. Standard geostatistical software packages are available to do this.
4. If the correlation range is greater than the representative radius of the averaging area, then the uncertainty of the spatially-averaged elevation difference (σ_A) is calculated according to Equation 11 in Rolstad et al. (2009).
5. If the correlation range is less than the representative radius of the averaging area, as may be the case when determining the geodetic mass balance over large areas, then σ_A can be approximated using

$$\sigma_A{}^2 = \sigma_{\Delta z}{}^2 \frac{1}{5} \frac{A_{cor}}{A} \qquad (3)$$

where A is the averaging area, and the correlation area A_{cor} is specified by the semi-variogram range (a_1) given by

$$A_{cor} = \pi a_1^{\ 2} \quad (4)$$

The factor 1/5 in Equation 3 is a result of the integration of the spherical semi-variogram model.

As discussed in Rolstad and others (2009) there may be more than one scale of spatial correlation related to the derivation of the DEMs. It must be emphasised that it is generally the largest correlation scale that has the most impact on the spatially averaged uncertainty.

Spatial scales of correlations are determined from the surrounding rock data for the three datasets, and calculated area averaged uncertainties are listed in Table 1.

Uncertainties determined for the surrounding rock surface, as described above, are assumed to be representative for the glacier surface, however, it is well known that the photogrammetrical measurement quality of various surface types varies. On snow covered glaciers with poor contrast it is difficult, and sometimes impossible, to get accurate elevation measurements, and interpolation using surrounding elevation measurements must be conducted. However, comparison of concurrent laser and photgrammetrical data for Svartisen ice cap (Rolstad and others, 2009) showed that this phenomena yields only short correlation scales, which contribute only little to the uncertainty when averaging over larger areas.

Table 1. Estimated spatially averaged glacier surface elevation change, and uncertainty (σ_A) (one standard deviation), area, and standard error of elevation difference ($\sigma_{\Delta z}$).

Years, data type	Elevation change (m) Uncertainty (σ_A) (1 st.dev) (m)	Area (km^2)	St. error of elevation difference ($\sigma_{\Delta z}$) (m)
2008 – 1949, SPOT 5 – Oblique photogram.	0.74 ± 3.4	105	8.7
2008 – 1975, SPOT 5 – Vertical photogram.	2.93 ± 1.7	43	4.9
1975 – 1949, Vertical – Oblique photogram.	–0.26 ± 0.7	43	4.8

Assessment of ice volume changes from the differentiated geodetic datasets

The differentiated elevation grid for glaciers provides the ice volume change for the mapped area in the period, and computed results for the periods 2008–1949, 2008–1975, and 1975–1949 are shown in Fig. 7. Two datasets suggest weak positive volume changes, however only the 1975 to 2008 dataset shows significant elevation changes relative to the estimated uncertainty. In this 33 year period the ice volume on the southern part of Jan Mayen has increased. Upper panel of Fig 7 also suggests that there is an increase in ice volume in this area for the 59 year period (1949 to 2008), while the volume is decreasing in the northern and western parts. Note that these results are not significant in regard to the uncertainties. In the earliest period the data suggest a small negative volume change, which is not statistically significant.

Geodetic mass balance requires a complete coverage of the entire drainage basin, to avoid elevation changes due to ice movement. Terrain models should ideally be from the end of the balance year, and if not density conversions of snow must be applied. As the 2008 data set does not cover the entire glacier, and in particular not in the area where glacier retreat is registered from 1949 and 2002 glacier boundaries, the geodetic mass balance cannot be determined for Jan Mayen.

Conclusion

The mapping history of Jan Mayen started in 1620, and extensive mapping was conducted during the first IPY in 1882-83. The first modern topographic mapping was conducted from photogrammetrical data recorded in 1949. Some glacier mass balance measure-

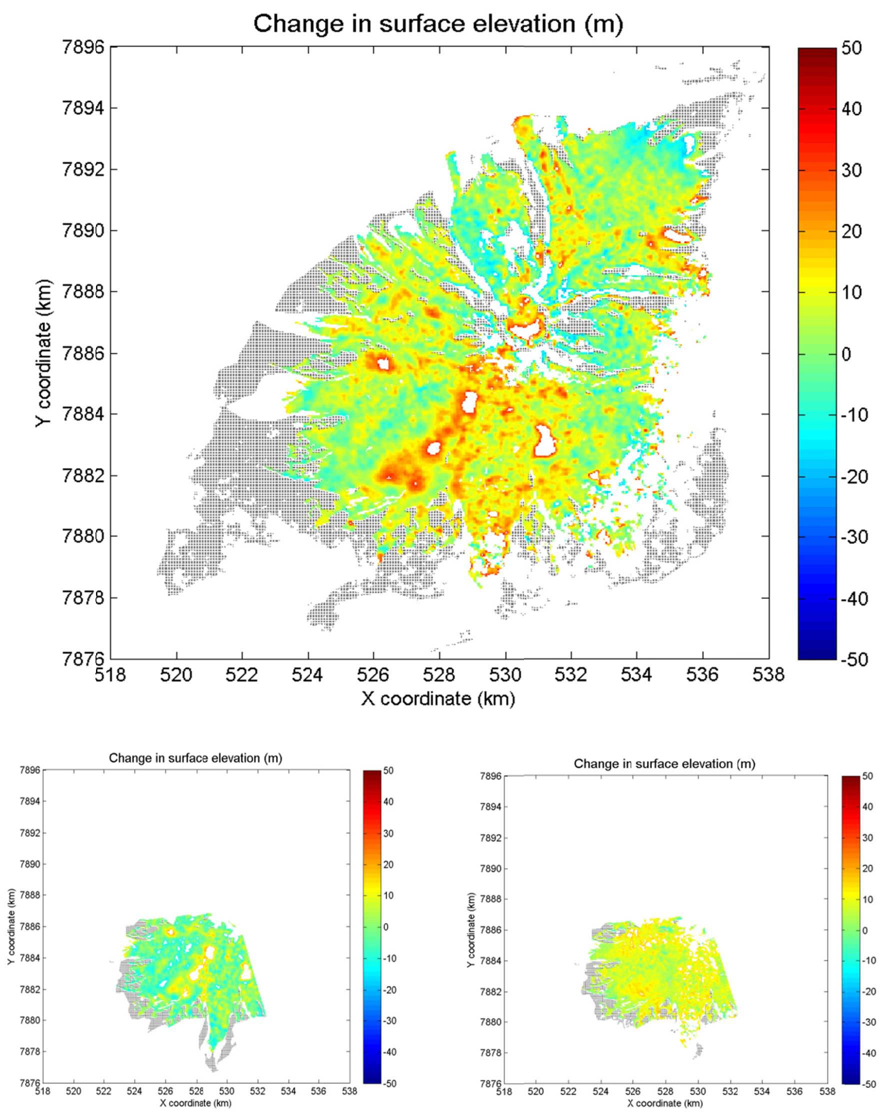

Fig. 7. Glacier surface elevation changes. Coordinate axes show Easting and Northing in UTM zone 29N. Upper panel: Elevation change 1949 to 2008, derived from SPOT 5, 2008 data minus oblique aerial photogrammetry 1949 data. Lower left: Elevation change 1975 to 2008, derived from SPOT 5, 2008 data minus vertical aerial photogrammetry 1975 data. Lower right: Elevation change 1949 to 1975, derived from vertical photogrammetry 1975 data minus oblique aerial photogrammetry 1949 data.

ments were initiated during the third IPY in 2007, and satellite data provide information on recent glacier boundaries and topography. However, analysis shows that the total mass balance of Jan Mayen glaciers is still not adequately determined, due to inaccurate data and incomplete data coverage. The following points can be concluded:

– On the southern parts the ice volume has increased slightly but significantly from 1975 to 2008.

- The assessment of the 2008–1949 topographic dataset shows no statistically significant glacier ice volume change in respect to the determined uncertainty of ±3.4 m for the 59 year period at Jan Mayen. This is an interesting result in regards to the clearly observed reduction of glacier ice volume on Iceland and Svalbard in the same period.
- The most recent DEM, the SPOT 5 2008, does not yield the required accuracy to map the apparently small volume changes that have occurred on Jan Mayen since 1949.
- The optical satellite data, SPOT 5, 10 Sept, 2008 (Korona and others, 2009), which is used for topographic mapping do not cover entire drainage basins due to clouds, in particular near the north eastern glacier boundaries where glacier retreat is registered in Landsat ETM+ 2002 images, compared to 1949 boundaries.
- There is clearly a need for more accurate mapping of the glacier surface elevations to determine future volume changes, and mapping of the *entire* drainage basins to determine the complete geodetic mass balance of Jan Mayen.
- Aerial laser scanning is suggested as an appropriate measurement method.

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