Correspondence

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

The volcanic island Jan Mayen (70°59′14″ N, 8°28′54″ W; area 373 km^2) is situated in the North Atlantic Ocean between Iceland and Svalbard (Fig. 1a). A reduction in ice volume has been observed since the mid-1990s for glaciers in Iceland (Björnsson and Pálsson, 2008; Pope and others, 2010; Gudmundsson and others, 2011) and in the western and southern parts of Svalbard (Nuth and others, 2010), and it is of interest to determine whether the same is true for Jan Mayen glaciers, where very few glaciological data are available. Twenty glaciers covering 105 km^2 flow down from the central Berenberg crater (2277 m a.s.l.). The direct glaciological mass balance of one glacier, Sørbreen (area ~15 km^2; Fig. 1b), was measured in 1972–74 and 1976–77 (Orheim 1976; Hagen, 1993), and new measurements were initiated in 2008 (Hulth and others, 2010). However, these sparse surface mass-balance data do not give adequate information on the total ice-volume changes. Neither has any mass-balance modeling been conducted, even though the Norwegian Meteorological Institute has measured meteorological data on the island since 1921 (location shown in Fig. 1b). We have therefore conducted an assessment of the existing elevation data from oblique and vertical aerial photographs, and a SPOT 5 (Système Probatoire pour l'Observation de la Terre) stereoscopic survey in order to provide initial information on the current status of the ice-volume changes, and to evaluate the need for new measurements to determine the complete geodetic mass balance of Jan Mayen.

Previous observations show variations in the ice volume of Jan Mayen glaciers. Maps and sketches of the front position of Sørbreen exist from 1632, 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 front is documented in aerial photographs in 1949, where the front had retreated 1200 m from the coastline. The glacier front advanced a few hundred meters during the 1960s. Field observations in 2008 showed that the front position was very close to the 1949 position.

GEODETIC DATA FROM OPTICAL IMAGES

The whole island was mapped by the Norwegian Polar Institute (NPI) using photogrammetry on oblique aerial photographs recorded in 1949 (Fig. 2a). Contours at 40 m elevation intervals have been digitized by NPI. A glaciated area of 43 km^2 south of the crater was mapped from vertical aerial photographs in 1975 (Figs 1b and 2b). We have now scanned the original contours and digitized at a 10 m elevation interval to generate a 40 m × 40 m digital elevation model (DEM). These datasets are combined with a DEM derived from the 2008 SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies (SPIRIT) by Centre National d'Etudes Spatiales, France (CNES; Korona and others, 2009). There are two 2008 SPOT 5 DEMs, from 25 July and 10 September. We use the 10 September image, because it has fewer clouds and is from the end of the melt season. Nine stake measurements from Sørbreen show surface melt of ~2–3 m in the period late July to early September 2008. The SPOT 5 DEM (40 m × 40 m grid size) covers most of the glaciated area, except for a cloudy area near the eastern glacier edge (Fig. 2c). The areas of poor correlation and thus interpolated values are masked according to Korona and others' (2009) recommendations. All DEMs are co-registered, using the SPOT 5 2008 DEM as reference, and horizontally and vertically shifted following a

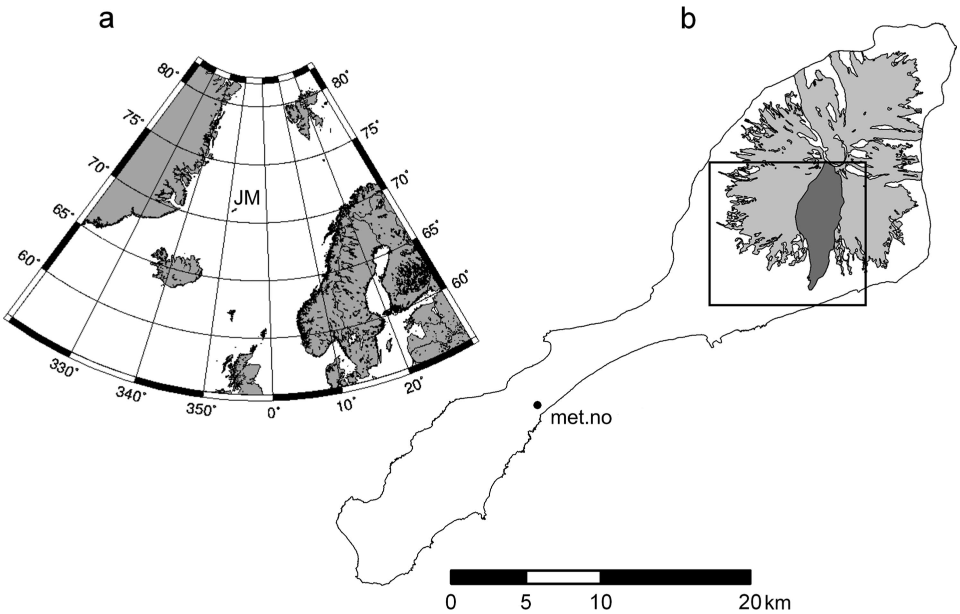

Fig. 1. (a) Location of Jan Mayen (JM), 550 km northeast of Iceland. (b) Outline of Jan Mayen, the glacierized area on the island (grey) and Sørbreen (dark grey). The box outlines the area mapped by vertical photogrammetry in 1975. The position of the meteorological station, operated by the Norwegian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

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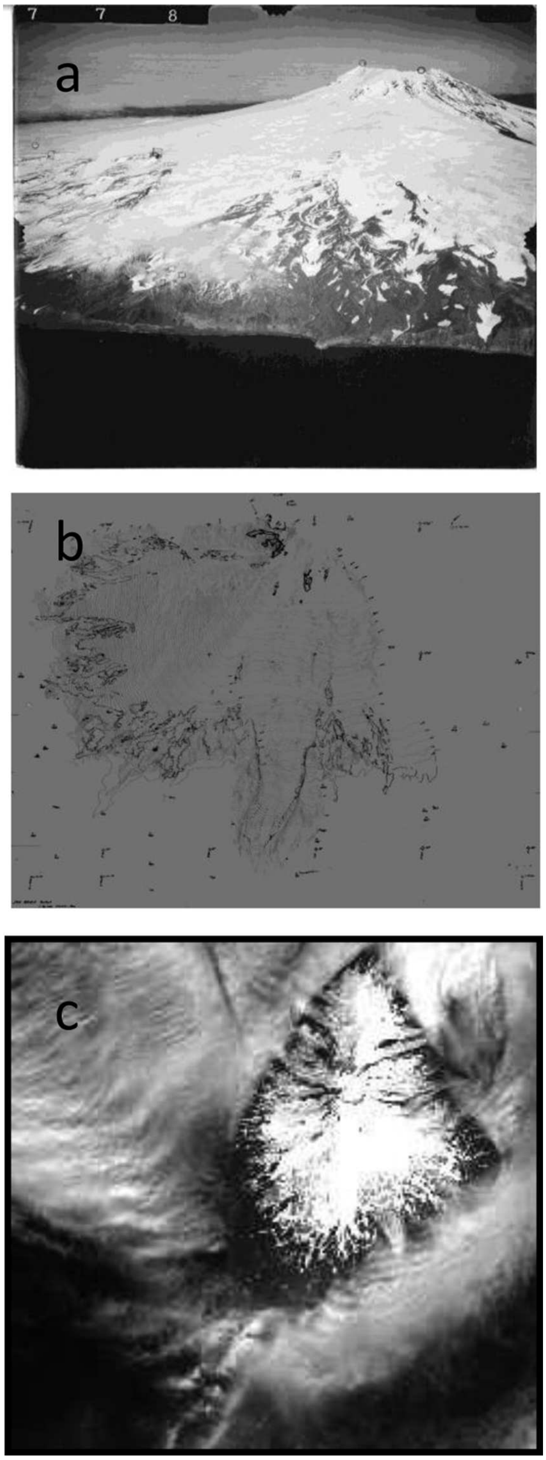

Fig. 2. Optical photogrammetric data. (a) Example of oblique aerial photo from late summer 1949, covering the Berenberg crater (NPI). (b) Scanned construction folio measured photogrammetrically from vertical aerial photographs, from 30 July 1975 (NPI). (c) SPOT 5 image, 10 September 2008.

method which involves slope calculations, described by Nuth and Kääb (2011). The 1975 DEM was shifted with $\Delta X = 22.5$ m, $\Delta Y = 35.8$ m and $\Delta Z = -20.7$ m, and the 1949 DEM with $\Delta X = 16.3$ m, $\Delta Y = 21.7$ m and $\Delta Z = -17.6$ m. Elevation differences are computed for the periods 2008–1949, 2008–1975 and 1975–1949, for two sets of elevation grids representing the surface types of surrounding rocks (Fig. 3a) and glaciers (Fig. 4) and for each period analyzed separately on the surrounding rocks (Fig. 3). The differentiated elevation grid for glaciers provides the ice-volume change for the mapped area in the period, and the differentiated grid for rocks is used to estimate the differentiated elevation uncertainty.

Table 1. Estimated spatially averaged glacier surface elevation change and uncertainty (one standard deviation), area, and standard error of elevation difference

Years, data type	Elevation change	Area	Std error of elevation difference
	m	km^2	m
2008–1949, SPOT 5 – oblique photogrammetry	0.74 ± 3.4	105	+8.7
2008–1975, SPOT 5 – vertical photogrammetry	2.93 ± 1.7	43	+4.9
1975–1949, vertical – oblique photogrammetry	-0.26 ± 0.7	43	+4.8

ERROR ASSESSMENT OF THE DIFFERENTIATED GEODETIC DATASETS

Spatially averaged uncertainty is dependent not only on the standard error of individual elevation changes, but also on the size of the averaging area and the scale of spatial autocorrelation (Rolstad and others, 2009). Semivariograms are created from the elevation differences over rocks to identify scales of spatial autocorrelation. From these semivariogram parameters the uncertainty of the spatially averaged elevation differences is calculated as described by Rolstad and others (2009).

Uncertainties determined for rocks are assumed to be representative for the glacier. The autocorrelation of elevation differences from optical photogrammetric data depends on absolute and relative orientation of the stereo models, and on photogrammetric measurement quality of the various surface types. On snow-covered glaciers with poor contrast it is difficult, and sometimes impossible, to obtain accurate elevation measurements, and interpolation using surrounding elevation measurements must be conducted. However, comparison of concurrent laser and photgrammetric data for Svartisen ice cap, Norway (Rolstad and others, 2009), showed that this phenomenon yields only short correlation scales, which make little contribution to the uncertainty when averaging over larger areas.

Spatial scales of correlation and uncertainties are determined from the surrounding rock data for the three datasets. For the 2008–1949 Jan Mayen dataset, spatial correlation at hundred-meter and kilometer scales was found, at 319 m and 11.3 km (Fig. 3b and c). The standard error in the elevation difference is ± 8.7 m, while the area-averaged uncertainty for 105 km^2 is calculated to be ± 3.4 m (Fig. 3d). For the 2008–1975 dataset, correlation scales were found at 243 m and 7.7 km. The standard error of the elevation difference is ± 4.9 m, while the area-averaged uncertainty for 43 km^2 is ± 1.7 m (Fig 3e). Finally, for the 1975–1949 dataset, two correlation scales were found, at 324 m and 4.1 km. The standard error of the elevation difference is ± 4.8 m, while the area-averaged uncertainty for 43 km^2 is ± 0.7 m (Fig. 3f). The results are summarized in Table 1.

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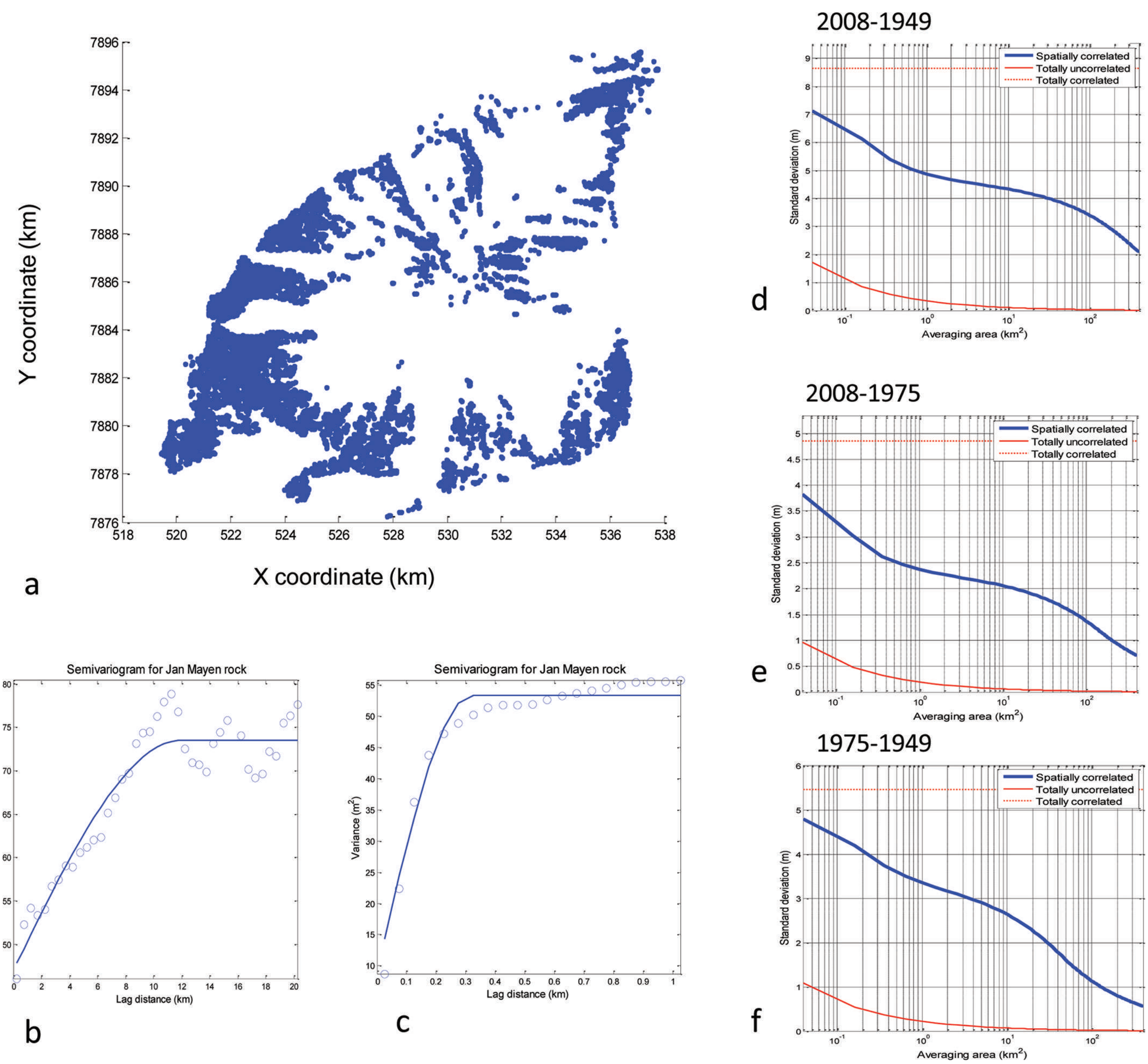

Fig. 3. (a) Blue dots show locations of differentiated (2008–1949) elevation points for rocks for determination of scales of spatial correlation. (b) Semivariogram, spatial scale 0–20 km (2008–1949). (c) Semivariogram, spatial scale 0–1 km (2008–1949). (d–f) Estimated uncertainty of spatially averaged differentiated rock elevations. Blue lines are the estimated uncertainty of the area-averaged elevation difference, using the derived semivariograms. Dotted red and solid red curves are included for reference, and represent the spatially averaged uncertainty for totally correlated elevation data (standard deviation of the elevation difference error) and totally uncorrelated elevation data.

The standard error of the elevation difference would represent the uncertainty if the data were completely spatially correlated. However, since there is a degree of spatial correlation, represented by the semivariograms, the area-average uncertainty will decrease with increased area. The derived correlation scales are comparable for the two differentiated datasets involving the SPOT 5 satellite data, and the area-averaged uncertainty decrease with increased area in a similar manner (Fig. 3d and e). When aerial photogrammetric data are combined, the kilometer-scale spatial correlation is shorter, at 4.1 km, compared to 8.6 and 7.7 km for the other two periods. Due to this shorter correlation scale, the area-averaged uncertainty decreases more quickly with increasing area, and the area-averaged uncertainty is smallest for the aerial photogrammetric dataset. It is also worth noting that for Sørbreen, with a relatively small area of 15 km^2, the area-averaged uncertainties are ±4.3 m (2008–1949), ±2.0 m (2008–1975) and ±1.1 m (1975–1949).

ICE-VOLUME CHANGES

Two datasets suggest weak positive volume changes; however, only the 1975–2008 dataset shows significant elevation changes relative to the estimated uncertainty. In this 33 year period the ice volume in the southern part of Jan Mayen has increased. Figure 4a also suggests there is an increase in ice volume in this area for the 59 year period 1949–2008, while the volume decreases in the northern and western parts. Note that these results are not significant in

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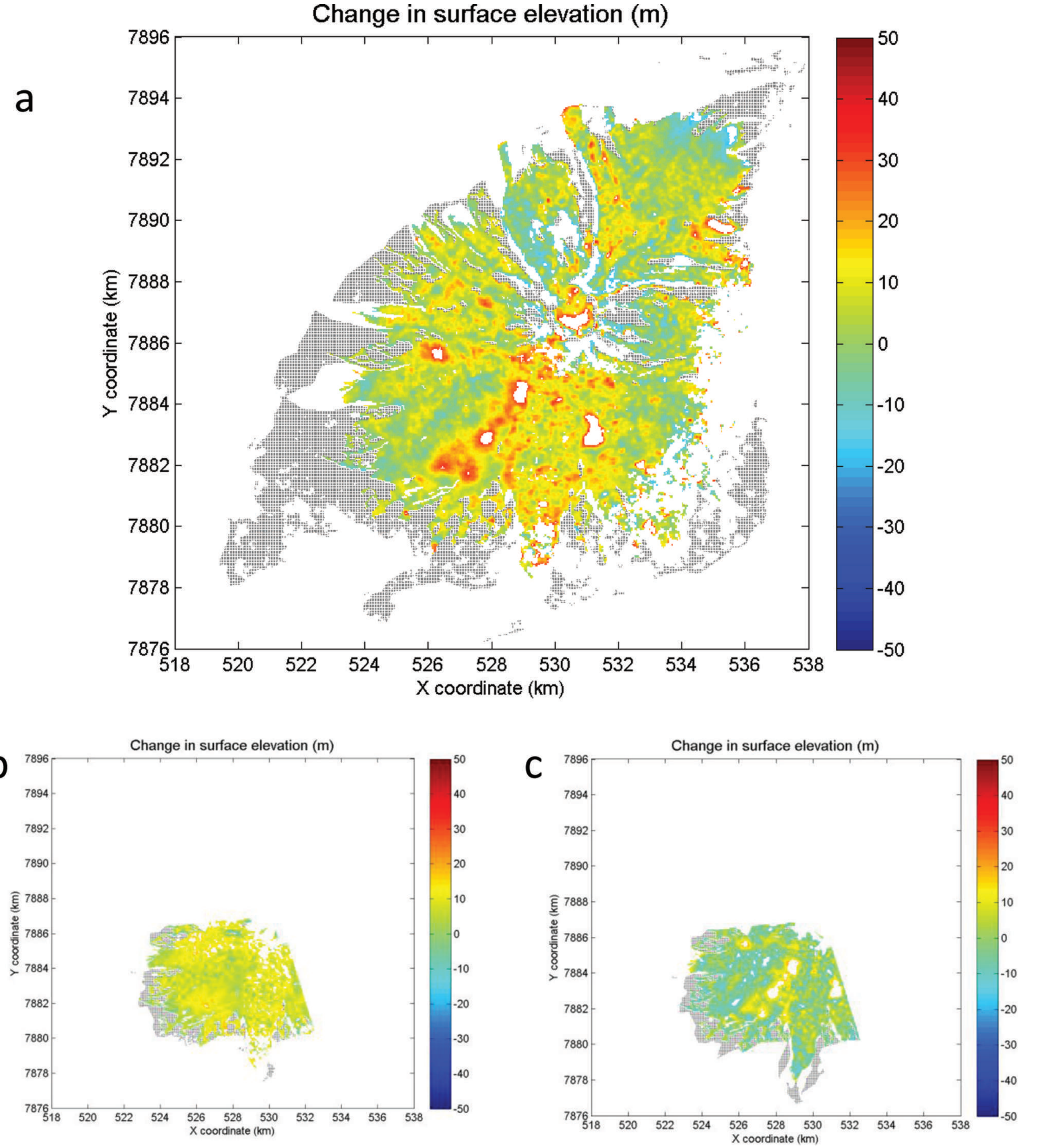

Fig. 4. Glacier surface elevation changes. (a) SPOT 5 2008 – oblique aerial photogrammetry 1949. (b) SPOT 5 2008 – vertical aerial photogrammetry 1975. (c) Vertical photogrammetry 1975 – oblique photogrammetry 1949.

regard to the uncertainties. In the earliest period the data suggest a small negative volume change, but this is also not statistically significant.

Climatic changes may explain the slight increase in ice volume from 1975 to 2008. The climate on Jan Mayen is polar maritime, with small fluctuations in temperature during the seasons (Hov, 2004). From the 1960s to the 1980s, sea ice surrounding the island was observed during winter (Orheim, 1993), but the sea-ice cover has now retreated. Temperature data from the Norwegian Meteorological Institute (Fig. 1b) (http://eklima.no) show a warming of 1.58°C in 30 years (mean annual temperature data from the normal period 1961–90 compared to the period 1991–2008). The mean annual precipitation for the same period decreased (from 682 mm to 654 mm), with winter precipitation increasing by 7% and summer precipitation decreasing by 19%. The increase in ice volume in the southern parts may be explained by orographic effects on the precipitation, as well as possible changes in winter precipitation patterns due to the observed retreat of the sea-ice cover. Mass-balance modeling which includes orographic effects may be required to explain the observed volume changes.

The results show no statistically significant glacier ice-volume change in respect to the determined uncertainty of ±3.4 m for the 59 year period 2008–1949 at Jan Mayen. This

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is an interesting result in regard to the observed reduction of glacier ice volume on Iceland and Svalbard in the same period. In the southern parts the ice volume has increased slightly but significantly from 1975 to 2008. The most recent DEM, the SPOT 5 2008, does not yield the accuracy required to map the apparently small volume changes occurring at Jan Mayen. 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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