A REMOTE SENSING INVESTIGATION INTO THE EVOLUTION OF FOLGEFONNA GLACIER OVER THE LAST 150 YEARS

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ABSTRACT

This is a summary of a Master Thesis, with a great deal of content, maps and graphs excluded. For the full document please email the author.

The change in glacier area, volume and transient snowline (TSL) elevation, a commonly used mass balance proxy, of Folgefonna glacier was assessed over the last 150 years. Folgefonna is a large maritime glacier comprised of three separate glaciers (Nordfonna, Midtfonna and Sørfonna) in Western Norway. A combination of optical and SAR satellite imagery, aerial photographs, and historical maps were utilised to determine the evolution of the glacier. Folgefonna was found to have retreated since the Little Ice Age (LIA) maxima at ~1860, with noticeable advances in the 1960s/70s, 1990s and mid-2000s. A lack of data from the early part of the time series prevents detailed analysis before the 1960s. In 2011 Nordfonna, Midtfonna and Sørfonna had respective areas of 24.8 km2, 9.1 km2 and 156.7 km2, reductions of 47%, 68% and 20% compared with their LIA maxima sizes in 1860. Absolute ice volume calculations are only possible for Nordfonna where the subglacial topography is known; Nordfonna measured 1.84 km3 in 2010, a reduction of 43% of its 1937 volume. If planar bedrock surfaces beneath 95% of the ice surfaces are assumed then rudimentary percentage losses can be calculated. Over the same time span Midtfonna lost 1441 million kg (50%) of mass, while Sørfonna lost 8268 million kg (18%) between 1987 and 2010, the portion of Sørfonna visible on the 1937 topographic map lost 5658 million kg (21%) between then and 2010. The TSL elevation was found to reflect changes in glacier mass balance over a number of balance years, and is therefore inferred to be in actual face the firn line.

INTRODUCTION

The retreat of Glaciers worldwide is one of the the clearest and most pronounced signals that exist in nature of a dynamic climate (Kääb et al., 2002). Maritime glaciers, such as those found along the coast of Scandinavia are especially sensitive to pertubations in the climate due to their large annual mass turnover (Winkler et al., 2009). The health of glaciers to the Norwegian economy is especially important, 98% of Norway's electricity is generated from Hydro-electric power (HEP), and 15% of this originates from glaciated catchments (Andreassen et al., 2005). South-western Norway has also seen changes in climate. Tourism is also depend on the spectacular glaciers of Western Norway, When Norwegian glaciers retreated in the 1930s, the interest in glacier tourism (summer skiing, hiking and climbing) also diminished.

The annual winter and summer precipitation between 1900 and 2000 in Bergen increased by 19% and 7% respectively, while the mean annual temperature and mean winter temperature increased by 0.71°C and 0.93°C per 100 years (Nesje et al., 2000). Summer ablation temperatures since the late 1990s have been 2°C above the normal for the period 1961 – 1990 (Winkler and Nesje, 2009). It is therefore imperative to understand how large Norwegian plateau glaciers, such as Folgefonna, have historically responded to changes in the climate, in order to comprehend future responses, and the impacts for the Norwegian economy.

METHODS

The three parameters investigated were the glacier area, glacier volume, and the elevation of the transient snowline (TSL), a commonly used proxy for glacier mass balance. The TSL can be defined as *“the lower boundary of last year's snow at the time of imaging”* (Østrem, 1975).

Glacier Area

The glacier area was determined both using manual delineation, and in the case of the multi-spectral data, using segregated band ratios. In total 26 Landsat images ranging from 2011 to 1976, one aerial photo mosaic from 1962, and three historical maps from 1937, 1864 and 1860 were used to measure the glacier area of the three ice masses. Error checking was conducted against a SPOT 5 image and a LiDAR DEM. The segregated band ratios were carried out using Landsat bands TM 3/TM 5 and TM 4/TM 5, threshold values were computed to be 4.0 and 3.5 respectively, a 5x5 medium filter was performed to remove noise before the results were converted to shapefiles and the areas read.

Glacier Volume

DEMs of the glacier surface topography were compared. Two ASTER DEMs were generated in *PCI Geomatica*, two DEMs were derived from digitised contour lines, provided as vector data from 1987 and scanned in from a 1937 topographic map. Two DEMs were also acquired from 1999 (NASA SRTM) and 2007 (LiDAR campaign conducted by Norwegian Water Resources and Energy Directorate (NVE)). Subglacial topography had was mapped beneath Nordfonna in April 2011 (Førre, 2012), this allowed absolute ice volumes to be calculated for Nordfonna, while rudimentary planar bedrocks were assumed for Midtfonna and Sørfonna that lay beneath 95% of the ice.

Transient Snowline (TSL) Elevation

The TSL was measured with two different methods. The fourth Landsat TM band is the most sensitive to snow grain size, images from the end of the ablation season were therefore used to map the altitude of the TSL for 15 of the Landsat images that were not blighted by seasonal snow at high elevations. ENVISAT ASAR images in wide swath mode were also used to map the TSL. 30 images from mid-winter were used. All images were first inverted, before two lee-sigma filters were performed in order to homogenise the different glacier faces as best as possible. This was carried out using *NEST 4B-1.1.* The microwave images can pass through cloud and are independent of weather which makes it easier to acquire images from the same time each year. The microwaves can also pass through dry-snow, thus allowing the TSL from the end of the ablation period to be visualised. Both methods used manual delineation, before a DEM was used to find the mean, maximum and minimum elevations.

RESULTS

Glacier Area

All of Folgefonna was found to have retreated since the LIA maxima at ~1860, with noticeable advances in the 1960s/70s, 1990s and mid-2000s. Generally since the turn of the millennium the rates of glacier retreat have dramatically accelerated. The areas that have retreated the most are the western margins, and the lower lying outlet glaciers. It was found that generally western Folgefonna was more reactive than eastern Folgefonna, which was more stable. This is explained by two factors, firstly that the prevailing westerly winds help feed eastern Folgefonna with wind blown snow, and secondly that the topography of the area casts eastern Folgefonna in shadow at the hottest part of the day (Evans, 2006).

Glacier Volume

There were less data points for the glacier volume time series, however the same trend has glacier volume is visible. Generally all of Folgefonna has shrunk since 1937, Nordfonna and Midtfonna both expanded between 1999 and 2002, while Sørfonna grew between 2002 and 2007. The expansion of Nordfonna however seems very unrealistic, and perhaps is exaggerated by errors in one of the DEMs used. Until 1987 the losses on the different segments of Folgefonna had stayed in track with each other (Figure 20), however from then onwards Midtfonna has lost proportionally the most mass, followed by Nordfonna, while Sørfonna has lost proportionally the least mass since 1987. Between 1937-1987 and 1987-1999 the rate of loss of mass on Nordfonna and Midtfonna accelerated considerably, from 9.1 million kgyr-1 and 8.2 million kgyr-1 respectively to 47.6 million kgyr-1 and 48.3 million kgyr-1. As the 1937 topographic map used to generate the DEM does not fully cover Sørfonna it is not possible to determine a true rate of ice loss before 1987, however Sørfonna also continued to lose mass. In the years following 2007 all of Folgefonna has lost mass at an increasing rate, Nordfonna and Midtfonna's rates of glacial downwasting increased by 390% and 360% respectively compared with between 2002 and 2007. Nord-, Midt- and Sørfonna lost 29.9%, 19.6% and 9.4% respectively of their mass between 2007 and 2010, although again the value for Nordfonna seems exaggerated

In August 2010 Nordfonna had an ice volume of approximately 1.84 km3 and had lost in total 1.40 km 3 of ice compared with its 1937 ice volume, equivalent to 1521 million kg or 43.2%. Midtfonna lost 1.32km3 of ice between 1937 and 2010, equivalent to 1441 million kg or 50.3%. Sørfonna shrank by 7.58 km3 or 8268 million kg (18.3%) between 1987 and 2010, and the area visible on the 1937 topographic map shrank by 21.1% (5.19 km3 or 5658 million kg) between 1937 and 2010.

Generally Folgefonna lost the greatest mass from its lower elevation, while the same west-east bias mentioned above is also evident. This bias becomes more evident in recent decades.

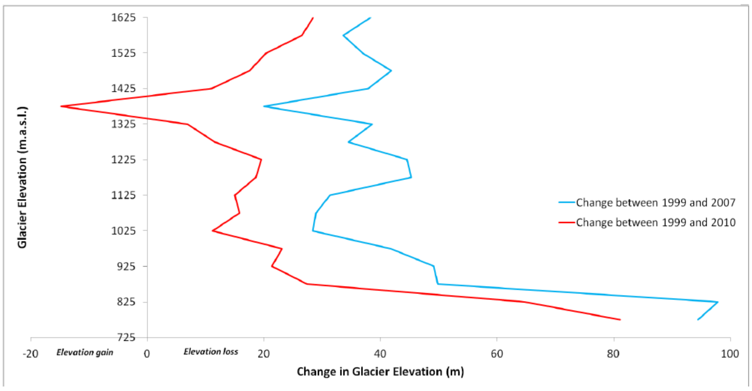


Figure 1: Change in glacier surface elevation at different heights across Folgefonna. As one would expect the lower elevations, which are exposed to greater ablation season temperatures, have ablated the most.

Transient Snowline Elevation

Both the Landsat and ENVISAT ASAR measurements show a similar trend of a rising TSL post-2005, although the ASAR measurements show the TSL rising at a rate approximately double that depicted by the Landsat data. Before that the results show that from August 1984 to August 1991 the TSL descended from 1448 m to 1408 m. From 1991 onwards the TSL elevation steadily rose by 5.1 myr-1 on average to 1449 m in 1999, this rate increased to 7.8myr-1 in the period from 1999 to 2010. By the start of September 2010 the TSL lay at an altitude of 1535 m.a.s.l., a total rise of 86 m since 1984. All the measurements agree that at the end of the 2010 ablation season the TSL lay at between 1535 and 1527 m.

The TSL correlates well with the in situ mass balance data, however at a reduced amplitude. It is therefore inferred that in actual fact the phenomenon measured is the firn line, and not the snowline.

Driving Force of the glacier

As a typical maritime glacier, Folgefonna has traditionally been driven by the amount of winter precipitation, with changes in the amount of summer ablation acting only to amplify or dampen this forcing (Nesje, 2005). When the glacier area record is compared to climatic data it can be seen that for the most of the time series the precipitation has been dominant, although Fealy and Sweeney (2005) state that it was actually lower than normal ablation temperatures in the 1960s/70s that caused the glacier to advance. The scarcity of data points in this part of the time series prevents this being verified.

It is however apparent that the increase in summer temperatures over the last few decades have become sufficient to melt away any surplus winter accumulation, thus making the ablation season temperature the dominant driving force of Folgefonna. The rapid retreat in glacier area and volume from 2000 onwards corresponds neatly to the increased summer temperature. It appears that the winter precipitation still acts to dampen and amplify the changes in temperature, as evident from both the mid-2000s advance, and the sharp glacier retreat in 2009. A combination of both factors continue to drive the glacier, for example Nesje (2005) states how the balance year of 2002/03 saw glaciers in western Norway receive 156% of their normal ablation, yet only 66% of their normal accumulation. This resulted in a considerable glacier retreat, which is evident in the data collected in this investigation.

Error checking and verification of results

In multitemporal analysis, the result of the time-series depends on the accuracy of every data-source. With this in mind, and that in total 26 Landsat images, as well as the aerial photographs, and the historical maps (which unfortunately do not possess error estimations) the error terms in the glacier area record seem considerable, however as table 1 illustrates when individual images are compared, such as in the maps produced, the error is much less. The total uncertainty for Nord-, Midt and Sørfonna if the changes are examined between 2011 and 1999 are **±16%, ±38%** and **±3%** respectively, if the changes are back until 1962 but excluding the 1976 image this error increases to **±20%, ±49%** and **±3%**, and if the 1976 Landsat image is considered this rises further to **±27%, ±64%** and **±6%** respectively.

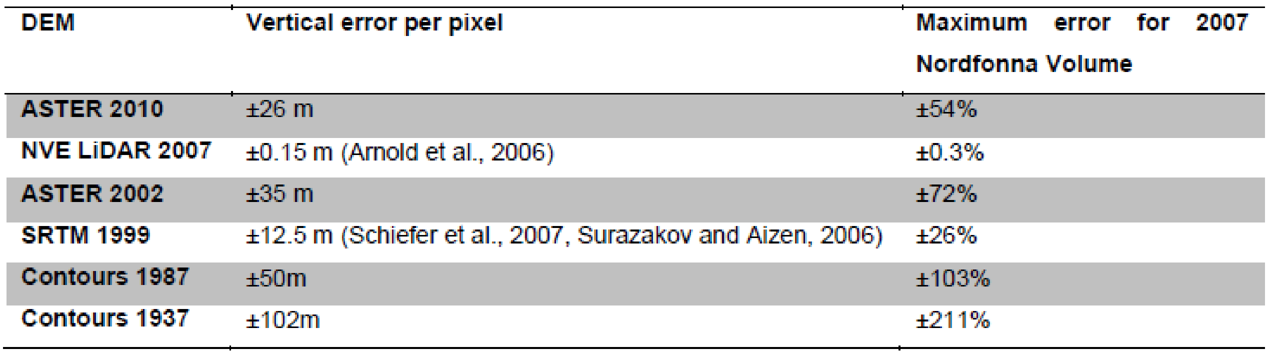
Table 1: The uncertainty from when comparing different Landsat images together.

Comparison	Pixel Size comparison	Error for Nordfonna	Error for Midtfonna	Error for Sørfonna
Landsat 7 ETM+ to Landsat ETM+	15 m:15 m	±4%	±10%	±2%
Landsat 7 ETM+ to Landsat 5	15 m: 30 m	±6%	±15%	±4%
Landsat 5 to Landsat 5	30 m: 30 m	±10%	±23%	±6%
Landsat 7 ETM+ to Landsat 1	15 m: 90 m	±17%	±41%	±11%
Landsat 5 to Landsat 1	30 m: 90 m	±18%	±43%	±11%

Without corresponding ground-data, it is unfortunately not possible to assess the contribution to the error from spectral similarities, obscurities from cloud or shadow.

The potential maximum errors in the volume measurements were also calculated (table 2), it is worth noting here that the error estimations for the two DEMs derived from contour data are most likely gross over-exaggerations. Only contour data over the glacier was used to generate the DEMs, therefore the terrain data was most likely deformed over the areas that error checking took place. Vignon et al. (2003) generated a DEM from a topographic map of the same scale (1:100,000) over Peru and found the finished product to be accurate to ±10 m. If the same level of accuracy is assumed for the contour DEMs used here then the accuracy is in line with the SRTM DEM.

Table 2: The vertical error per pixel for the 6 DEMs used in this investigation, and the maximum error for Nordfonna's volume measurements in 2007. The vertical error and the glacier area were used to calculate the potential largest and smallest volumes of Nordfonna which was then used to calculate the maximum percentage error.



DEM	Vertical error per pixel	Maximum error for 2007 Nordfonna Volume
ASTER 2010	±26 m	±54%
NVE LiDAR 2007	±0.15 m (Arnold et al., 2006)	±0.3%
ASTER 2002	±35 m	±72%
SRTM 1999	±12.5 m (Schiefer et al., 2007, Surazakov and Aizen, 2006)	±26%
Contours 1987	±50m	±103%
Contours 1937	±102m	±211%

The accuracy of the TSL measurements depends on the pixel size of the data used, so that is ±30 m for the Landsat measurements, and ±75 m for the ENVISAT ASAR measurements.

The data collected in this investigation were compared with in-situ mass balance data from Sørfonna, which due to its scarcity was interpolated based on the relationship with nearby glacier Hardangerjøkulen, which dates back to 1963. Generally the data corresponded together excellently, with only minor disparities due to seasonal snow or prevalent cloud.

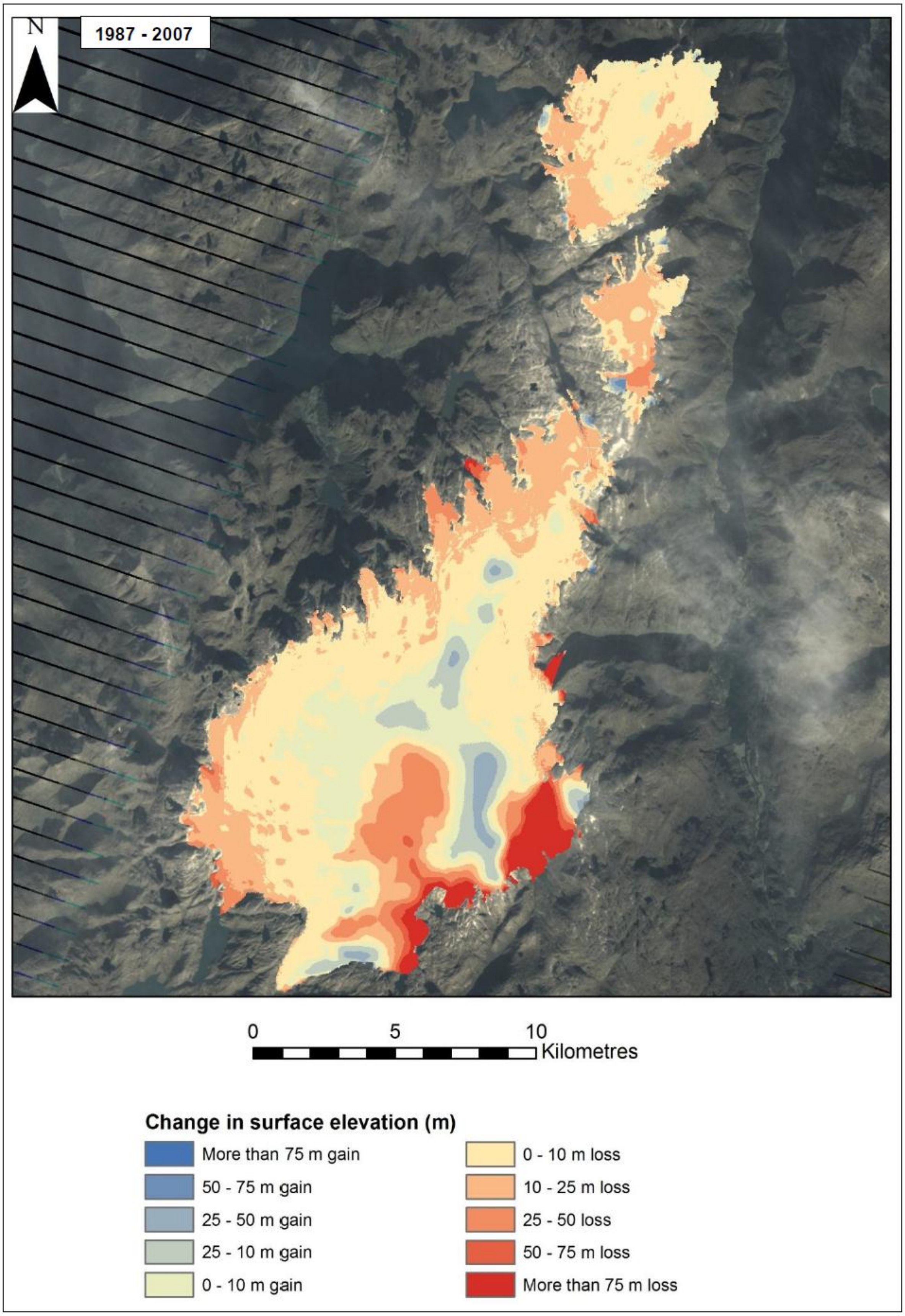


Figure 2: Change in surface elevation of Folgefonna between 1987 and 2007. Other than some extreme losses on parts of eastern Sørfonna which are most likely errors (*6.1.2.3*), a general predominant western loss of mass can be seen, small gains in elevation occurred in the interiors of Nordfonna and Sørfonna.

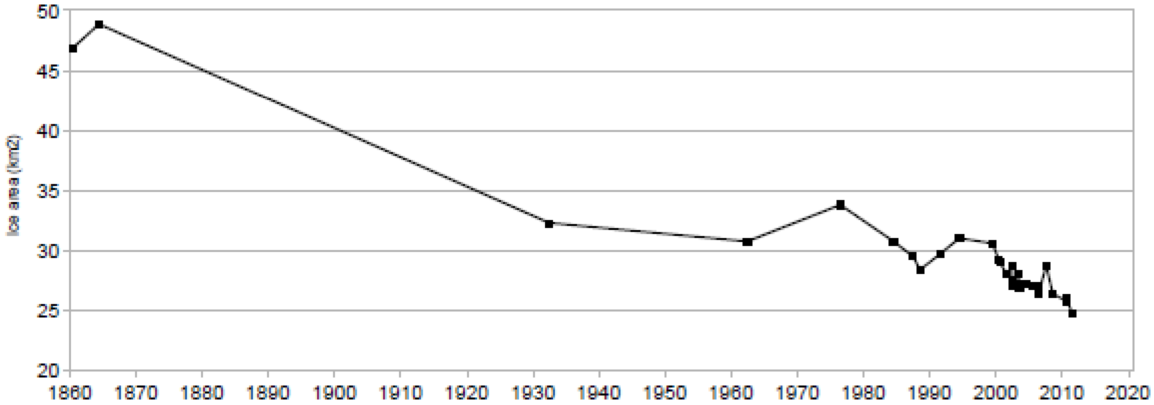


Figure 3: The ice covered area of Nordfonna from 1860 to 2011 measured using a combination of Landsat images, aerial photographs and old maps.

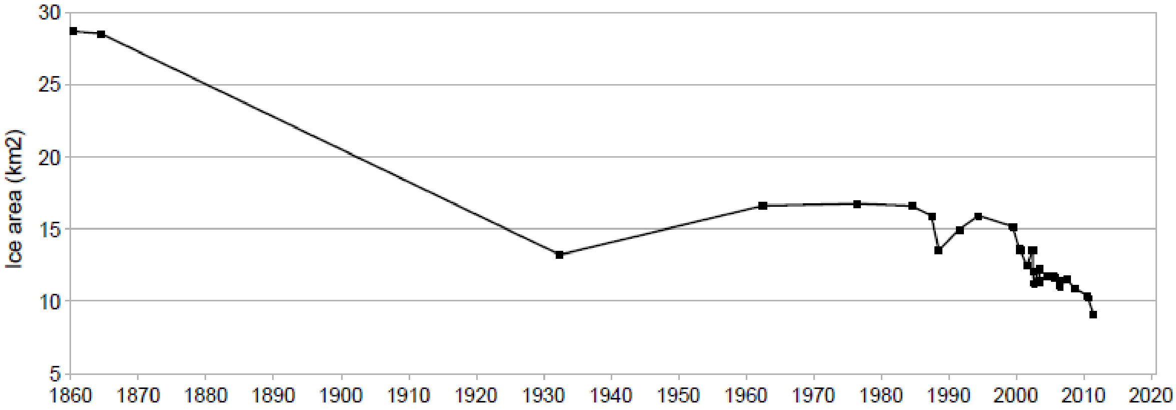


Figure 4: The ice covered area of Midtfonna from 1860 to 2011 measured using a combination of Landsat images, aerial photographs and old maps.

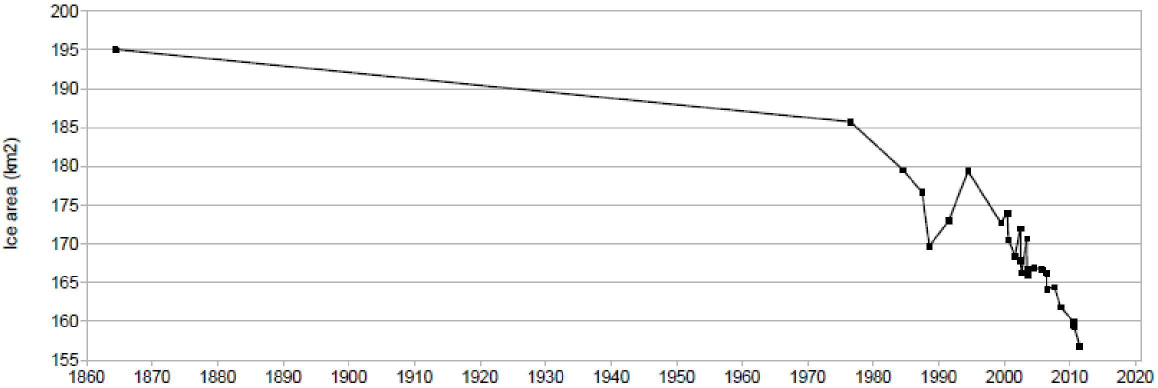


Figure 5: The ice covered area of Sørfonna from 1860 to 2011 measured using a combination of Landsat images, aerial photographs and old maps. For comparability reasons all glacier outlines are trimmed to the extent of the 1937 map.

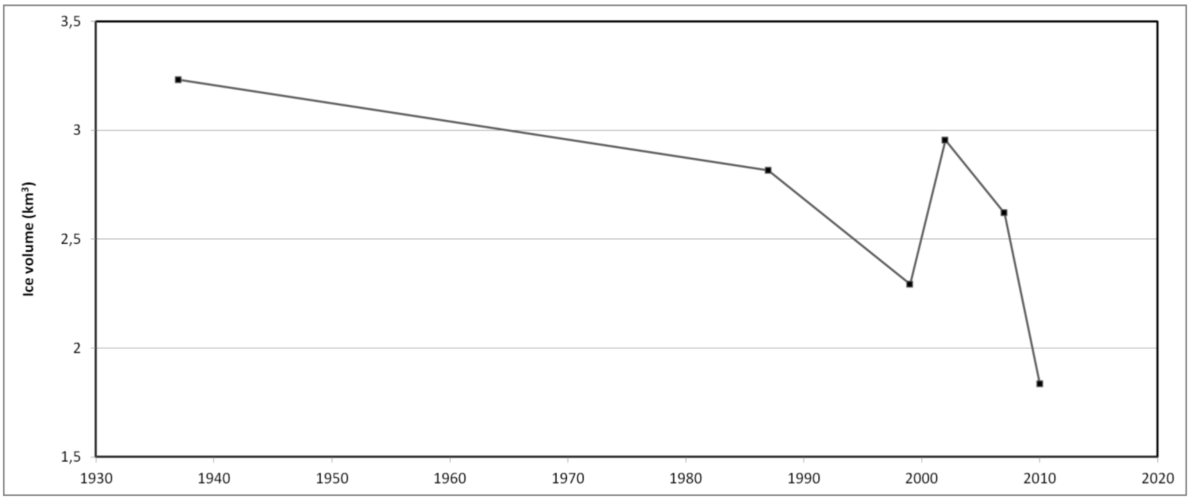


Figure 6: Volume of Nordfonna between 1937 and 2010 measured by comparing DEMs generated from digitised contour lines, ASTER images and provided pre-prepared. The volume trend shows the same trend as glacier area albeit not at the same resolution. Nordfonna is depicted having shrunk since 1937, a noticeable gain in mass occurred between 1999 and 2002.

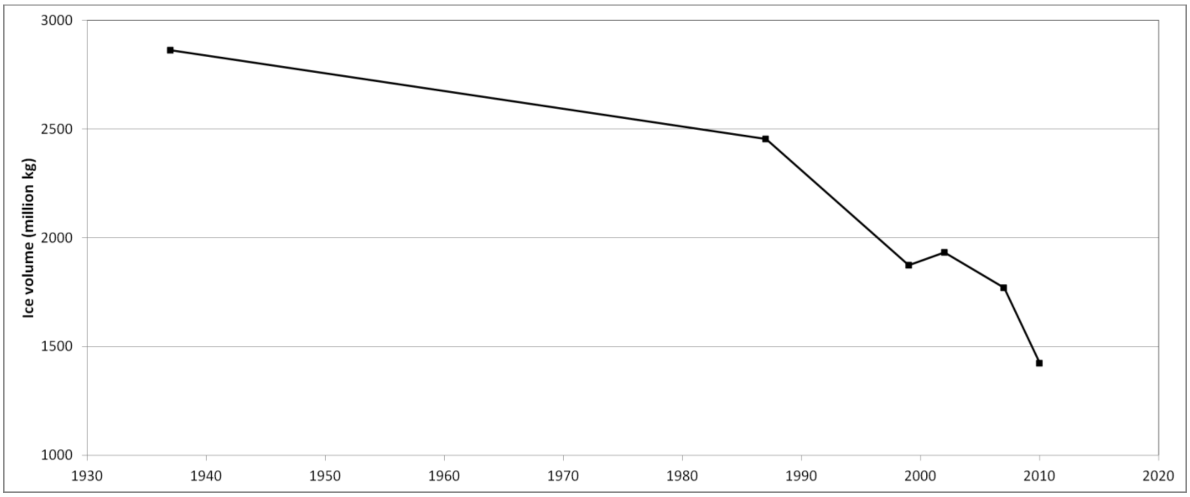


Figure 7: Change in volume of Midtfonna between 1937 and 2010 measured by comparing DEMS generated from digitised contour lines, ASTER images and provided pre-prepared. The volume trend shows the same trend as glacier area albeit not at the same resolution. Midtfonna is depicted having shrunk since 1937, a noticeable gain in mass occurred between 1999 and 2002. As the bedrock topography is unknown the volume cannot be calculated, only the change in volume.

Figure 8: Change in volume of Sørfonna measured by comparing DEMS generated from digitised contour lines, ASTER images and provided pre-prepared. The volume trend shows the same trend as glacier area albeit not at

CONCLUSIONS

Based on these results, remote sensing can be recommended for future glaciology studies, both as an error-checking and verification assessment, as well as as a methodology in its own right. It would be interesting in the future to also map the sub-glacial topography beneath the other two ice masses, this would allow the response times of each catchment, as well as the relative stability to be assessed. Also the volume time series could be expanded using InSAR data, this would be especially interesting throughout the 1990s to visualise the expansion and subsequent retreat of the glacier. Lastly, if data with sufficient temporal and spatial resolution could be obtained, it would be interesting to measure the glacier velocity from feature tracking. As the velocity is perhaps the most important glacier processes, this data could be used to estimate the processes occurring at Folgefonna's base.

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