MAPPING GLACIER CHANGES, SNOWLINE ALTITUDE AND AAR USING LANDSAT DATA IN SVARTISEN, NORTHERN NORWAY

J. HEISKANEN (1), K. KAJUUTTI (1) & P. PELLIKKA (2)
(1) Department of Geography, University of Turku (kari.kajuutti@utu.fi)
(2) Department of Geography, University of Helsinki

1. INTRODUCTION

The changes in the glacier area and mass balance indicate changes in the local climate. The water stored in the glaciers is utilized also in the hydropower production and agriculture. Although the glacier monitoring is important it has been restricted only to a small number of glaciers due to laborious field measurements. However, the optical remote sensing offers possibilities to expand the monitoring efforts by mapping *the glacier area*, *the snowline altitude* and *the accumulation area ratio* (*AAR*) that respond to the glacier mass balance i.e. the change in the glacier volume.

Several problems, however, hinder the applicability of the optical remote sensing data for glacier monitoring. The glaciers are usually situated in the mountainous areas, which cause geometric and radiometric distortions like relief displacement and topographic shadowing. The frequent cloud cover limits the amount of the useful data recorded in the optimal time i.e. late summer just before the first snow when snowline correspond roughly with the glacier equilibrium line. Furthermore, the dynamic ranges of the sensors are usually not optimized for highly reflective glacier surfaces, which cause the sensor to saturate.

2. STUDY AREA

The Svartisen area is located in the Polar Circle in the northern Norway (figure 1). The area consist of two main ice caps, Vestisen (220 km^2) and Østisen (148 km^2), and several smaller glaciers. Although the area comprise of numerous glaciers the massbalance measurements has been carried out in a very few of them. Only *Engabreen* (38 km^2), the second largest outlet of the Vestisen, has a long and continuous massbalance series. Therefore, more data is necessary to monitor the local variability of the glacier dynamics.

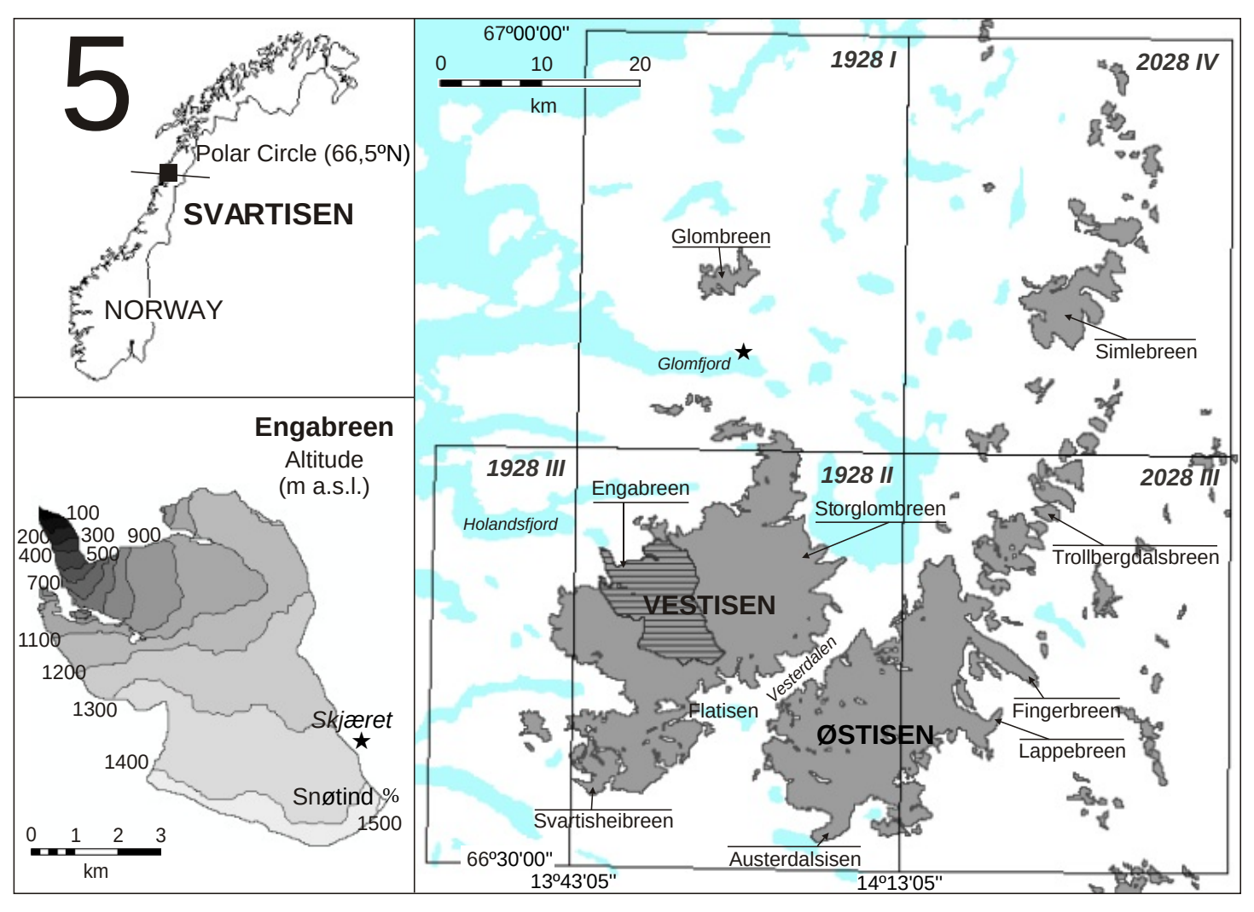

Figure 1. The location of the study area, the major glaciers in the area and the elevation map of the Engabreen.

Table 2. The total glacier area and the relative change between the recording dates.

n		Area (km^2)				Change (%)		
1978-99	2001	1978	1994	1999	2001	1978-94	1994-99	1978-99
165	68	478,74	475,33	449,72	238,24	-0,7	-5,4	-6,1

3. OBJECTIVES

- Formulate an image processing and interpretation chain to map changes in glacier area, snowline altitude and AAR using Landsat satellite data.
- Use the developed methodology to describe the variability in the changes of the glacier area, the snowline altitude and AAR in and around the Svartisen ice caps.

Table 1. The Landsat images used in the study. The images were recorded over different kinds of net balance years.

Image	Path	Row	Date	Solar zenith	Solar azimuth	Net balance (m w.eqv., Engabreen)
Landsat-2 MSS	214	13	15.8.1978	55	152	-0,51
Landsat-5 TM	198	13	25.8.1994	58	158	0,42
Landsat-7 ETM+	199	13	7.9.1999	61	170	-0,03
Landsat-7 ETM+	200	13	19.9.2001	66	171	-1,53

4. DATA

The satellite data included altogether four Landsat MSS, TM and ETM+ scenes recorded in 1978, 1994, 1999 and 2001 **(**table 1**)**. However, 2001 scene covered only the western part of the Svartisen. All the images were orthorectified. Solar elevation angles were low due to northern location and late summer acquisition date. Severe sensor saturation occurred in the visible bands of the sensors.

The digital elevation model (DEM, 25 meters cell size) was used to make a topographic correction for the satellite data, to interpret the snowline altitude and to characterize the morphology of the glacier basins.

The mass balance statistics from Engabreen were used as ground truth data to assess the interpretation of the satellite images. Some meteorological data was used to assess how the recording dates correspond with the end of the melting season situation.

The study area was divided into glacier basins according to the watersheds and ice divides. Every glacier basin was enclosed by the separate polygon in the vector layer to allow the interpretation of the glacier area and other parameters. The area was divide into 165 basins. Only 65 basins were visible in the 2001 image.

5. METHODS

The methodology applied is summarized in the figure 2. Gray-level thresholding of was used to make glacier masks. The *thermal infrared band* was used for ETM+ images. *Normalized difference snow index* (*NDSI*) was combined with the separate water mask for TM image. The MSS image required the manual delineation of the glacier borders, due to lack of short-wave infrared band. The manually finished masks were used to calculate the glacier area inside every glacier basin polygon.

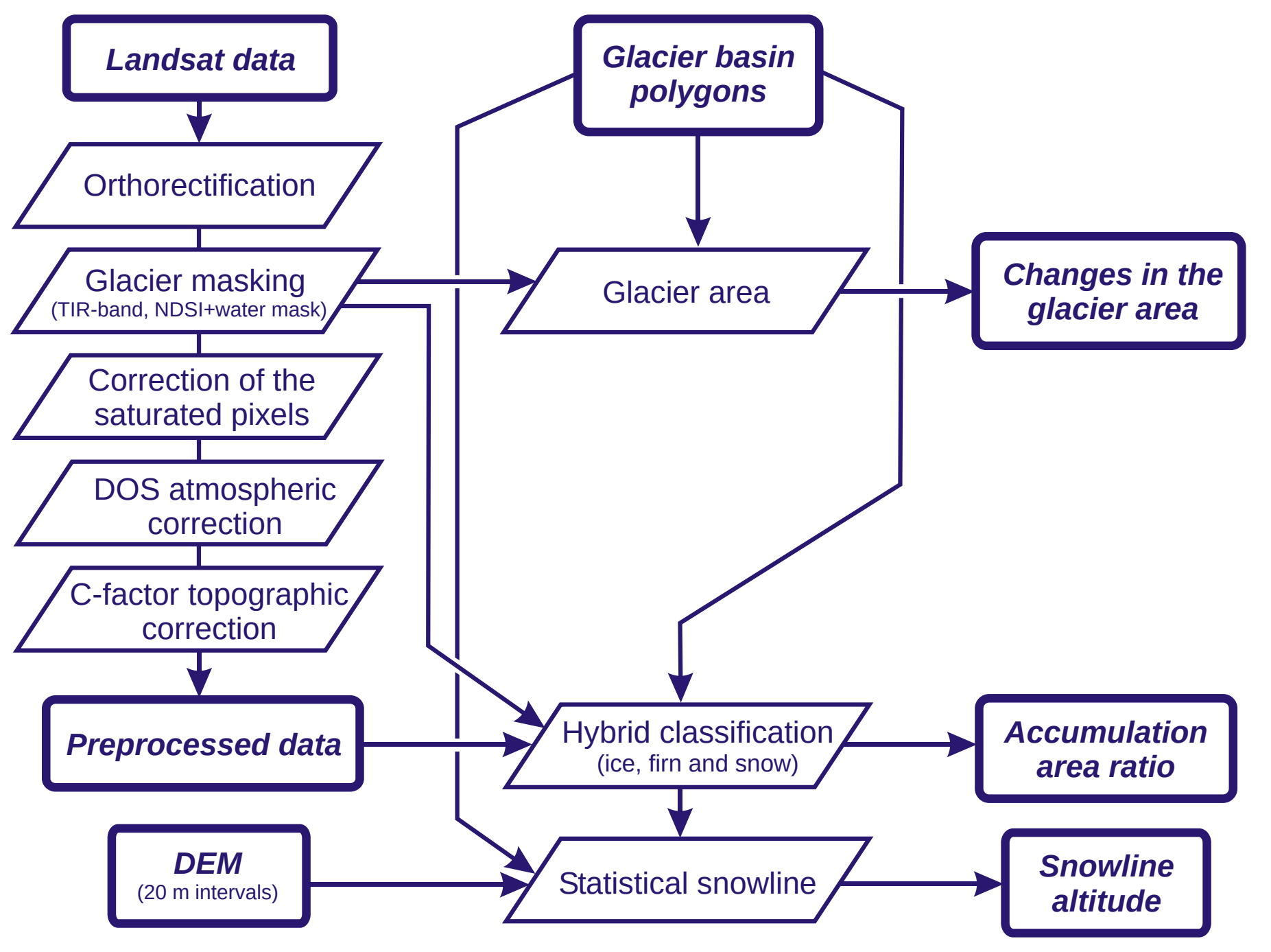

Figure 2. Flowchart summarizing the applied pre-processing and interpretation chain.

Some preprocessing steps were necessary prior the glacier zone classification. The sensor saturation in the visible bands was found to distort the topographic correction later on. Therefore, the unsaturated NIR bands were used to extrapolate the DNs of the saturated pixels in the visible bands. The linear equations were fit to the scatterplots of the DNs of the glacier pixels in the visible and NIR bands.

The corrected DNs were converted into reflectance using the DOS atmospheric correction, which aims to remove the path radiance. The correction was assumed to make the multi-temporal dataset more consistent, although the reflectance of the glacier zones differs considerably between years.

The C-factor topographic correction (Teillet *et al.* 1982) was applied to remove the effect of the varying slope and aspect, and hence to improve the glacier zone classification. The C-factors were defined separately for the glacier pixels since they depend on the anisotropic reflectance characteristics of the surface.

After the preprocessing, the glacier pixels were classified into *ice*, *firn* and *snow*. A hybrid of the unsupervised and supervised classification approaches was applied. The training areas were clustered using Isodata-classifier and clusters were visually interpreted into one of the tree classes. The interpreted clusters were used to derive the signatures of the different glacier zones, and to carry out the supervised maximum likelihood classification for the whole study area.

The *snowline altitude* was calculated using the statistical methodology of Seidel *et al.* (1997). According to the definition, the snowline altitude is the altitude of the lowest elevation interval in which the snow coverage is over 50 percent. Here, the snow coverage was calculated in each 20 meters elevation interval. The *AAR* was calculated by dividing the snow-covered area by the total area of the glacier derived from the glacier mask.

6. RESULTS AND DISCUSSION

The glaciers in the Svartisen areaseem to have been receding during 1978–1999 (table 2), but also positive changes have occurred in parts of the Vestisen and Østisen (figure 3). The relative change in the area has been largest in the small glaciers (figure 4a), which are likely to have the shortest response time, but are also the most likely to have interpretation errors. The relationship with the aspect includes considerable variation from glacier to glacier (figure 4b).

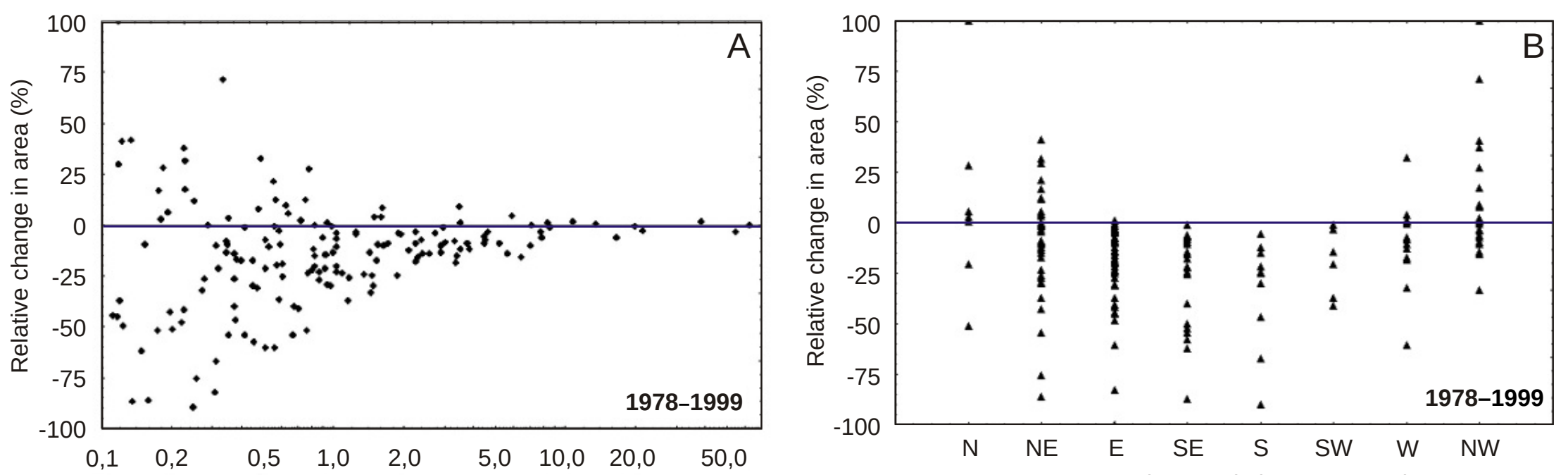

Figure 4. The change in the glacier area (%) in relation to the size of the glacier (A) and the aspect of the accumulation area (B).

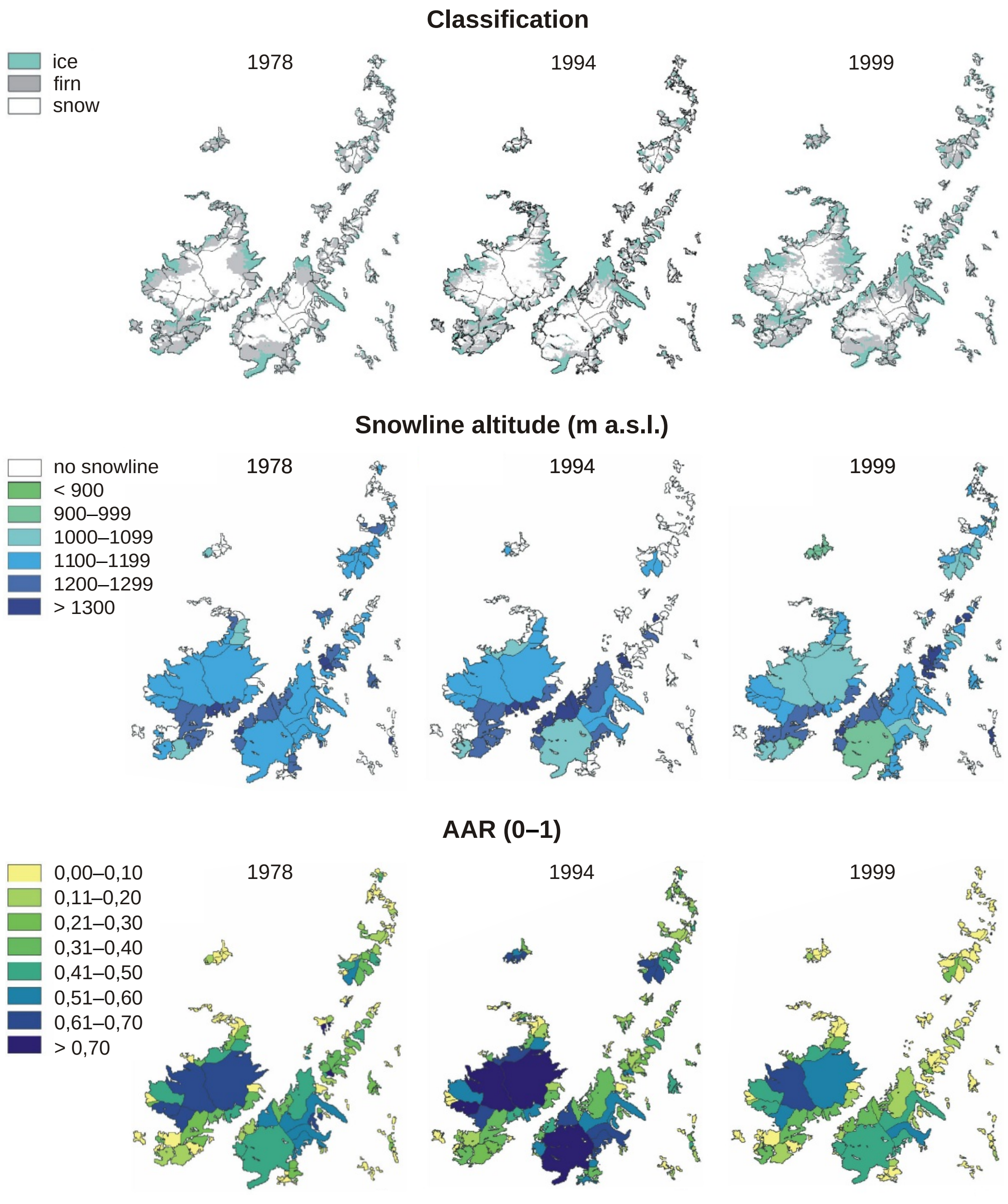

Figure 5. The distribution of the glacier zones, interpreted statistical snowline altitude and AAR in 1978, 1994 and 1999.

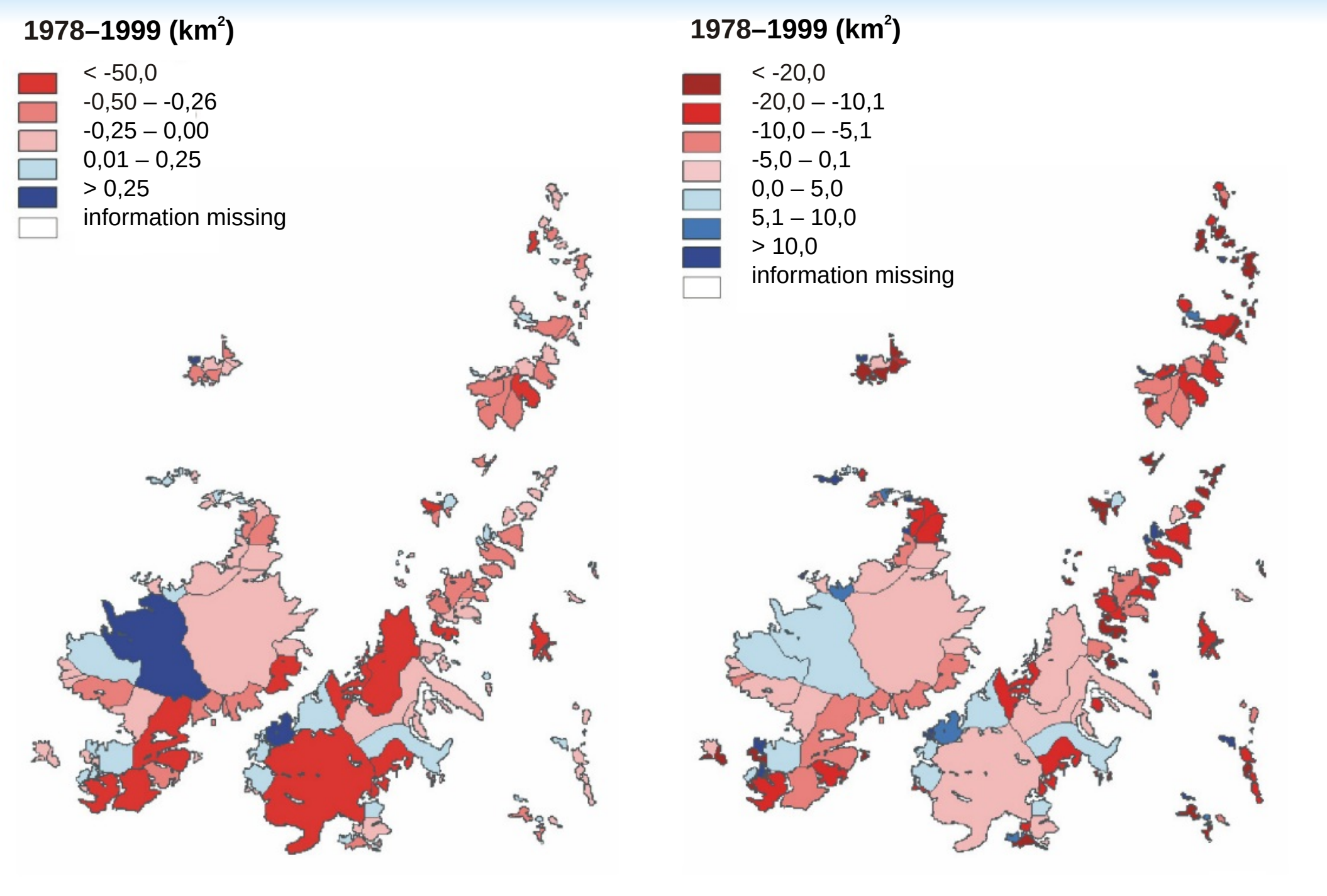

Figure 3. The absolute (km^2) and relative (%) change in glacier area 1978–1999.

The snowline is situated higher and AAR is smaller in eastern parts than in western parts of the Svartisen area, but there is lots of local variation in the pattern (figure 5). The statistical snowline altitude and AAR well correspond withobserved snowline altitude (2001) and measured ELA and AAR (figure 6). In 1978 the snowline altitude and AAR does not correspond with the measured ELA and AAR due to snowfall before the image recording. In 1999 the melting season continued for a while after the image recording and the snowline altitude was underestimated.

The snowline altitude and AAR have a relatively weak correlation probably due to differences in glacier morphology (table 3). In contrast, the coefficient of correlation is higher when the snowline altitude and AAR are compared between different years (table 4). This suggests that mass balance variations have similar relative pattern between years independent of the absolute mass

Table 3. The coefficient of correlation between the snowline altitude and AAR (*p<0,05).

r			
2001	1999	1994	1978
-0,18	-0,42*	-0,37*	-0,21

Table 4. The coefficient of correlation of the snowline altitude and AAR in different years (*p<0,05).

r	Snowline altitude			
	2001	1999	1994	1978
2001	1,00	0,68*	0,02	0,70*
1999		1,00	0,81*	0,85*
1994			1,00	0,70*
1978				1,00

r	AAR			
	2001	1999	1994	1978
2001	1,00	0,59*	0,41*	0,51*
1999		1,00	0,61*	0,55*
1994			1,00	0,61*
1978				1,00

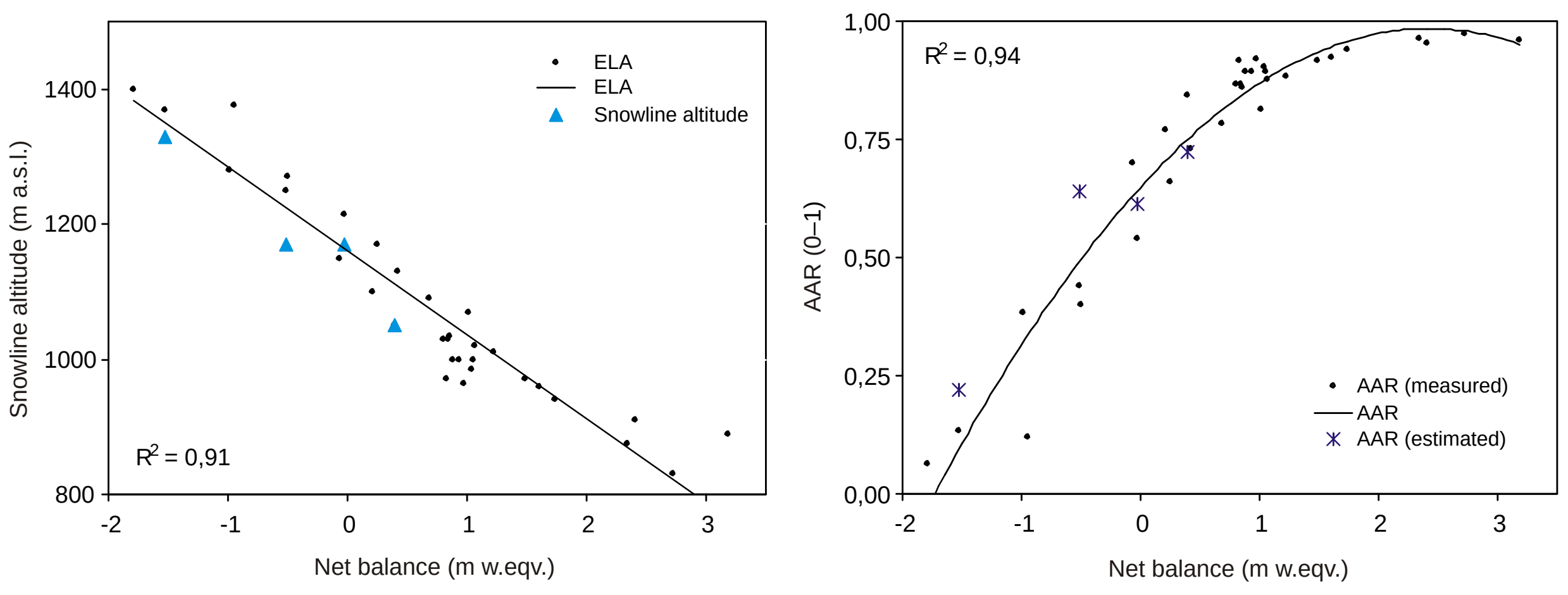

Figure 6. The relationship of the net balance, ELA and AAR based on mass balance measurements, and compared with the statistical snowline altitude and AAR estimated from the classification. Mass balance data: Norwegian Water Resources and Energy Directorate (NVE).

6. CONCLUSIONS

The preparation of the glacier masks is hindered by the shadows and snow patches. The supraglacial debris is not a problem in the Svartisen area. However, by using ETM+ thermal infrared band it is possible to identify the glacier borders also in the shadow, but the spatial resolution is 60 meters in contrast to 30 meters in the visible to shortwave infrared bands. The reflectance of the snow patches can not be separated from that of the glaciers. Therefore the glacier area was probably overestimated in 1994 and possibly also in 1978. The results shown here are interesting, but need more images are necessary to study the glacier changes in the area.

The hybrid classification quickens the visual interpretation of the glacier zones. The use of the statistical snowline reduces the subjectivity of the snowline interpretation and makes it faster compared to the manual delineation. The statistical snowline and AAR have a good correspondence with the available glaciological measurements, and the differences between measurements are well explained by the meteorological data. The accuracy of the classifications should be assessed, but it was not possible due to lack of realtime *in situ* data. However, the errors in the satellite image classification seem to be relatively small compared to the importance of timing of the data acquisition. Optical remote sensing and used methodology can be used to monitor the snowline altitude and AAR. However, ideal timing is difficult to achieve and several data sources needs to merged for operational monitoring.

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