ASSESSMENT OF GLACIOLOGICAL PARAMETERS USING LANDSAT SATELLITE DATA IN SVARTISEN, NORTHERN NORWAY

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ABSTRACT

The aim of the study was to assess mass balance related glaciological parameters using Landsat data in Svartisen, in northern Norway. Four Landsat (ETM+ 2001 and 1999, TM 1994 and MSS 1978) scenes were used in order to classify the glacier into zones of ice, firn and snow using maximum likelihood classifier. The pre-processing of the data included ortho-rectification, topographic correction and relative radiometric normalisation. Glacier borders were delineated and classifications were used for the assessment of snowline and AAR (accumulation area ratio), which were compared to *in situ* front position and net balance measurements. The Landsat 7 ETM+ thermal infrared band was found to be an effective means to separate glacier and surroundings, even in the areas of very pronounced topographic effect and shade. Classifications were considered to be accurate because of the simple classification scheme used and good differentiation between classes. Visual interpretation of the snowline was found to be essential. A good fit between mass balance measurements and assessed snowline and AAR was found. The results showed also that the pre-processing methods used could increase the value of the data, and that meteorological data is crucial in order to assess the suitability of the acquisition date. The results support the high potential of optical Landsat data for operational monitoring of glaciers.

INTRODUCTION

Mass balance studies of small glaciers are important as they respond to changes of regional climate and can thus serve, at least to some extent, as indicators of climate change (Oerlemans 2001). Glaciers can, however, have dissimilar dynamic behaviour even within small areas (Kuhn et al. 1985). Monitoring of the state of glaciers is important, for such purposes as hydropower production and natural hazard forecasting. Traditionally glaciological research has been carried out using laborious field measurements (e.g. Kjøllmoen 2001), which limits monitoring efforts to a relatively small number of glaciers.

Remote sensing data, including aerial photographs, optical satellite data and satellite radar data have been used in glaciological research over a long period (Gao & Liu 2001). New very high resolution optical sensors, satellite radars and laser scanners, offer new opportunities for the remote sensing of glaciers in the future. Furthermore, remote sensing has a strong potential for producing an operational monitoring system for glacier changes (Pellikka et al. 2001). Landsat data (available since 1972) have been widely used in glaciological research, and because of the long time continuum of the data, Landsat can provide insights into the past and present condition of glaciers. However, the extreme elevation differences of Alpine glaciers cause geometric and radiometric distortions, such as relief displacement and slope and aspect effect (Meyer et al. 1993). The dynamic range of most optical sensors is not optimised for high reflectance of snow, and sensor saturation often occurs. It is also rare to acquire a very clear scene for each year of interest, because of low temporal resolution and typically cloudy conditions in the mountains. Furthermore, the quick-looks provided are not reliable to confirm whether the glacier was snow covered or not during the satellite overpass.

The basic glaciological concepts are the extent of the accumulation and ablation areas (e.g. Oerlemans 2001). The accumulation area is the area of a glacier where the amount of snow accumulation exceeds the amount of snow and ice lost. Conversely, in the ablation area the amount of snow and ice lost exceeds the amount of accumulation. If the total annual accumulation exceeds the ablation, the net mass balance of a glacier is positive, and if ablation exceeds the accumulation it is negative. The zone of zero net mass balance is called the equilibrium line (EL), and its elevation the equilibrium line altitude (ELA). Glaciological studies have illustrated the high correlation between the net mass balance and the ELA (e.g. Østrem 1975). Similar qualitative information about the net balance is offered by accumulation area ratio (AAR), the ratio between the area of accumulation and the total area of the glacier (Rott & Markl 1989). Basically the accumulation area is covered by snow whereas the ablation area is bare-ice or firn at the end of the melt season. However, the visible snow line may differ somewhat from the EL derived from the accumulation and ablation measurements. Several studies have shown that snow, firn and ice can be discriminated using Landsat data. Hence, the accumulation and the ablation area can be distinguished if the time of acquisition is adequate, namely, late summer just before the new permanent snowfall. In this study the glacier is divided simply into zones of ice, firn and snow, regardless of the glacier facies concept (Williams et al. 1991).

The purpose of this study is to develop a useful procedure to derive glaciological parameters from Landsat satellite data, and examine how well the mass balance of Engabreen glacier in northern Norway can be estimated using Landsat data and the relationship between late summer snowline and EL. Four Landsat scenes (2001, 1999, 1994, 1978) from different kinds of mass balance years are used in order to classify the glacier area into zones of ice, firn and snow. The glacier borders have been delineated and classifications used assessing the snowline and AAR, which are compared to *in situ* net mass balance measurements. Special emphasis is addressed to careful pre-processing of the satellite data and appropriateness of the acquisition dates.

DATA

Study area

Svartisen ice cap is located in northern Norway and is intersected by the Arctic Circle (66º5'). It consists of two main ice caps, West and East Svartisen (Vestisen and Østisen) which are 220 and 148 km² respectively, as well as smaller glacial units (Figure 1a). There is a progression in climatic conditions from the more maritime on the western side of West Svartisen to drier and more continental on the eastern side of East Svartisen. The difference in climatic conditions is also reflected in a difference in glacier behaviour over recent years. Several of the glaciers of West Svartisen have shown advances in their front positions, while front positions in East Svartisen have generally retreated. Engabreen is one of the largest of the Svartisen glaciers with an area of about 38 km². It covers a considerable difference in elevation, from the top of Snøtind at 1594 m a.s.l. down to Lake Engabrevatnet, at only a few metres above sea level (Figure 1b). Over 86% of the area lies on the plateau above 1000 m a.s.l. Below this elevation, all the way down to the snout the ice is heavily crevassed with some extensive ice falls. Mass balance measurements have been carried out on Engabreen since 1970. There has been a net mass surplus since measurements began. The glacier front position has advanced about 200 m since 1991 reaching its farthest extent since the 1950s.

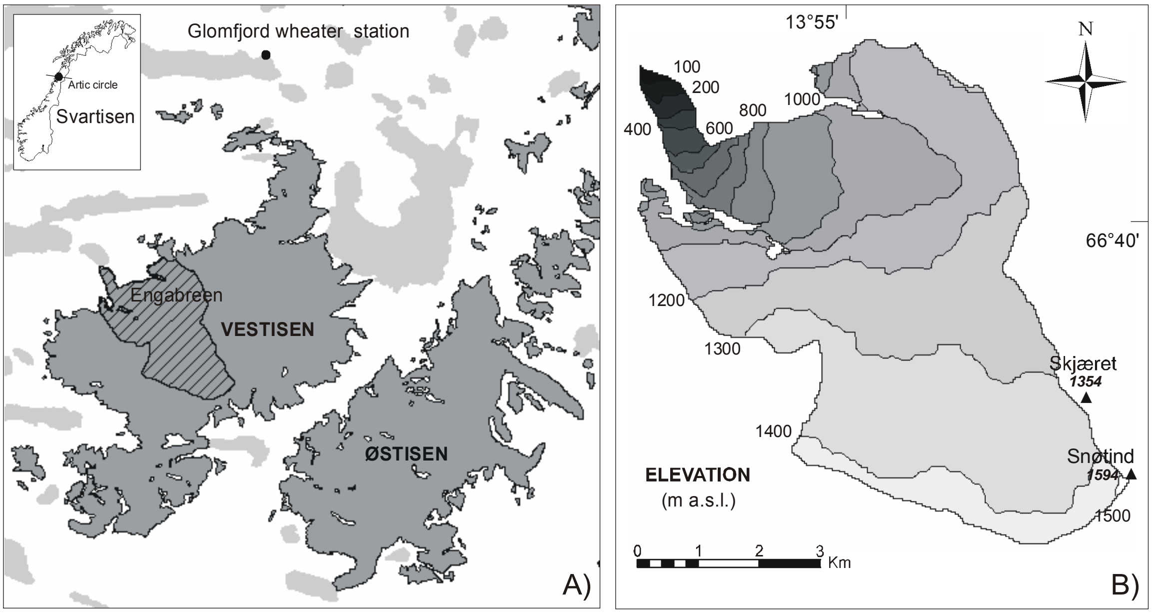

Figure 1: Location map (A) and elevation model (B) of the Engabreen study area.

Data

Four Landsat scenes were used (Table 1). Scenes were acquired under relatively clear atmospheric conditions and were cloudless. In the 2001 scene, there appeared to be some haze. The solar elevation angles are low because of essential late summer acquisition date and high northern latitude causing slope and aspect effects and shading. Severe sensor saturation occurred over the glacier in the visible bands of the Landsat data (Table 2). Ancillary data for the 2001 scene included visual observations of the glacier zones between 21st and 24th August and digital aerial photographs acquired on 24th September. A digital elevation model (DEM) of 100 metres grid size was provided by Statens Kartverk of Norway. The DEM is based on interpolation of the contour lines of the Norwegian 1:50 000 topographic maps.

Mean daily temperature and precipitation were used in order to assess the appropriateness of the recording dates. Meteorological data were recorded at a weather station situated in Glomfjord located 20 km north of Engabreen (39 m a.s.l.). Data are supplemented by hourly temperature measurements collected at the weather station Skjæret (1 360 m a.s.l.) located on the glacier at the border of Engabreen. In 2001 there was no new snowfall observed on the glacier five days after the scene recording, when autumn 2001 stake measurements were performed. In 1999 there was abundant precipitation over the preceding six days. However, the temperature was relatively high and there was no snowfall. In 1994 there was no major precipitation and temperature was relatively high during the weeks preceding scene acquisition. Conversely, in 1978 there was 25 millimetres precipitation over the preceding five days. Mean daily temperature was less than 10 degrees at Glomfjord (39 m a.s.l.) during the same period suggesting the probability of snow fall in the mountains.

The mass balance is calculated using the traditional (stratigraphic) methods, which give the balance between two successive summer surfaces. Methods and the mass balance records of Engabreen are summarised annually by the Norwegian Water Resources and Energy Directorate (NVE), (e.g. Kjøllmoen 2001). The glaciological data includes also the measurement of a distance from reference points to the glacier front.

METHODS

The geometric correction by ortho-rectification applying the DEM was used to remove the distortions introduced by rough topography. The general residual RMS error was 0.77 for 2001, 0.52 for

1999, 0.74 for 1994 and 1.70 for the 1978 scene. Nearest neighbour resampling was used in order to maintain the original digital numbers (DN).

Rough topography of the study area introduced variable illumination conditions and related radiometric distortions on slopes oriented in different directions. In order to produce a reliable multitemporal classification this slope and aspect effect has to be removed by topographic correction. In this study the C-factor method introduced by Teillet et al. (1982) was applied. However, C-factor correction reduces only slope and aspect effects, and does not remove the impact of adjacent slopes on illumination, variations in the optical thickness at the different elevations or cast shadows.

Table 1: The Landsat scenes used in the study.

Platform/Sensor	Path/Row	Date	**Solar elevation (º)**	**Solar azimuth (º)**
Landsat-7/ETM+	200/013	19.9.2001	24	171
Landsat-7/ETM+	199/013	7.9.1999	29	170
Landsat-5/TM	198/013	25.8.1994	32	158
Landsat-2/MSS	214/013	15.8.1978	35	152

Table 2: The percentage of saturated pixels belonging to the West Svartisen ice cap.

Band	ETM+ (2001) / %	ETM+ (1999) / %	TM (1994) / %	MSS (1978) / %
1	3.97	26.86	45.72	38.25
2	1.46	6.37	0.00	60.48
3	5.09	21.01	0.01	53.75
4	0.00	0.02	0.00	6.37

In the C-factor method the observed DN is assumed to be proportional to the cosine of the solar incident angle (*i*). The solar incident angle is the angle between the surface normal and the solar beam. The angle was calculated from the original elevation data, but was resampled to 30 or 80 metre spatial resolution depending on the resolution of the data using bilinear interpolation. The C-factor method assumes a non-Lambertian reflectance from the surface, and the correction is performed using

$$L_H = L_T \left[\frac{\cos(sz) + c}{\cos(i) + c} \right] \quad (1)$$

where: L_H = radiance over horizontal surface, L_T = radiance over inclined surface, sz = solar zenith angle. The parameter c should model the diffuse sky radiation but it simulates also the degree of the non-Lambertian behaviour of a surface. The value for c is defined by the linear regression of the DNs on the y-axis and cos (i) in the x-axis, and c is the ratio of the slope (m) and intercept (b) of the regression line ($c = b/m$). The degree of the correlation indicates the rate of success of the correction. The c-factor has to be defined for the specific surface of interest because the degree of the non-Lambertian behaviour differs between surfaces.

One c factor was defined for the whole West Svartisen ice cap. In that way, wider variation of i was represented than only in the part of Engabreen facing the north-west. The glacier mask was generated by thresholding for 2001 and 1999 scenes using ETM+ thermal infrared band, which showed a clear contrast between the glacier and the surroundings, even in areas of shadow. Because of a pronounced topographic effect none of the most common band ratios or principal components could offer sufficient contrast to set one threshold value to delineate the boundaries of the whole ice cap. Masks were roughly modified to fit for 1994 and 1978 scenes. Pixels applied to regression analysis had to fulfil the three criteria. Angle i should be smaller than 90° because otherwise the pixel is in a shadow and cannot be corrected. Pixels located in flat (slope < 1°) were excluded because variations in the DNs are greater due to the surface properties than because of topographic effects. Cast shadows are not corrected by the method and they were removed by the scene-based threshold in NIR band. All these criteria were tested to give better correlation between DNs and cos (i).

Factors such as solar zenith and azimuth angles, Earth-sun distance, sensor calibration and atmospheric conditions will still affect the DN of the pixel and hamper quantitative analysis of multi-temporal scenes. The impact of these factors was reduced by relative radiometric normalisation (Heo & FitzHugh 2000) after which visual comparison of the scenes and training of the classification was less subjective. Regression equations were applied to the 1978, 1994 and 2001 scenes to predict what a given pixel's DN would be if it had been acquired using the same instrument and under the same conditions as the 1999 reference scene. The 1999 ETM+ scene was selected as the reference because it had relatively wide dynamic range and only moderate saturation in visible bands. Atmospheric haze was also minimised. Equations were defined separately for each band by fitting regression lines to the DNs of the target areas of the reference scene and the scene being normalised. The 1978 MSS scene band 1 was fitted to 1999 ETM+ band 2, band 2 to band 3 and band 4 to band 4, respectively. The relative method was favoured over transformation into absolute reflectances because of the lack of atmospheric data and inaccurate sensor calibration.

Target areas were delineated from three surface classes - sea, bare rock outcrops and snow. Deep and clear water acts as the darkest target in the normalisation. Bare rock that has only minimal amount of vegetation cover represents a moderately bright target. Snow was included to cover a wider dynamic range by the targets. It was assumed that the reflectance of snow is not likely to change significantly between scenes. Three targets of size 20 to 30 pixels were delineated from all three surface types.

The borders of Engabreen were digitised on screen and glacier divides were defined from NVE reports (Kjøllmoen 2001). All the pixels inside the borders were assumed to be ice, firn or snow. Pixels were classified by the maximum likelihood classifier. The training areas were defined first for the 2001 scene, using the training areas sampled in the field in 2001 and checked from the digital camera data. Other classifications were trained in relation to this first classification. Separate training areas were needed for shadowed-ice, ice, shadowed snow and snow because of cast shadows in the glacier. Several training areas were needed also for the firn zones of different age.

The distance to the glacier front from the reference points was measured. The position of the snowline was interpreted and digitised from the classification results, and the snow lines overlaid to DEM to give mean elevation. AAR^1 was defined so that all the pixels above the altitude of the interpreted snowline belong to the accumulation area. This is comparable to AAR derived from mass balance data. AAR^2 was defined so that ice and firn were assumed to correspond to ablation area and solely snow to be equivalent to accumulation area.

RESULTS

The topographic correction decreased the slope and aspect effect, which was very pronounced before correction between north-eastern and south-western slopes. The correlation coefficient (r) in the regression analysis varied between 0.5 and 0.6 for bands 1–4 of 2001, 1999 and 1994. For bands 5 and 7 the correlation was only 0.2. For the 1978 scene the correlation was between 0.4 and 0.5. Saturated pixels were kept in the regression analysis, because it led to smaller visual distortions of the regression lines than their removal. Saturated pixels were corrected as well, even though their corrected values can be considered as artefacts. To prevent new saturation the data type was changed to 16 bits. Maximum i was set to 80 degrees because pixels that had i over 80 degrees were overcorrected and visual appearance was distorted. Noise in the DEM produced some striping to the scenes. Topographic correction showed some overcorrection in the mountain ridges, caused by the inaccuracy of the DEM and errors in the ortho-rectification. As a consequence, well-illuminated pixels on the sun facing slopes were wrongly corrected by the cos i values of the slopes oriented away from the sun. Errors caused by the differences in topography between the DEM and the glacier could not be observed, probably because of coarse resolution of the DEM. Cast shadows appeared dark grey when cast over ice or old firn, or light grey when cast over snow or new firn. The relative radiometric calibration succeeded in increasing the visual comparability of the scenes. However, the areas of ice and snow had a very different visual appearance, even though they belong to the same thematic class.

The classification results show considerable variation in the area of the glacier zones at different times (Table 3). The classifications were visually assessed to be of good accuracy. It was also indicated by the simple classification scheme and good separability of the spectral signatures. The only confusion was between firn and shaded snow in places. In the positive net balance year (1994), the firn zone is small compared to negative net balance years, and vice versa (Figure 2, Table 3). Changes in the area of snow zone, or AAR, are opposite. According to the results, Engabreen seems to be at its largest in 1994 when the snout was actually at the highest position. Therefore, the error in the area of Engabreen can be greater than the real variations. That is possible due to inaccuracies in glacier border delineation due to shadows cast.

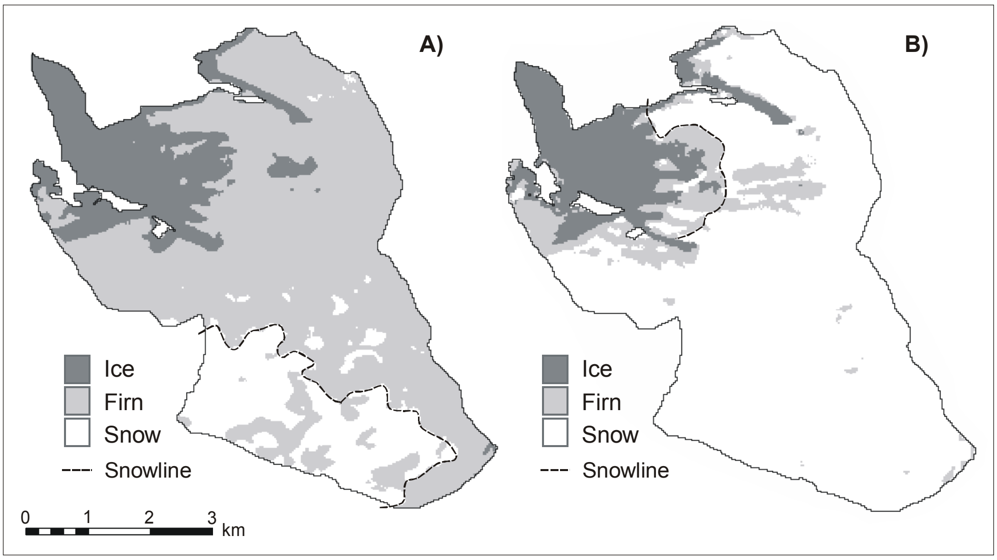

Figure 2: Classifications of the negative net balance year 2001 (A) and the positive net balance year 1994 (B). Classifications have been filtered by 3 x 3 majority kernel.

The borders of Engabreen and the glacier mask of West Svartisen were assessed in relation to front position measurements (Table 4). The borders of Engabreen have an error that is smaller than one pixel (30 metres for 2001 and 1999, and 80 metres for 1978). Similar accuracy (60 metres) has been achieved with masks that cover the whole of West Svartisen. Distances were to the edge of the outermost pixel that was assumed to belong to the glacier. Those pixels are usually mixed pixels of unknown extent and frontal changes smaller than pixel size could not be detected. In the case of Engabreen the visual interpretation of the glacier front is hampered by the shadows of the very steep glacier front. The thresholding of the thermal infrared band needs to be done carefully because of small differences in temperature between cold water and glacier ice and snow. The difference in DN values is only within 1-2 DNs.

Visual interpretation was considered to be the most accurate way to delineate snowline in the scale of one outlet glacier because it is the only method to take topography into account (Figure 2). The steepest areas of the glacier are ice in all scenes despite the state of the glacier. This could lead to misinterpretation if automatic methods are used. In 1999 and 1994 there seems to be a good fit between snowline altitude assessed from the satellite scenes and ELA (Table 5). In 2001 net balance of the glacier was negative in all of the elevation zones, which can be the case in negative net balance years. However, autumn 2000 was exceptional because of abundant melting in October after the ground measurements. Taking this into account the ELA in 2001 should be considerably lower than the mass balance measurements suggest, which is consistent with our image interpretation. In 1999 the weather was relatively warm and the ablation season continued after scene acquisition on 7th September until 28th September, when the first snow fell and the weather became colder. This suggests that the snowline was situated somewhat higher at the end of the ablation season than in the satellite image. In 1994 the first snowfall probably occurred on 30th August, only five days after the scene acquisition, and hence the recording date was optimal. However, ablation continued until 11th September.

In the 1978 data, the snowline is located 200 meters below the ELA, evidently because of new snowfall several days before the acquisition date. New snow explains also why the firn zone was relatively small and blue ice light toned. It also partly explains extensive saturation of the scene.

AAR^1 and AAR^2 vary quite considerably, but AAR^1 had slightly better fit with AAR derived from mass balance measurements. As methods, AAR and AAR^1 are also more comparable, generalising the spatial pattern of the ablation. There is an apparent linear relationship between ELA and the net balance of Engabreen for the time period 1978–2001 (Figure 3a). However, the relationship between AAR and net balance is not so straightforward (Figure 3b). The lowest elevation zones of the Engabreen tongue are so near sea level that they have a negative mass balance even in the most positive balance years. Satellite based measurements fit the field measurements well if 1978 is excluded. Mass balance can be estimated if a regression line is fitted to the mass balance data (Table 4). Estimated values for 2001, 1999 and 1994 give a coarse estimate of the net balance with an accuracy of approximately 0.2–0.3 m w. eqv. On Engabreen, zero mass balance seems to correspond to ELA of about 1100 - 1200 m a.s.l. and AAR of about 60 %.

Table 3: Classification results showing the areas of the different glacier zones, percentages of the zones and the total area of the glacier.

Year	**Ice /km²**	**Ice / %**	**Firn /km²**	**Firn / %**	**Snow /km²**	**Snow / %**	**Glacier area /km²**
2001	7.1	18.2	25.3	64.5	6.8	17.4	39.2
1999	6.5	16.6	6.9	17.6	25.8	65.8	39.2
1994	5.8	14.7	4.2	10.6	29.6	74.7	39.6
1978	6.5	16.7	2.0	5.1	30.6	78.2	39.1

Table 4: Comparison of the distance from the reference points to the glacier snout based on the field survey and Landsat data.

Year	**Coordinates of the reference point (east, west)**	**Measurement direction /deg**	**Field survey /m**	**Satellite scene /m**	
				Visual delineation	**Glacier mask**
2001	445200; 7397418	155	30	40	20
1999	445179; 7397462	155	45	50	70
1978[1]	445217; 7397382	155	20	0	-
1978[2]	445278; 7397420	168	60	0	-

Table 5: Comparison of the glaciological parameters assessed from satellite scenes with field measurements.

Year	Satellite scene				Field measurements		
	Mean snowline altitude /m a.s.l.	AAR^1 / %	AAR^2 / %	Estimated net balance / m w.eqv	ELA / m a.s.l	AAR / %	Net balance / m w.eqv.
2001	1350	20.9	17.4	-1.30	>1594	0.0	-1.53
1999	1180	60.2	65.8	-0.18	1220	53.0	-0.03
1994	1050	81.7	74.7	0.68	1070	78.7	0.39
1978	1060	79.5	78.2	0.61	1260	40.9	-0.51

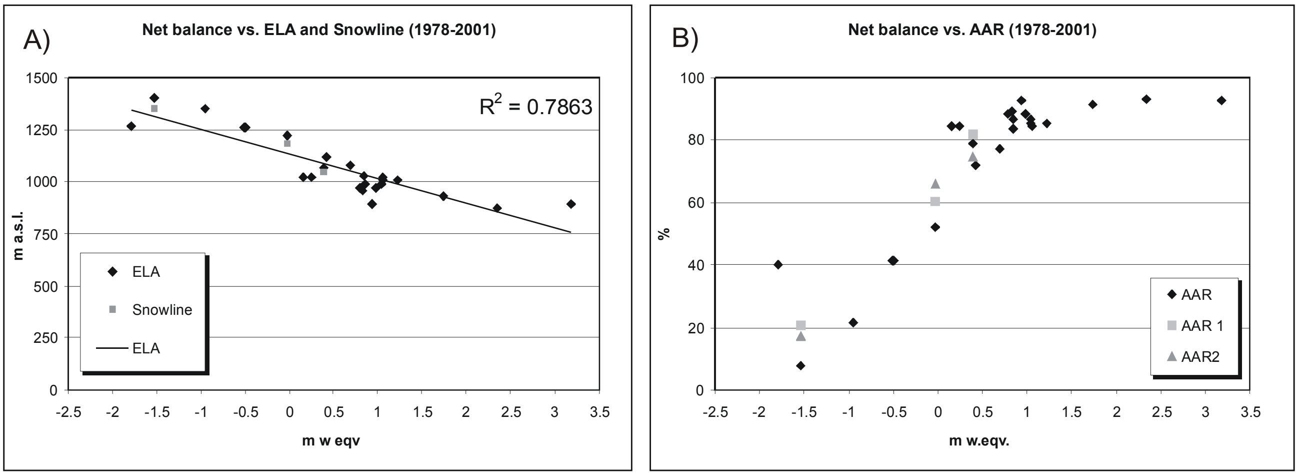

Figure 3: The relationship of the ELA and net balance (a) and AAR and net balance (b).

DISCUSSION AND CONCLUSIONS

The study showed that rather simple topographic correction and radiometric normalisation will increase the interpretability of the individual scenes and comparability of the multiple scenes, even though coarse spatial resolution of the DEM caused some distortions. The grid size of the DEM should be at least the same as the satellite data (Meyer et al. 1993). However, C-factor correction can be used in order to correct all Landsat bands, differently from the band ratioing method that has been used in glaciological studies (Rott & Markl 1986). Defined c-factors are possibly not the optimal ones due to the fact that the bi-directional reflectance function of the ice and snow are different (Winther 1993). In the relative radiometric calibration it was also assumed that the reflectance of snow does not vary between scenes, which is not exactly true.

The thermal infrared band of Landsat 7 ETM+ was found to be useful for separating glacier from the surroundings and to assess changes of glacier borders. It is especially effective when grey level thresholding of the visible bands or any of the principal components (Sidjak & Wheate 1999) cannot be used. However, more comparisons with the *in situ* measurements are needed to estimate the accuracy of the method, even though preliminary comparisons suggest it to be about one pixel (60 m). One pixel accuracy for visual delineation was also concluded by Williams et al. (1997).

The maximum likelihood classifier yielded accurate classifications due to good separability between classes and due to a simple classification scheme. Visual interpretation of classified scenes was considered a useful means for delineating snowline in the scale of one outlet glacier. Classification produces also a measure of AAR that considers spatial variations of ablation better than the one calculated from field measurements. On Engabreen the border between firn and snow corresponded well to the EL derived from the mass balance measurements. Also AAR showed a good fit in the mass balance years inspected supporting the results of Rott and Markl (1989) but more scenes from extreme net balance years are needed. The use of meteorological data for assessing scene quality proved to be important particularly for the 1978 MSS scene.

In general, the results support the high potential of optical Landsat data for monitoring glaciers, which requires the reliable delineation of glacier borders and classification of glacial zones. However, the timing of optimal data causes problems in operational monitoring, since applicable data cannot be acquired for each year. Future studies will concentrate on processing and analysing more Landsat scenes and outlet glaciers from the Svartisen area and from Austria, in combination with glaciological measurements. Pre-processing of the data will be improved by DEM of higher spatial resolution, which should allow better topographic correction, and to separate the cast-shadows by a line-of-sight algorithm. The benefits of the conversion of DNs to some estimate of reflectance will be considered also. These results will be used in developing an operational monitoring system of glaciers (Pellikka et al. 2001).

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REFERENCES

1. Kuhn, M. et al. 1985. Fluctuations of climate and mass balance: Different responses of two adjacent glaciers. Z. Gletsch.kd. Glazialgeol. 21: 409–416.
2. Kjøllmoen, B. (ed.). 2001. Glaciological Investigations in Norway in 2000, NVE Report 2. (The Norwegian water resources and energy directorate (NVE))Oerlemans, J. 2001.Glaciers and climate change. (A.A. Balkema Publishers)
3. Gao, J. and Liu, Y. 2001. Applications of remote sensing, GIS and GPS in glaciology: a review. Prog. Phys. Geogr. 25(4): 520–540.
4. Pellikka et al. 2001 Development of an operational monitoring system for glaciers – Synthesis of earth observation data of the past, present and future. Proc. Int. Workshop on Geo-Spatial Knowledge Processing on Natural Resource Management. Varese, Italy, 2001: 28–29.
5. Meyer, P. et al. 1993. Radiometric corrections of topographically induced effects on Landsat TM data in an alpine environment. ISPRS J. Photogramm. 48(4): 17–28.
6. Østrem, G. 1975. ERTS data in glaciology–an effort to monitor glacier mass balance from satellite imagery. J. Glaciol. 15(73):403–415.
7. Rott, H. and Markl, G. 1989. Improved snow and glacier monitoring by the Landsat Thematic Mapper. Proc. of a Workshop on ‘Earthnet pilot project on Landsat Thematic Mapper Applications’. Frascati, Italy, 1987: 3–12. ESA SP-1102.
8. Williams, R. S., Hall, D. K. and Benson, C. S. 1991. Analysis of glacier facies using satellite techniques. J. Glaciol. 37(125):120–128.
9. Teillet, P.M., Guindon, B. and Goodenough, D.G. 1982. On the slope-aspect correction of multispectral scanner data. Can. J. Remote Sens. 8(2):84–106.
10. Heo, J. and FitzHugh, T.W. 2000. A standardized radiometric normalization method for change detection using remotely sensed imagery. Photogramm. Eng. Rem. S. 66(2):173–181.
11. Sidjak, R.W. and Wheate, R.D. 1999. Glacier mapping of the Illecillewaet icefield, British Columbia, Canada, using Landsat TM and digital elevation data. Int. J. Remote Sens. 20(2):273–284.
12. Winther, J-G. 1993. Landsat TM derived and in situ summer reflectance of glaciers in Svalbard. Polar Res. 12(1),37–55.
13. Williams, R.S. et al. 1997. Comparison of satellite-derived with ground-based measurements of the fluctuations of the margins of Vatnajökull, Iceland, 1973-92. Ann. Glaciol. 24:72–80.