Comparison of remote sensing derived glacier facies maps with distributed mass balance modelling at Engabreen, northern Norway

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Abstract Calibration and validation of glacier mass balance models typically rely on mass balance data derived from measurements at individual points, often along altitudinal gradients, thus neglecting much of the spatial variability of mass balance. Remote sensing data can provide useful additional spatially distributed information, e.g. on surface conditions such as bare ice area, firm cover extent, or snow. We developed a semi-automated procedure to derive glacier-facies maps from Landsat satellite images, and applied it to Engabreen, an outlet glacier from the Svartisen ice cap in northern Norway. These maps, discriminating between firm, snow and ice surfaces, are then used as a reference for mass balance modelling. Facies information shows a general agreement with the available few field observations and results obtained by distributed mass balance modelling. We conclude that Earth Observation products provide a powerful, although as yet poorly exploited tool, for calibration and validation of distributed mass balance models.

Key words Engabreen; glacier facies; glacier mass balance; Landsat; modelling; Norway; remote sensing

INTRODUCTION

Glacier mass balance models are a basic requirement for climate sensitivity studies of glaciers. They are commonly calibrated and validated using measured mass balance (e.g. Braithwaite et al., 2003) or discharge data (e.g. Hock, 1999). Such data are only available from a small number of glaciers due to constraints given by access, logistics and costs, particularly in remote areas. In addition, mass balance programmes generally suffer from a small number of in situ measurements upon which reported area-averaged mass balance and gradient values are based. Consequently, these data neglect much of the spatial small-scale variability typical for mass balance and, hence, they are of only limited value in validating the spatial pattern of mass balance as generated by distributed mass balance models. In recent years a trend towards fully distributed modelling can be observed, i.e. a mass balance is calculated for each grid cell of a digital elevation model (e.g. Klok & Oerlemans, 2003; Braun & Hock, 2004).

Remote sensing offers a powerful tool to provide enhanced spatial information as a base to validate and calibrate spatially distributed mass balance models and it also provides data for sites void of direct mass balance measurements. Repeated glacier
facies maps delineating the areas of firn, snow and ice can be used to validate modelled snow line retreat during the melt season. Glacier facies maps have been generated from optical and microwave satellite data for many years (e.g. Hall et al., 1987; Hall et al., 1988; Williams et al., 1991; König et al., 1999; Braun et al., 2000), but rarely have such data been incorporated in calibration or validation of mass balance models. Heiskanen et al. (2003) have previously combined some glacier facies maps with in situ mass balance measurements (snow line and equilibrium line altitude) for the Engabreen site.

The purpose of this study is: (1) to develop a semi-automated processing chain to derive glacier facies maps; (2) to demonstrate their suitability to support the validation of a glacier mass balance model. As a test site we chose Engabreen, a steep outlet glacier from the Svartisen ice cap in northern Norway. We used satellite derived glacier facies maps to validate the results obtained from a distributed mass balance model. The model and its application to Engabreen are described in detail by Schuler et al. (2005).

STUDY SITE

Engabreen is located close to the northern Norwegian coast (66°40′N, 13°45′E) and parties an outlet glacier of the western Svartisen ice cap (Fig. 1). About 14% of the 38 km² glacier area is located in a channel-like narrow valley, whereas the main part is located on the rather flat plateau of the ice cap above 1100 m a.s.l. The glacier has an altitudinal range of about 1500 m, reaching almost down to sea level. Engabreen has shown considerable changes in mass balance and resulting frontal changes since the 1950s (Kjøllmoen et al., 2003). Changes in glacier front position have been monitored since 1970, but sporadic measurements exist back to about 1900. During the 1990s the glacier advanced again, reaching the proglacial lake, but started retreating again in about 2000. The Norwegian Water Resources and Energy Directorate (NVE) have additionally operated an extensive mass balance programme, which started in 1970 (e.g. Kjøllmoen et al., 2003).

METHODOLOGY

Facies maps

For this study, a total of eight Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) scenes (30-m spatial resolution, seven spectral bands) acquired between 1984 and 2002 were available. Emphasis was given to data from the ablation period (summer). Table 1 gives an overview of the data sets. The few data available until 1999 also show the paucity of the previous operational acquisitions over glaciated areas. With the operation of Landsat-7 ETM+ since 1999 and its Long Term Acquisition Plan (LTAP) the amount of multi-temporal data sets within one season increased considerably. The theoretical repeat cycle of 16 days is even higher in high latitudes where satellite orbits converge and ground coverage of one area is
Fig. 1 Map of Engabreen and location in Norway.

**Table 1** Overview of Landsat satellite data utilized in this study.

<table>
<thead>
<tr>
<th>Sensor / Platform</th>
<th>Path</th>
<th>Row</th>
<th>Acquisition date</th>
<th>Centre longitude</th>
<th>Centre latitude</th>
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<td>13</td>
<td>1984-08-13</td>
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<tr>
<td>Landsat-7 ETM+</td>
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<td>13</td>
<td>2002-09-08</td>
<td>15.20°E</td>
<td>66.56°N</td>
</tr>
</tbody>
</table>

provided by various satellite tracks (images with different path/rows in the Landsat reference system). However, the theoretical improvement is still limited by the frequent cloud cover at our study site.

To extract the thematic information from the multiple Landsat satellite images a semi-automated procedure was developed (Fig. 2). The first step comprised the geocorrection and clipping of the data to a master scene (15-AUG-1999) by manual tie-point search in the imagery. A root mean square error below one pixel could be achieved for co-registration of all images, which was also proofed by the visual
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inspection. Sidjak & Weathe (1999) previously reported the suitability of Principle Component Analysis (PCA) for facies mapping. In this study, a Tasseled Cap Transformation (Richards, 1995) was applied to reduce the data redundancy of the three visible channels as well as to increase the separation between clouds and snow surfaces. The resulting data set was classified into 10–15 classes using the unsupervised ISODATA algorithm (Richards, 1995). The ISODATA algorithm automatically generates a user-specified number of thematic classes based on the (spectral) information of the input image. Subsequently the output classes were merged for each image to generate masks to distinguish glacier and snow covered areas as well as clouds from other surfaces. The merging of the thematic classes was performed by visual inspection of an experienced operator. In the present study, cloud masking was slightly better in the Tasseled Cap imagery than in the PCA data. Using the snow and glacier mask the PCA data for the remaining area was then used to apply a second unsupervised classification (ISODATA) to extract the three facies types (bare ice, firn and snow). Snow refers to last winter’s or fresh snow, and firn refers to snow that has survived at least one summer. In a first iteration 10 classes were used. In case operator inspection revealed no adequate separation of the surface types, an ISODATA run with 20 classes was performed. The final step comprised the export to the model format (ArcInfo ASCII). Results mainly rely on the visual interpretation of the operator but also some limited ground control data from direct observations were available for accuracy assessment.

Distributed mass balance modelling

We compare the satellite derived facies maps with surface types modelled by Schuler et al. (2006). They modelled the mass balance of Engabreen (and hence also surface

![Flowchart of the processing chain.](image)
type) for the mass balance years 1974/1975–2001/2002 using a grid-based mass balance model utilizing a 25-m resolution digital elevation model and driven by daily temperature and precipitation data from Glomfjord (39 m a.s.l.), a meteorological station located about 20 km north of Engabreen. Snow accumulation was computed using a linear increase of precipitation with increasing elevation along with a fixed threshold temperature to discriminate snow from rain, while melt was modelled from a temperature-index approach incorporating potential direct solar radiation (Hock, 1999), thus considering topographic effects other than elevation. Model parameters were calibrated for the period 1993/1994 to 2001/2002 and left unchanged for the modelling of the remaining period (1974/1975–1992/1993) used for model validation. Schuler et al. (2005) used mass balance measurements (area-averaged mass balances, mass balance gradients and point data) for model calibration and validation. Using satellite glacier facies maps we provide additional data for model validation and test the performance of the model to reproduce the snow line retreat derived from the satellite images.

RESULTS AND DISCUSSION

We validate the satellite derived facies maps by comparison to direct surface observations taken during mass balance measurements. Such data are limited since field visits rarely coincided with satellite overpasses. However, based on all available data, observations at stake locations agreed with the satellite derived classification of the nearest grid cell in 35 out of 38 cases (92%) giving some confidence in the facies analysis, although more ground data would be desirable.

The comparison of the satellite derived facies maps and the modelled surface type maps reveals an overall reasonable agreement (Fig. 3), thus providing additional confidence in the results of the distributed mass balance model. The strong altitude dependence of the melt on Engabreen is clearly captured by both data sets. Bare ice areas coincide during both the model validation (especially e.g. 13 August 1984) and the model calibration period (especially e.g. 17 July 2001 or 07 August 2002). Generally, the model results show less small-scale spatial variability in facies types compared to the observations, which can be expected if we bear in mind the simple formulation of accumulation within the model. Redistribution of snow is not considered in the accumulation model, and only spatial effects related to elevation and solar radiation are incorporated in the melt model. In contrast, the satellite-based facies maps show a patchier pattern, including small-scale effects of lower accumulation on convex terrain form, crevasse patterns, etc. This is especially visible in the data from 15 August 1988 and 08 September 2002. The comparison of the firn areas is hampered due to lack of available detailed data; Schuler et al. (2005) ran the model with a constant firn line. The area above 1100 m a.s.l. was assumed to be underlain by firn once the winter snow cover has melted. For areas below this elevation an ice surface was assumed.

The bare ice areas can be classified with a high accuracy, whereas the spectral signatures in the wet snow areas leave more room for interpretation by the operator during the recoding of the unsupervised classification. The satellite based facies map in September 2002 shows snow on surfaces previously classified (August image 2002) as bare ice or firn. This is most likely due to late summer snowfalls that are not adequately
reproduced by the model. Although concurrent field observations are not available, field visits in late summer (20 August and 26 September) indicated snowfall events.

Fig. 3 Comparison of the satellite derived facies maps (right) and the results of the glacier mass balance model (left) for seven dates from 1984 to 2002. In 2002 three Landsat acquisitions enable more detailed model validation. Arrows mark feature discussed in the text.
The satellite data shows a narrow elongated feature (marked by an arrow in Fig. 3), which is persistent in all data sets. This striking pattern is not reproduced by the model results. However, the feature coincides with an area of enhanced topographic shading and reduced potential direct solar radiation (Fig. 4) compared to its immediate vicinity. This suggests that the feature detected in the satellite image may have been caused by illumination effect in the satellite data. Alternatively, the area accumulates less snow due to the topographic anomaly, and thus firn is exposed earlier than in the surroundings. In any case, the synergetic use of the distributed mass balance model also supports the interpretation of the satellite data and *vice versa*. For accurate topographic correction, radiative transfer modelling and an accurate DEM are needed. As the DEM quality was not considered sufficient, simpler approaches were taken into account. Hall *et al.* (1987) used a band ratio TM4/TM5 to improve the discrimination of facies in shadow areas and Dozier (1989) deployed a normalized differential snow index \((\text{TM2} - \text{TM5})/\text{(TM2} + \text{TM5})\) to overcome illumination effects as well as pixel saturation over glaciated and snow covered areas. For the present study these measures did not reveal significant improvements in the classification. Heiskanen *et al.* (2003) confirm this indirectly. They applied a cosine correction to eliminate terrain effects at the Engabreen site; however, their pre-processing steps obviously could not remove the reported feature. This might be interpreted as a further indication for a real bare ice area due to reduced accumulation.

In the lower right corner of the satellite facies maps partially outside Engabreen but on the ice cap, some bare and firn patches appear in some of the images. This is most likely a real feature related to blowing snow and resulting lower accumulation and consequently earlier bare ice appearance.

![Fig. 4](image.png) Annual mean potential direct solar radiation for Engabreen as computed by the distributed mass balance model. Arrow marks feature discussed in the text.
CONCLUSIONS AND OUTLOOK

We have presented a comparatively fast and efficient method to extract glacier facies maps from Landsat satellite data. As well as a suitable reference, an experienced operator is required for recoding of the unsupervised classifications. Some direct observations at various locations agreed well with the surface types derived for the closest pixel from the satellite images. Although more ground truth data would be needed to independently validate the glacier facies maps, the comparison with the model results suggests that the remote sensing products provide a valuable additional base to validate a distributed mass balance model. Agreement was generally reasonable, although some ambiguities arising from the spectral similarity of snow and firn in the remote sensing data still remain and require further refinement of the method. Furthermore, the distributed modelling was limited by insufficient input data leading to the assumption of a fixed firn line at 1100 m altitude. Discrepancies between the model and remote sensing maps can be explained either by the complex pattern of snow accumulation, which is not captured by the model formulation, or by illumination effects which are difficult to extract from the Earth Observation data. The remote sensing product would certainly also support the validation of more complex accumulation routines incorporating other variables than altitude.

Although, as yet, remote sensing cannot provide quantitative information on, e.g. snow water equivalent, the summer facies maps enable highly valuable spatial information (difference between bare ice, snow and firn, and thus snowline retreat) for the validation of the mass balance models at different dates. At the same time the precisely co-registered satellite images can be used to extract and visualize changes in glacier front positions.

Future activities should also incorporate weather independent SAR data as a more frequent source of facies maps (or maps of radar glacier zones – terminology is ambiguous). The direct use of remote sensing products to initialise the model will also be analysed. Another option would be to investigate if the temporal evolution of SAR backscatter on the glacier over a season can be brought into a relationship or correlation with observed mass balance.

Acknowledgements This project is part of the Global Monitoring for Environment and Security (GMES) initiative “The Northern View” financed by the European Space Agency (ESA) under ESRIN/contract no. 17062/03/I-IW.

REFERENCES


