Geoinformation for European-wide Integration, Benes (ed.)

Radar facies on the West Greenland ice sheet: Comparison with AVHRR albedo data

Ian A. Brown
Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden

Keywords: SAR, Greenland ice sheet, glacier facies, AVHRR, albedo

ABSTRACT: The distribution of glacier facies is strongly inter-related with the energy budget and hence mass balance and runoff from ice masses of all sizes. On the Greenland ice sheet where surface topography is often unpronounced, facies can migrate on scales of 10s or 100s of kilometers horizontally on the inter-annual time scales. Significant differences in ice sheet mass balance, radiation fluxes, and runoff may result. Over longer time periods facies trends will feedback into the north Atlantic and thus hemispheric climate system. Glacier facies are typically mapped in aerial photographs and optical satellite imagery. The reliance on optical imagery however introduces an uncertainty related to cloud attenuation and the availability of cloud free imagery. Here the utility of ERS SAR data in comparison with a previous study using AVHRR imagery is examined. In this experiment SAR facies derived from Quicklook scenes with a similar spatial resolution to those of AVHRR are mapped in a GIS environment. The movement of facies such as the (transient) snow line and slush line are mapped and compared, where possible, to the AVHRR series reported by Greuell and Knap (2000). The Quicklooks are found to have a degree of utility but suffer from poor spatial resolution which limits their usefulness. However, low resolution SAR data (pixel spacing of 100-400 m) are found to be optimal for wide coverage of ice sheets such as west Greenland.

1 INTRODUCTION

The Greenland ice sheet is a significant influence on atmospheric and ocean circulation in the northern hemisphere and has global impact through, for example, the thermo-haline circulation. The response of a glacier or ice sheet to climate perturbations is reflected in the glacier volume and annual mass balance. The former is a long-term integrated measure of the glaciers reaction to climate whilst the latter is the annual budget of the glacier (the net balance of accumulation minus ablation). Analysis of glacier volume change are complicated by factors such as glacier response on multiple (coincident) time scales, non-climate influences (geothermal heat flux, atmospheric circulation change etc). Mass balance measurements are typically less complex and can be related directly to climate data. However, mass balance measurements normally require intensive field investigations in hostile or even dangerous environments.

Proxy measurements and models of mass balance have become useful tools for assessing trends in glacier mass balance where *in situ* measurements are not available. Equilibrium line altitudes (ELAs), glacier facies, degree-day and energy balance models have all been related to glacier mass balance (e.g. Ohmura et al 1992, Brown et al 1999, Hock 1998). Remote sensing has become a major tool for the monitoring of mass balance proxies such as the end of summer snow line. Williams and Thorarisnsson (1973) and Østrem (1975) were amongst the early proponents of remote sensing in glaciology using ERTS-1 (Landsat) imagery to map glaciological features. Since then numerous investigations, including but not limited to, Williams (1987), Williams et al. (1991) and Dowdeswell et al. (1994) have derived new techniques to map glaciological features using remote sensing.

Greuell and Knap (2000) have related the movement of the slush line line (the upper limit of saturated snow) to mass balance on a sector of the West Greenland ice sheet. Their methodology was based on albedo variation in NOAA Advanced Very High Resolution Radiometer (AVHRR) imagery. Greuell and Knap (2000) and Greuell (2000) found that the albedo contrast between slush and unsaturated snow was more pronounced than that between the bare ice and slush zone. Hence the slush was delineated and compared with mass balance data. The slush line series accounted for 70% of the mass balance compared with 82% using a degree-day factor. Only 60% of the images revealed the slush line position and the mapping resolution was reduced to 5000 m in post-processing.

In this paper ERS-1 and –2 quicklook images are used to examine the potential for facies mapping using low resolution SAR. The aim is to delineate the snow line (lower boundary of snow and slush cover) and the slush line. The former is most likely to correlate with the specific balance. The latter should be comparable with the AVHRR time series collected by Greuell and Knap (2000) as a form of quality control. The goal of the investigation is to assess the potential of low resolution SAR products for use in ice sheet monitoring, glacier-climate modelling and related activities. SAR imaging is not subject to cloud attenuation or differential solar illumination and at high latitudes has a short revisit time. Thus SAR imagery may offer a higher resolution alternative to AVHRR imagery without the loss of temporal resolution but with a greater potential for accurate detection of the migration of facies boundaries. SAR data are sensitive to physical scatterers such as ice inclusions enabling the mapping of different glacier-climate zones or facies (e.g. Rott et al. 1993; Jezek et al. 1993). Furthermore, the sensitivity of C-band SAR to liquid water content may allow spatio-temporal analyses of melt water production and drainage. Thus SAR data are be able to provide products for use in both mass balance and glacier-hydrology investigations.

2 SITE AND DATA

Over 110 ERS SAR quicklooks with coverage of the study site were downloaded from the European Space Agency's (ESAs) browse service, ODISSEO (http://odisseo.esrin.esa.it/). The study site corresponds to that of Greuell and Knap (2000) centred on the K-transect at ~ 67.4ºN 48.0ºW (Fig. 1). The region is ca. 250000 km^2.

The data were geo-referenced to GIS layers from the Digital Chart of the World (DCW) with a minimum absolute accuracy of less than ±5000m (DCW is accurate to within ca. 7000 ft). The SAR images were contrast enhanced and in some cases classified using unsupervised algorithms to enhance backscatter boundaries. The quicklooks are 8-bit images with a nominal resolution of ca. 200 m. Translation to sigma-nought was not performed. Additional data used in the study included the National Snow and Ice Data Center (NSIDC) Greenland SAR mosaic, a full resolution ERS-2 SAR scene from December 1999 and Terra ASTER imagery from August 2001.

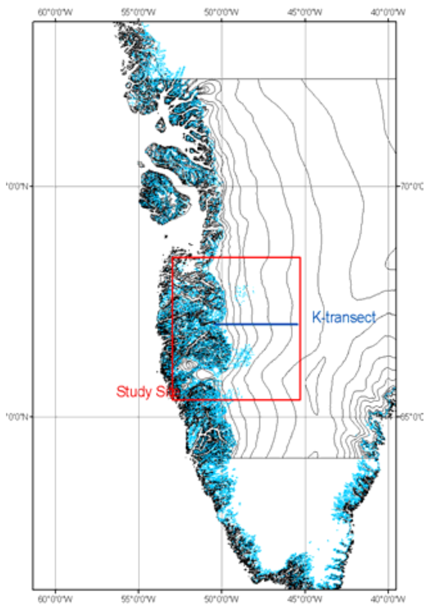

Figure 1. Site map showing the region surrounding the K-transect, West Greenland

2.1 *Comparison of AVHRR Images and ERS Quicklooks*

The nominal spatial resolution of the AVHRR data is 1.1 km; the data used by Greuell and Knap (2000) was over-sampled to a resolution of 1 km. The slush line mapping algorithm used reduced the resolution to 5000 m through the application of a 5 x 5 pixel kernel to map the standard deviation of the albedo. Geo-referencing accuracy was reported to average 2000 m. The cumulative error margin is therefore in the approximately 7000 m. Temporal resolution was reduced by the occurrence of cloud over the ice sheet. Greuell and Knap were nevertheless able to compile a dataset with an impressive repeat time of 7 days on average although there were occasional gaps of up to 14 days. In total 113 images were acquired covering the melt seasons from 1990-1997 (thus averaging 1 acquisition per seven days over the entire period).

The SAR data acquired in this study were confined to those available as quicklooks from the ESA online image browser. 110 images from 1992-1995 were acquired including a number of winter images used to define the percolation zone and ELA. The temporal resolution was significantly worse than the AVHRR series although this is largely due to the availability of the free data. Only around 30-50% of ERS SAR acquisitions have quicklooks available (depending on date and platform). The total back catalogues over the study site are 573 images and 1057 images for ERS and Radarsat respectively (averaging 2 acquisitions per week). SAR overpasses in fact occur approximately every 2 days. The nominal resolution (pixel spacing) based on the number of samples was 200 m but in reality the degradation of the imagery and issues relating to classification in the presence of local topographic variation and significant speckle meant that the operational resolution was limited to around 1000 m.

2.2 *Backscatter zonation in C-band SAR imagery over terrestrial ice masses*

The ERS SAR coverages were mapped in a GIS. Delineation of boundaries in individual images was not possible based on contrast enhancements and calibration to sigma-nought values was not feasible using the 8-bit quicklooks. Thus the backscatter boundaries were mapped using mosaic-ed images.

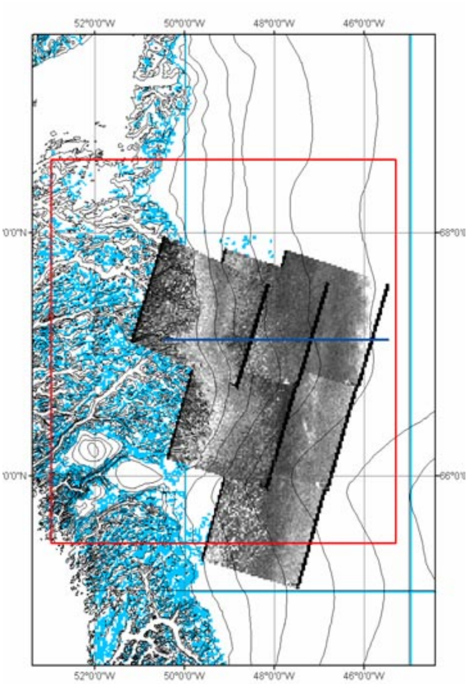

Figure 2. A sample of the ERS SAR dataset geo-referenced to the DCW Greenland boundary, hypsometry and drainage polygons. The sample data are from July 1994.

The zonation of radar backscatter over glacier and ice sheets has been addressed by a number of authors (Fahnestock et al. 1993; Jezek et al 1993, Partington 1998, Ramage et al 2000, Hall et al. 2000). On the Greenland ice sheet zones such as the bare ice facies (a bright scatterer) or the percolation facies (a very bright scatterer) may extend over much of an image making delineation difficult. Mosaicing improves the contextual information and limits erroneous zonation that may be due to the frequency distribution of pixel values used in contrast enhancements. In a typical image covering the whole glacier the zonation expected might be (see also Fig. 3):

- Bare ice facies- a bright scattering zone in summer due to high surface scattering from the rough ice surface
- Wet snow facies- a dark zone corresponding to the region containing significant liquid water in the upper snow pack resulting in absorption
- (Frozen) Percolation facies- a bright scatter due to effective diffuse (also known as volume) scattering from ice inclusions such as lenses and pipes
- Dry Snow facies- a dark zone resulting from low surface and diffuse scattering and the extinction of the signal through transmission and diffusion.

The physical processes of scattering have been identified through the application of field investigations (including scatterometry) and modeling (Rott et al. 1993; Shi et al. 1993; Forster et al. 1999).

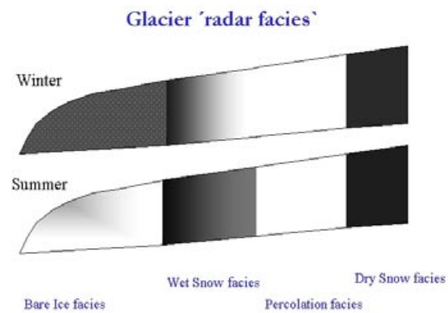

Figure 3. Facies scheme for radar backscatter from a glacier or ice sheet (after Benson 1959 and others).

3 RESULTS

Within certain constraints the SAR imagery exhibited boundaries relating to the slush line and snow line as well as other facies zonation (Figure 4). On average the quicklooks allowed about four slush line and snow line positions to be mapped for each melt season. The slush line was problematic in many images due to poor contrast between the wet and saturated (slushy) snow: the snow line normally presents a clearer boundary. In addition the firn edge at the end of summer and the upper extent of near-surface melt water percolation were mapped. With an extension of the study site to the east annual changes in the dry snow line might also be mapped.

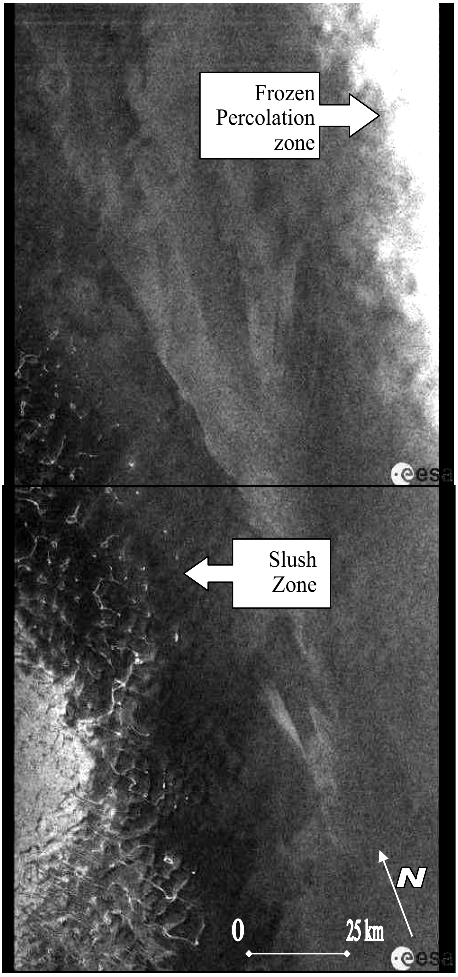

Figure 4. Uncorrected adjacent ERS-1 SAR quicklooks from 22nd July 1994 showing the frozen percolation zone as a bright region in the north east corner of the image and the slush zone as a black region in the center-west of the images.

The zonation was less clear than expected. The discontinuous nature of the snow line meant that the structure of the boundary was fractal and thus the position of the mapped boundary was a product of the mapping resolution. In such cases image classification was used to assist decision-making. Nevertheless the resolution of the SAR data was insufficient to support accurate delineation where the snow line was discontinuous.

Only limited comparison with the AVHRR results was possible based on published material in Greuell and Knap (2000) and Greuell (2000). However, where possible the SAR slush line appeared to conform to the AVHRR derived slush line (within error margins). There were four acquisitions in 1994 roughly contemporaneous with the AVHRR time-series data; the SAR slush-line conformed to the AVHRR slush-line within the error margin. For other years the pattern of the snow and slush lines was compared with data from other years (NSIDC SAR mosaic) and was found to conform to the pattern observed in those data. Facies mapping in Iceland has shown that such boundaries tend to maintain a stable retreat pattern that is often topographically determined (Brown 1998).

4 DISCUSSION

4.1 *Quicklook Performance*

Quicklooks provide rapid access to low resolution data that have proven useful for a variety of applications in the past (Carrivick and Brown *in press*; Rau et al. 2001). Here they have been shown to provide potentially useful data where low spatial resolution is acceptable and poor radiometric resolution is not an issue. In the case of Greenland the temporal resolution was found to be relatively high with regular coverage of the study site (assuming access to all acquisitions). Presumably the regular coverage of the west coast of Greenland is related to sea ice monitoring for navigation and will therefore be maintained. Rau et al. (2001) report poor temporal resolution over a study site in Antarctica suggesting that this may be a limitation for some study sites. Rau et al. also regard the lack of radiometric quality to be a limitation although for facies mapping this does not seem entirely warranted.

The accuracy of mapping with the quicklooks was problematic. The resolution of the data was significantly worse than the nominal resolution (based on number of pixels). The degradation of the data is assumed to be a product of the Quicklook generation process. The relative performance of full resolution data and low resolution data were also assessed. A full resolution scene acquired in winter 1999 was found to delineate the firn edge only to within a few hundreds of metres. The full resolution scene contained significant speckle. The hummocky ice surface also had a significant radiometric influence complicating delineation of the firn edge. ASTER data show that hummocky topography occurs near the ELA over much of the West Greenland ice sheet. Full resolution data from glacier such as Hofsjökull Iceland have performed well in other investigations (e.g. Hall et al. 2000).

As a proxy for low resolution SAR data the NISDC Digital SAR Mosaic of Greenland was also analysed (Figure 5). The mosaic has a pixel spacing of 100m as a result of resampling of full resolution data. The mosaic showed that at resolutions on the order of 100s of metres SAR data can accurately map facies boundaries and with wide spatial coverage (e.g. ScanSAR). Locally however mapping accuracy can be reduced by the discontinuous nature of the boundaries. In such cases a rigorous rule must be established in order to maintain the integrity of the mapping.

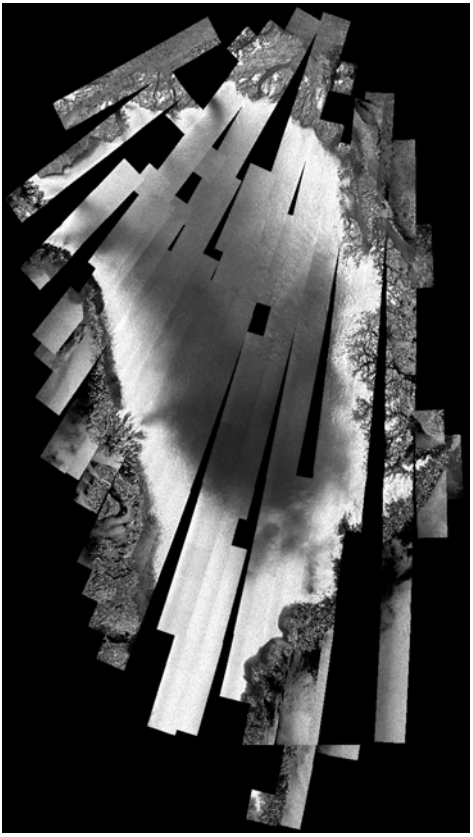

Figure 5. The NSIDC Digital SAR Mosaic of Greenland

The use of the mosaic-ed quicklooks and the NSIDC Digital SAR Mosaic emphasise the importance of wide spatial coverage. Individual scenes or quicklooks are limited in their context and are therefore difficult to map. Wider coverage improves the contextual information considerably improving the confidence with which boundaries can be identified and mapped. In the region of the K-transect individual facies zones may extend over 30 km wide. Hence a single scene may include only one full zone. In such cases the backscatter interpretation may also be complicated by, for example, a hummocky snow/ice surface or unusual surface conditions such as temporary, unexpected refreezing leading to an erroneous classification and mapping. Such anomalies are likely to be recognised during the compilation of data but illustrate the potential problems associated with taking small samples in isolation: Greenland is big.

4.2 *Firn loss in Greenland*

The facies zonation found in the data series shows a steady retreat of the snow line and slush line over the summer. In the frozen percolation zone, indicators of melt were also mapped as the maximum position of surface/near-surface melt. These varied significantly between years (28 km between the maximum and minimum position in the period 1992-1995). However, more acquisitions would be required to make definitive statements about maximum altitude of surface melt and percolation. The firn edge retreated ca. 29 km (±5 km) in the period 1992-1998 at 67ºN. Another transect at 67.3ºN also found a retreat of 29 km between the quicklooks from 1992 and 1999 (1998 mass balance season). Laser altimetry over the region has found that significant localised thinning has also occurred (Krabill et al. 1999).

4.3 *Surface Drainage*

Frozen and thawed lakes are readily apparent in many scenes. The lakes occur frequently (estimated as 5% of surface area). The lakes were found to be largely stable and could be used to check georeferencing between years. ASTER data showed that very few drained lakes could be found and that the drainage network was inter-annual and presumably had a co-dependence with the local ice topography. Over longer periods changes were discernable in lake extent suggesting that a time series could be established to analyse the surficial drainage.

5 CONCLUSIONS

This study has shown that the potential exists to use ERS SAR Quicklooks for glacier facies monitoring over large ice masses. This corroborates a previous investigation on the Antarctic Peninsula (Rau et al. (2000). For slush line monitoring the data offer an alternative to AVHRR data but do not necessarily improve upon the algorithm of Greuell and Knap (2000). However, the data do offer an alternative: the snow line which for many applications may be preferable to the slush line. Furthermore the SAR data can delineate the frozen percolation zone well. This zone and its upper limit is of interest in terms of melt progression and glacier hydrology. The firn edge has also been mapped using in winter data and a significant retreat recorded.

Quicklooks have poor spatial and radiometric resolution. Full resolution PRI data were not found to resolve the facies any better without the acquisition of large data volumes. Swath width was found to be as important as spatial resolution. Thus the optimal image product might have the following characteristics:

- Wide swath- of at least 200 km
- Moderate/Low spatial resolution of 100-400m
- Regular temporal acquisitions to allow for anomalies that result in poor analysis

Future work may therefore adopt ScanSAR or similar SAR imagery for facies mapping. In the region of West Greenland regular acquisitions are undertaken to support ship navigation and hence data should be available.

ACKNOWLEDGEMENTS

All ERS SAR imagery are copyright of the European Space Agency. The author is grateful to ESA for the opportunity to use these data. The National Snow and Ice Data Center (NSIDC) Digital SAR Mosaic was developed by Mark Fahnestock (University of Maryland, Department of Meteorology) and Ron Kwok (JPL, California Institute of Technology, Pasadena) and distributed through the NISDC, Boulder Colorado. The digital Chart of the World GIS layers were provided by Penn State University and is copyrighted by ESRI. The author would like to thank the Swedish National Space Board for funding the conference attendance.

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