CHARACTERISTIC SNOW AND ICE PROPERTIES OF A NORWEGIAN ICE CAP DETERMINED FROM COMPLEX ERS SAR DATA

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ABSTRACT

The transient snow line (TSL) and equilibrium line altitude (ELA) on a glacier are extremely sensitive to climate regime. Hence, variations in TSL position and ELA can be used as early indicators of climate change. This paper examines the utility of ERS SAR imagery for monitoring the TSL on Hardangerjøkulen ice cap, southern Norway, in 1995 and 1996. SAR products are used in two complementary ways. First, we demonstrate the utility of backscatter responses from precision SAR data to assist with quantification of snow and ice conditions over the ice cap surface. Calibrated backscatter signals are sensitive to snow and ice surface roughness and snowpack structural features. Areas of free liquid water content within the snow can also be detected using SAR backscatter data and hence be used to identify areas of snowmelt. Second, we demonstrate the possibility of using interferometric coherence information to track the TSL through the summer melt season. Coherence maps were derived from single look complex image pairs acquired from successive ERS-1 and ERS-2 Tandem. Change in the position of steep coherence gradients on the ice cap between successive tandem passes indicates migration of the TSL zone over the ice cap. Results from analyses of processed SAR data show good agreement with field data collected during ablation seasons suggesting that ERS SAR is an effective tool for ELA monitoring.

1. INTRODUCTION

The need to quantify and predict global climate change is an ever pervasive need within the natural environmental sciences. Current estimates predict mean surface global temperatures to rise by 1-3.5°C by 2100 (Houghton *et al.*, 1995). The resulting changing climate will have potentially significant effects on glaciers and ice caps and may lead to substantial changes in runoff regimes in glacierised catchments. In Norway there are over 1600 glaciers many of which make an important contribution to commercial and industrial water supply. Thus, there is a requirement to monitor accurately snow and ice conditions from year to year in order to manage water supplies efficiently and plan for future climate changes.

The transient snow line (TSL) and equilibrium line altitude (ELA) are glacier parameters that are related to the mass balance of a glacier or ice cap system (Paterson, 1994). Laumann and Reeh (1993) have modelled the impact of CO2 doubling and resulting temperature changes on the mass balances of selected glaciers in southern Norway. They found that unless accompanied by significant precipitation increases, southern Norway glaciers will experience ELA rises of approximately 200-300 m corresponding to very negative mass balances. Hence, locating the annual ELA at the end of the melt season can indicate whether a glacier mass is increasing or decreasing.

In glacierised catchments TSLs have been monitored and mass balances calculated using visible/infra-red satellite remote sensing systems (e.g. Østrem, 1975). However, on many occasions in Norway, ice caps and glaciers are continually cloud obscured rendering visible and infra-red sensors ineffective for glacier monitoring. Active microwave systems, however, can be use to monitor snow and ice and Dowdeswell *et al.* (1994) suggested that SAR imagery acquired during autumn and winter can be used to locate the ELA at the end of the previous melt season. Several other studies have demonstrated the utility of SAR for snow and ice monitoring (e.g. Bernier and Fortin, 1991, Guneriussen, 1997, Kelly, 1996, Rott *et al.*, 1988). The aim of this project is to use ERS SAR data to monitor snow and ice characteristics and the progression of the TSL over a Norwegian ice cap in order to locate the ELA at the end of the melt season.

2. STUDY AREA AND MASS BALANCE CHARACTERISTIC

The ice cap that we are investigating as a test case is Hardangerjökulen in southern Norway (Figure 1). It is located at 60°32'30" North, 7°11'25" East and covers an area of approximately 73 km2. It is situated on the main water divide between Hardangerfjorden and Hallingdal. Mass balance measurements of Hardangerjökulen have been made by the Norwegian Polar Institute since 1963 with the Norwegian Water and Energy Administration taking over in 1987. Records show that from the early 1980s, the ice cap's net mass balance has generally been positive although there has been an increase in annual variability from the mid-1980s.

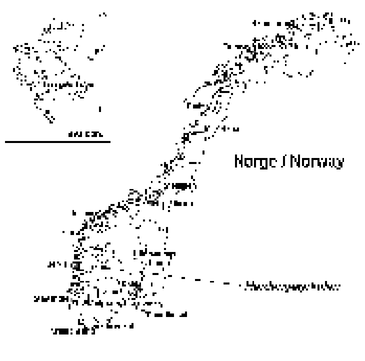

Figure 1. Study site location

3. METHODOLOGY

Our approach to ELA monitoring has two parts. The first part examines the ERS SAR backscatter return (0) from Hardangerjökulen and attempts to quantify the 0 variations encountered in terms of climatic and meteorological conditions. Backscatter signals from snow and ice are known to vary depending on several factors. Surface scattering and volume scattering are the prime controls and these are affected by the presence of free liquid water in the snow pack (Guneriussen, 1997) and by snowpack stratigraphy (Kelly, 1996, Dowdeswell *et al.*, 1994, Rott *et al.*, 1988). Fresh, non-metamorphosed dry snow is effectively transparent to ERS SAR (on account of its C-band frequency). Wet snow absorbs emitted radar signals at C-band yielding low 0 values (typically -10 to -20 dB) (Guneriussen *et al.*, 1996). Snow packs that contain evidence of crustal layers throughout and ice lenses also affect the backscatter signal through complex scattering mechanisms (Kelly, 1995). Hence, for TSL monitoring, where moist and complex stratigraphy snow types are present, C-band SAR can be a useful tool. However, it is important to quantify the direct impact of these physical parameters on the radar backscatter.

Once, these climatic controls and snowpack stratigraphic characteristics have been identified, the second part of the project aims to apply interferometry to repeat pass SAR data to try and model the TSL progression throughout the melt season. Since the TSL can be viewed as a mobile zone of diurnally changing snow conditions, it should be possible to monitor the zone using coherence maps from repeat pass interferometry. The zone is surrounded by relative stability with high coherence at higher elevations, due to of relatively stable snowpack conditions, and high coherence at lower elevations due to stable surface ice conditions. By selecting SAR passes at optimum times during the summer season, our objective is to monitor movement of the TSL low coherence zone.

4. DATA USED IN THE STUDY

Several sources of data are being used in this study. The primary satellite data source is ERS SAR data acquired from ERS-1 and ERS-2. SAR data are used in two ways. First, amplitude data obtained from precision PRI SAR data is used to assess snow and ice conditions on the ice cap at different times during the year. Second single look complex (SLC) paired data are used for generating coherence maps for the interferometric part of the project. In addition, one SPOT scene has been acquired for late summer 1992 and we have obtained Landsat TM data for three consecutive years in mid to late summer time for 1994-1996. These data are useful for indicating the extent of ice and snow towards the end of each melt season. SAR PRI images were obtained to coincide as far as possible with these optical data sources. Field campaigns were conducted in March and April 1996 to examine snow conditions (grain size, general stratigraphy, snow pack temperature) at time of ERS overpass. Temperature data collected at Finse (2 km north of Hardangerjökulen) by the DNMI is also used as an index of temperature on the ice cap. A DEM of the area is also being used for SAR correction procedures.

5. SAR IMAGE PRE-PROCESSING

Several SAR images have been acquired via UK/Italian and German PAFs. Amplitude PRI data are processed differently than SLC data. For the PRI data, image speckle reduction is achieved using a technique described by Smith (1996) and image calibration is performed using the procedure described by Laur (1996). Initial image mapping to a UTM Zone32 projection (based on WGS84) is achieved using a combination of satellite ephemeris and image warping. SAR image terrain distortion, applied prior to mapping, is performed using a technique developed by Kelly (1995). However, application of this techniques is in early stages on account of the recent arrival of the DEM to the project. For SLC data, pre-processing consists of simple data extraction. Generation of interferograms (fringes) and coherence was initially investigated for SLC pairs acquired during the Tandem ERS phase in 1995/1996. Interferogram generator software (ISAR) was acquired through the Fringe Group at ESRIN and tested on two SLC pairs (22.3.96/23.3.96 and 26.4.96/27.4.96). Unfortunately, performance of the software was not satisfactory because different results were obtained for different initial seed points. In addition, it was found that for an image pair where one SLC images were processed at a different PAFs, resulting interferograms and coherence maps were unsatisfactory. Currently, extraction of interferometric information from SLC image pairs has been performed by colleagues at Mullard Space Sciences Laboratory.

6. RESULTS AND DISCUSSION

6.1 Results from amplitude PRI data

Figure 2 shows four ERS-1/2 SAR PRI subsets for Hardangerjökulen that have been speckle reduced and calibrated. The four images were acquired towards the end of the summer melt seasons (late August - September) of 1992, 1994, 1995 and 1996 and were acquired to coincide as closely as possible with TM and SPOT scenes for this area. Records from NVE show that 1992 had a large positive mass balance at the end of the year suggesting that the ELA was relatively low (perhaps as low as 1400 m.a.s.l.). This accounts for the relatively low backscatter returns from the ice cap (-5 dB to -15 dB) as the ice will have been covered by a layer of wet snow. The 1994 image (Figure 2b) is even darker suggesting that either the surface was covered in wet snow or bare ice undergoing significant melting. Meteorological records reveal that the summer temperatures at the index station rose above 0C in mid to late April. Mass balance data show that the net mass balance was approximately zero suggesting that the low 0 values encountered are the result of forward scattering away from the antenna or the absorption of the emitted signal by a very wet snow/ice layer. Since the surface is uniformly dark, we suggest that the cause is a very wet snowpack throughout most of the region. This explanation agrees with the fact that there were large snow accumulations in 1992 and 1993 (2.5-3.7 m water equivalent) suggesting that the snowpack was still thick at the start of the 1994 summer melt season.

In 1995 and 1996 (Figures 2c and 2d), the 0 values are greater than those in 1992 and 1994 suggesting either there was less moisture in the snowpack and the snow was much thinner than in previous years (resulting in a stronger return signal from underlying glacier ice surface), or there were ice layers and lenses within the snow producing a complex 0 values (c.f. Kelly, 1995). Comparison of the August 1995 image with data acquired earlier in the year (5.3.1995) suggests that moisture within the snow pack is responsible for the decreased backscatter signal. Figure 3 shows the March 1995 pass (Figure 3a) and the August 1995 pass (Figure 3b) and demonstrates the difference in ice cap backscatter between the start and end of the melt season. The increased 0 response from the March scene is the result of complex snowpack stratigraphy (lenses and crustal zones) which act as backscatter surfaces within the vertical profile of the snowpack. In addition, in areas where the snowpack is relatively homogeneous (small ice crystals and no layering), the 0 return signal is strongly determined by the glacier ice surface below. Analysis of March 1996 and April 1996 SLC amplitude data plus field work carried out by the team, agree with this explanation of differences between end of winter and end of summer season 0 values. However, what does emerge is that the idea of a TSL or snow line zone is not as well defined as initially expected. It is possible that at the end of the season, the ELA can be identified by location of wet snowpacks, but the traditional concept of a slowly rising TSL will be further investigated.

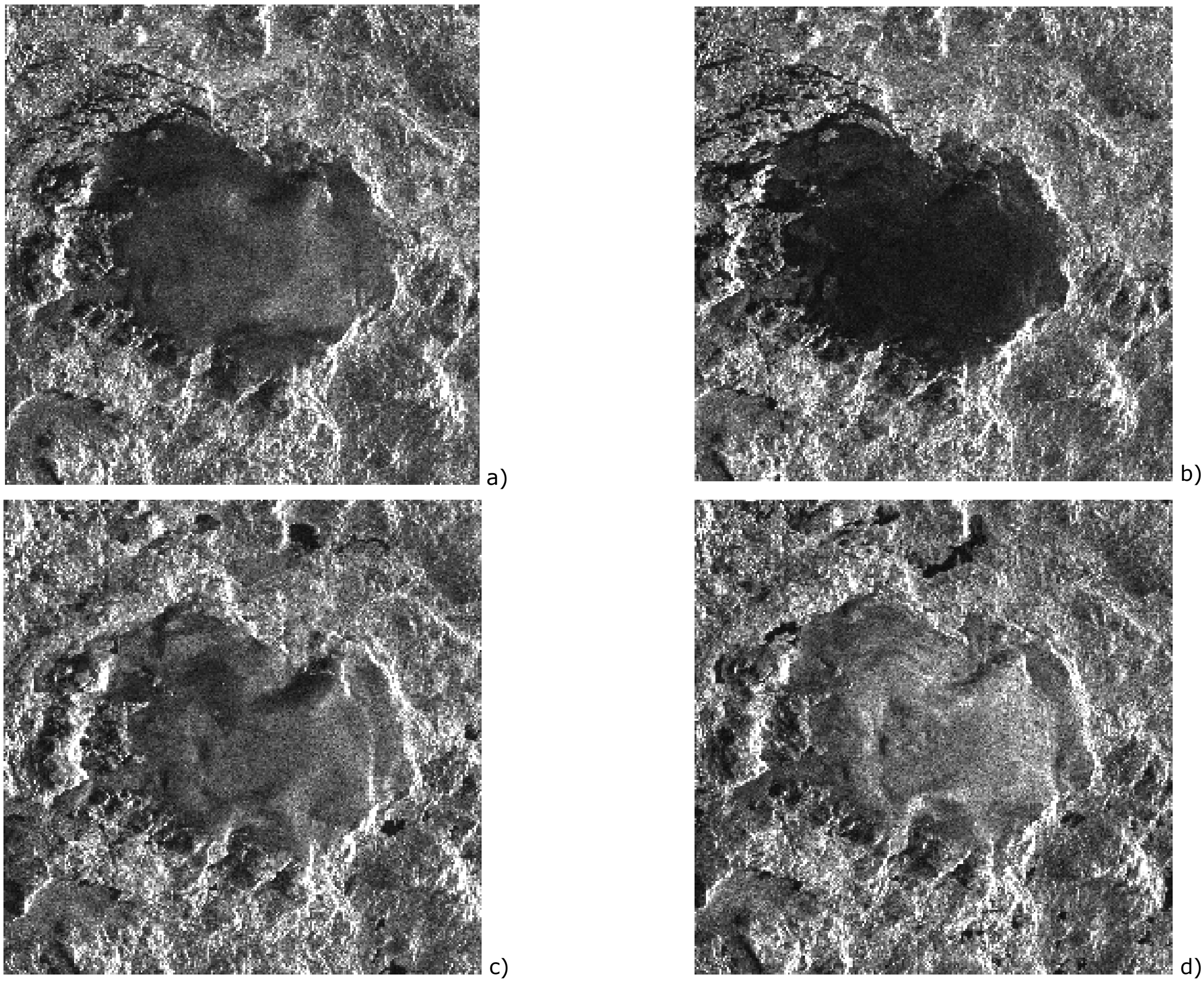

Figure 2 SAR PRI scenes acquired over Hardangerjökulen (frame 2385) on: (a) 16.9.1992, ERS-1 orbit 6122; (b) 29.8.1994, ERS-1 orbit 16321; (c) 25.8.1995, ERS-1 orbit 21496 and (d) 14.9.1996, ERS-2 orbit 7334.

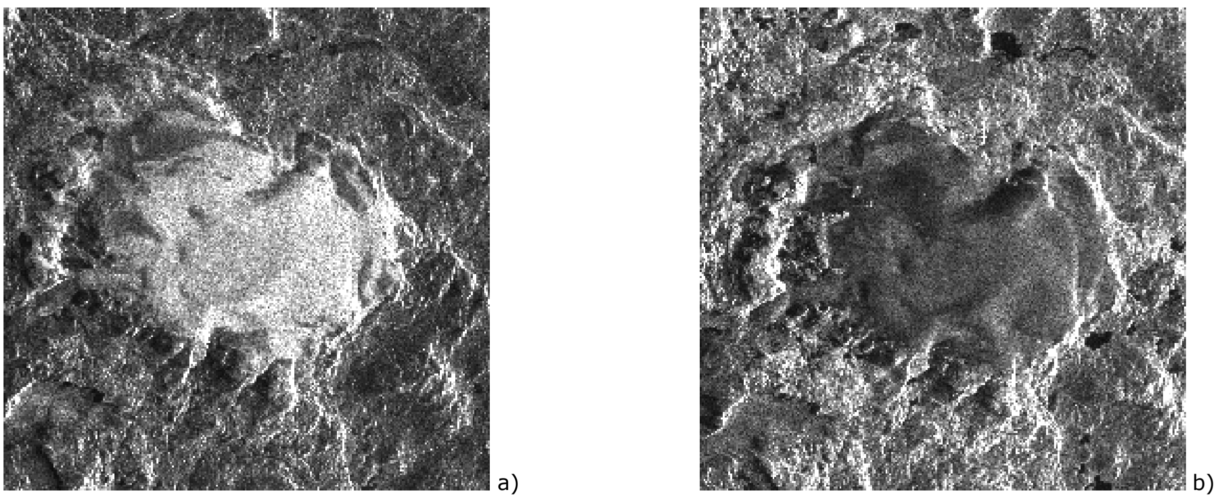

Figure 3 SAR PRI scenes acquired over Hardangerjökulen (frame 2385) on: (a) 5.3.1995, ERS-1 orbit 19019 and (b) 25.8.1995, ERS-1 orbit 21496. The difference in 0 is significant.

6.2 Results from SLC data

Strong coherence between SLC pairs (50-100%) is related to the stability of the target surface between one SLC pair and next. If conditions change (snow or ice surface changes), then coherence decreases (0-50%) for areas that have experienced significant change. The March and April coherence maps are shown in Figure 4 with high coherence represented by light grey and low coherence by dark grey. For the March data, generally, there is high surface stability between the first and second image (during the Tandem phase, passes were separated by a day) and coherence is high over most of the map. This is expected since air temperatures were cold (-5 to -10C at Finse) and weather conditions were stable. On both 22 and 23 March skies were clear and there was very little wind. Consequently, with high insolation rates during the day, some surface roughnesses on the ice cap changed in response to localised surface melting and re-freezing. These areas are shown by the darker shades in Figure 4a and are located mostly in areas at the margins of the uppermost plateau of the ice cap.

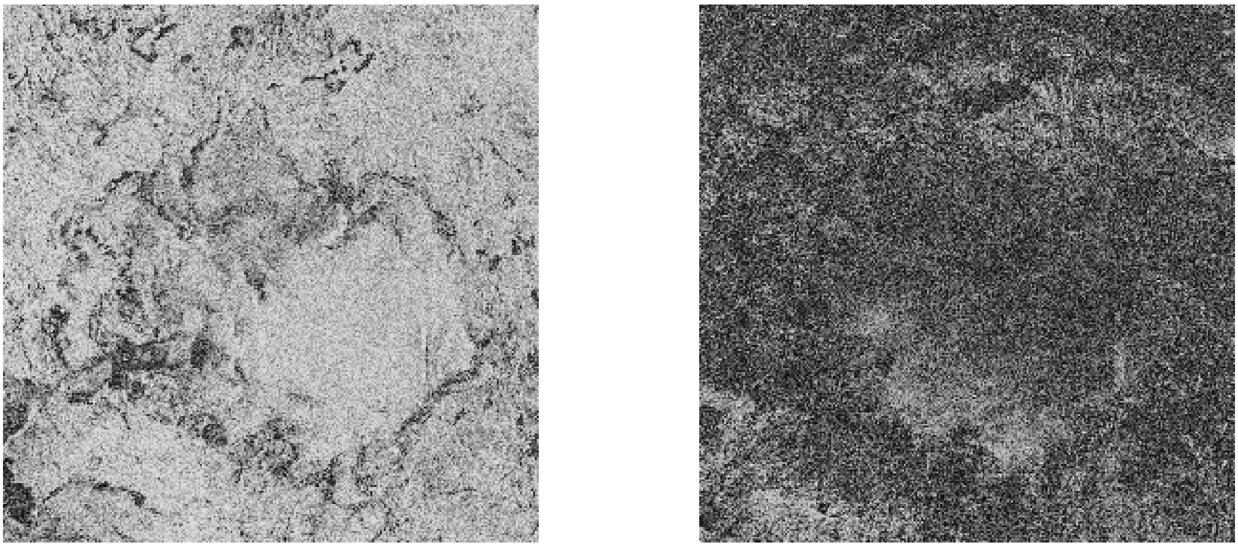

Figure 4 Coherence maps of Hardangerjökulen on : (a) 22.3.96/23.3.96 and (b) 26.4.1996/27.4.1996.

On 26 and 27 April, weather conditions changed significantly from one day to the next. Figure 4b shows the coherence map for these data and that generally coherence is low. A field campaign found that on 26 April, weather conditions were very stable with cloudless skies and little or no wind. Air temperatures were approaching 0C at Finse suggesting a strong potential for surface melting. However, on the following day, a strong wind significantly changed the surface of the ice cap by generating ripples, dunes and cornicing in the snow. At lower elevations, temperatures were at or above 0C for sufficient time to thaw the snow cover over a large area. Hence, the backscatter roughness surfaces were substantially altered between the first and second passes producing widespread incoherence. Although this result is useful, for these conditions, interferometry is not successful in identifying the TSL or ELA since the entire image area is subject to change.

7. CONCLUSIONS

This project is currently in progress. However, initial results to date demonstrate that backscatter responses from Hardangerjökulen snowpacks are not purely determined by wet snow and glacier ice but also by complex snow stratigraphy (snow crusts at surface and depth and ice lensing). Also, the project objective of monitoring the TSL through the summer season and fixing its position at the end of the season can probably only be achieved through interferometric techniques (provided that weather conditions are favourable). SLC interferometry analysis is still at an early stage of development. It is clear that if meteorological conditions between successive acquisitions are changeable over the area, the chance of identifying TSL locations is diminished. However, it is possible to monitor snow and ice changes over the glacier surface as demonstrated by the March 1996 coherence map.

8. FURTHER WORK

The project is currently expanding its coverage of PRI images to include passes acquired during winter and at different times of the summer. Correction of geometric distortion within the SAR PRI imagery is also to be applied as the DEM becomes fully available. However, the ice cap was chosen partly because it has relatively low angle surface slopes and thus require less geometric correction than imagery acquired over high alpine glaciers. Optical imagery (Landsat TM and SPOT-PAN) data are being used for snow/ice feature identification. These data will provide further detail about surface snow conditions. For cloud-free days, ATSR data is also being analysed to establish routine variations in snow and ice characteristics at meso-scale. Full examination of 1995/1996 SLC paired data obtained during the Tandem phase is currently in progress. Together, these satellite data provide a unique opportunity for observing changes to surface snow and ice conditions.

9. ACKNOWLEDGEMENTS

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