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SUBALPINE LAKES

The development of new algorithms for remote sensing of snow conditions based on data from the catchment of Øvre Heimdalsvatn and the vicinity

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Abstract The catchment of Øvre Heimdalsvatn and the surrounding area was established as a site for snow remote sensing algorithm development, calibration and validation in 1997. Information on snow cover and snowmelt are important for understanding the timing and scale of many lake ecosystem processes. Field campaigns combined with data from airborne sensors and spaceborne high-resolution sensors have been used as reference data in experiments over many years. Several satellite sensors have been utilised in the development of new algorithms, including Terra MODIS and Envisat ASAR. The experiments have been motivated by operational prospects for snow hydrology, meteorology and climate monitoring by satellite-based remote sensing techniques. This has resulted in new time-series multi-sensor approaches for monitoring of snow cover area (SCA) and snow surface wetness (SSW). The idea was to analyse, on a daily basis, a time series of optical and radar satellite data in multi-sensor models. The SCA algorithm analyses each optical and synthetic aperture radar (SAR) image individually and combines them into a day product based on a set of confidence functions. The SSW algorithm combines information about the development of the snow surface temperature and the snow grain size (SGS) in a time-series analysis. The snow cover algorithm is being evaluated for application in a global climate monitoring system for snow variables. The successful development of these algorithms has led to operational applications of snow monitoring in Norway and Sweden, as well as enabling the prediction of the spring snowmelt flood and thus the initiation of many lake production processes.

Keywords Remote sensing · Retrieval algorithms · Fractional snow cover · Snow surface wetness · Snow surface temperature

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Introduction

Knowledge of the timing, progression and scale of the spring snowmelt is crucial to an understanding of ecosystem dynamics of mountain lakes such as the subalpine lake, Øvre Heimdalsvatn. This applies to the several aspects of the lake ecosystem, including the supply of allochthonous plant material to the lake from the terrestrial environment (Larsson & Tangen, 1975; Brittain & Bjørnstad, 2010), zooplankton dynamics (Larsson et al., 2010) and the inflow of Chernobyl radionuclides from contaminated catchment snows (Brittain et al., 1992; Salbu et al., 1992). Snow depth, snowmelt progression and snow conditions also affect the timing of ice breakup in Øvre Heimdalsvatn (Kvambekk & Melvold, 2010), another structuring factor for the lake ecosystem (Larsson et al., 1978).

In the late 1970s, the Norwegian Water Resources and Energy Directorate (NVE) proposed a method for remote sensing of fractional snow cover (FSC) (percentage of snow per pixel) (Østrem et al., 1979). The main objective in the first instance was to obtain an indication of the snow water equivalent from the measured snow cover in the snowmelt season. The data source at that time was the two-channel version of the NOAA AVHRR sensor. The methodology was gradually refined by NVE (e.g. Andersen, 1982) and later by the Norwegian Computing Center (NR) for Statkraft, the largest hydropower company in Norway (Solberg & Andersen, 1994).

In the mid-1990s, collaboration was strengthened between various Norwegian institutions interested in remote sensing of snow. The first collaborative effort was in the Okstindan area, in particular at Kongsfjellet, in Nordland County. A multi-frequency multi-polarisation airborne radar (EMISAR) was flown three times over the site giving valuable data for the understanding of how a radar measures snow (Guneriussen et al., 1997). More formal collaboration began within the European Commission (EC) project SnowTools in 1996. The experience with Kongsfjellet showed that it was quite costly to carry out frequent field campaigns in such a remote area with unpredictable weather, and it was concluded that much could be gained from finding a site with more predictable weather conditions. After a comprehensive evaluation of various sites in southern Norway, the Heimdalen–Valdresflya region in the Jotunheimen Mountains was selected.

The main objective for establishing such a site was for the development and improvement of algorithms for retrieval of snow variables from remote sensing data, as well as calibration and validation of such algorithms. Algorithm development, calibration and validation require 'ground truth data'. Ground truth is in this case a combination of airborne measurements and field measurements. Accurate snow coverage over a larger area is not practically obtainable by fieldwork, but high-resolution optical data can be the basis for accurate delineation of snow figures on the ground. On the other hand, reference measurements of snow variables, like grain size, temperature and wetness, require measurements taken in the field.

In recent years, various SAR (synthetic aperture radar) algorithms have been tested and improvements undertaken (Malnes & Guneriussen, 2002; Malnes et al., 2004). A new generation of 'multi-source' algorithms have been developed: a time-series multi-sensor retrieval algorithm for fractional snow cover, FSC (Solberg et al., 2005), and a time-series multi-parameter algorithm for snow surface wetness, SSW (Solberg et al., 2004). The aim of this article is to present and summarise data on the algorithms and some of the experimental results in the context of ecosystem studies of Øvre Heimdalsvatn, located in the midst of the field area. The Heimdalen–Valdresflya site's variable topography, with mountain and valley terrain in the Heimdalen part and a flat mountain plateau in the Valdresflya part, has also provided an opportunity for studying local topographic effects.

Materials and methods

Study site

The area around Øvre Heimdalsvatn was established as a site for snow remote sensing algorithm development, calibration and validation in 1997. Field campaigns combined with data from airborne sensors and spaceborne high-resolution sensors have been used as reference data in experiments. Several satellite sensors have been applied in the development of new algorithms, including Terra MODIS and Envisat ASAR. The experiments have been motivated by operational prospects for snow hydrology, meteorology, climate monitoring and their relevance to ecosystem driving processes.

The original site included only the catchments of the lakes, Øvre and Nedre Heimdalsvatn (Fig. 1).

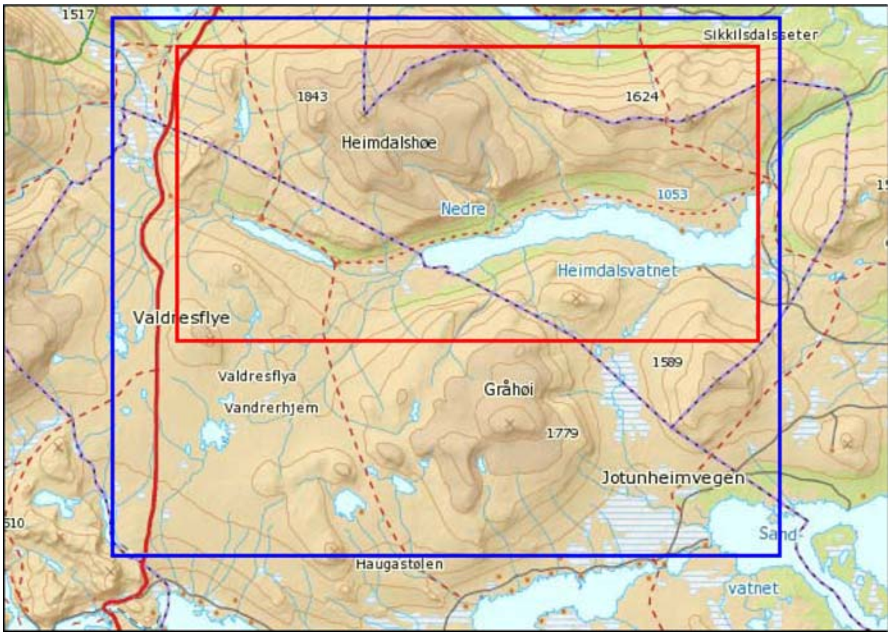

Fig. 1 The Heimdalen–Valdresflya site for snow algorithm development and validation. The *red rectangle* shows the original (Heimdalen) site, while the *blue rectangle* shows the extended site

The snow measurements in the area were then able to be linked to runoff measurements from Nedre Heimdalsvatn. The topography of the area was also considered suitable for remote sensing: typical mountain topography without being too steep. However, for some of the experiments, in particular when testing out new algorithms, it was concluded that it would be valuable to do initial tests and calibration/validation without having 'topographic noise' in the variable-retrieval results. The test site was then extended to the south-west by including the Valdresflya, a rather flat mountain plateau at altitudes of about 1,200–1,300 m a.s.l., and where topographic effects could be discarded in our experiments. The Heimdalen site was originally about 100 km^2 with an elevation range of 1,050–1,840 m a.s.l. After the inclusion of Valdresflya and the terrain south of Heimdalen in 2001, the site was expanded to about 265 km^2 (Fig. 1). When the activities at the Heimdalen–Valdresflya site commenced in 1997, a high-resolution digital terrain model based on aerial photographs was established to be able to understand and model topographic effects in the satellite data. A detailed vegetation map was also developed, based on a combination of satellite images (Landsat Thematic Mapper) and field mapping.

Field measurements

Since the Heimdalen–Valdresflya test site has been established, fieldwork has taken place almost annually. Most field campaigns and parallel acquisition of airborne and high-resolution satellite data have taken place in the snowmelt season, typically between April and July. The SnowTools project (1996–1998) was followed by two other EC projects, EuroClim (2001–2005) and EnviSnow (2002–2005). The Research Council of Norway's project SnowMan was run in parallel to these (2001–2004). The site and region in the vicinity was also used in Master and Ph.D. thesis projects during this period (Orthe, 2003; Vikhamar, 2003). After these projects, the site was used less frequently until a new period of snow projects started, including the European Space Agency project GlobSnow (2008–2011), which uses the Heimdalen–Valdresflya area for regional calibration and validation of algorithms for global snow mapping to quantify regional climate changes.

A total of 32 snow field measurement campaigns were carried out in the period 1997–2006. A typical field campaign included measurements as listed in Table 1. These point measurements were typically taken in terrain slopes over a range of elevations to establish the variability of various snow variables at

Table 1 Snow variables measured and instruments applied in the Heimdalen–Valdresflya study site

Variable	Instrumentation
Density	Snow tube and scale
Depth	Measurement stick
Water equivalent	Calculated from volume and density
Liquid water contents	Dielectric moisture meter
Temperature	Electronic thermometer
Snow grain size	mm-grid/photography
Spectral reflectance	Field spectroradiometer
Snow coverage	Aerial photography and/or TM/ETM+

the site. The spectral reflectance measurements were taken with an Analytical Spectral Devices FieldSpec Pro spectroradiometer. The instrument covers the spectral range 350–2,500 nm. The Bidirectional Reflectance Distribution Function (BRDF) has been sampled in some of the campaigns using FieldSpec Pro and a goniometer construction to fix the measurement angles. The reflected sunlight was measured in four azimuth planes, 0, 22.5, 45 and 90° relative to the solar plane. In each plane, the measurements were performed in steps of 10° from 0 to 80° measured from zenith. In the solar plane, the measurements were performed from −80 to +80°. In angles of 22.5, and 45 to the solar plane, the measurements were performed from 0 to 80° only in the direction towards the sun. At 90° to the solar plane, the measurements were performed from 0 to 80° on one side, assuming symmetry around the solar plane.

Spectrometer measurements have also been undertaken to determine how the snow reflectance is influenced by impurities, e.g. from vegetation and bare ground. The spectral reflectance has been measured at snow surfaces in different distances from bare ground.

Remote sensing reference data

Point or transect measurements from field campaigns were not sufficient for an accurate assessment of algorithms' ability to retrieve snow cover area (SCA) or FSC. For the Heimdalen–Valdresflya site, aerial photographs have been acquired to obtain very accurate maps of the snow cover. The period 1997–2005 has been well covered with aerial photographs throughout the melting season. The photographs were acquired with a Leica RC30 aerial camera system applying either panchromatic or colour infrared film.

The aerial photographs have been orthorectified by an aerial mapping company using control points and photogrammetric methods. Most resulting orthophoto mosaics have been processed to 1-m spatial resolution. For producing snow reference maps, similar semi-manual classification approaches as applied for the Landsat images (see below), have been used for the arial photographs. However, radiometric effects due to the high variable incidence angles of an aerial camera have made orthophoto mosaic snow classification particularly challenging. Significant manual editing was necessary and was not always successful.

Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper Plus (ETM+) images have also been used to make snow reference maps. The period 1997–2004 is well covered with images throughout the melting season. Several of the images have undergone comprehensive classification combining automatic methods (unsupervised clustering and use of the Normalised Difference Snow Index, NDSI) and manual methods (local thresholding of band combinations and NDSI, or careful combination of clusters from the unsupervised clustering). Areas in the shade of mountain tops and the bottom of valleys have been challenging to achieve correct results. The resulting snow maps have 30- or 25-m pixel resolution with three snow classes. For comparison with snow products derived from moderate resolution images (e.g. 250-, 500- and 1000-m pixel resolution), the Landsat snow maps have been applied to derive FSC at the same resolution as the snow maps from the moderate resolution sensors. Some of the stages in the process of making Landsat snow reference maps are illustrated in Fig. 2.

Validation approaches

It is usually a challenge to fully validate the output of a remote sensing retrieval algorithm. The performance of an algorithm will often vary with ground as well as atmospheric conditions. The variable topography of the Heimdalen–Valdresflya site, with mountain and valley terrain in the Heimdalen part and a flat mountain plateau in the Valdresflya part, has provided a relatively unique opportunity for studying local topographic effects. Having these two terrain types so close made it possible to carry out

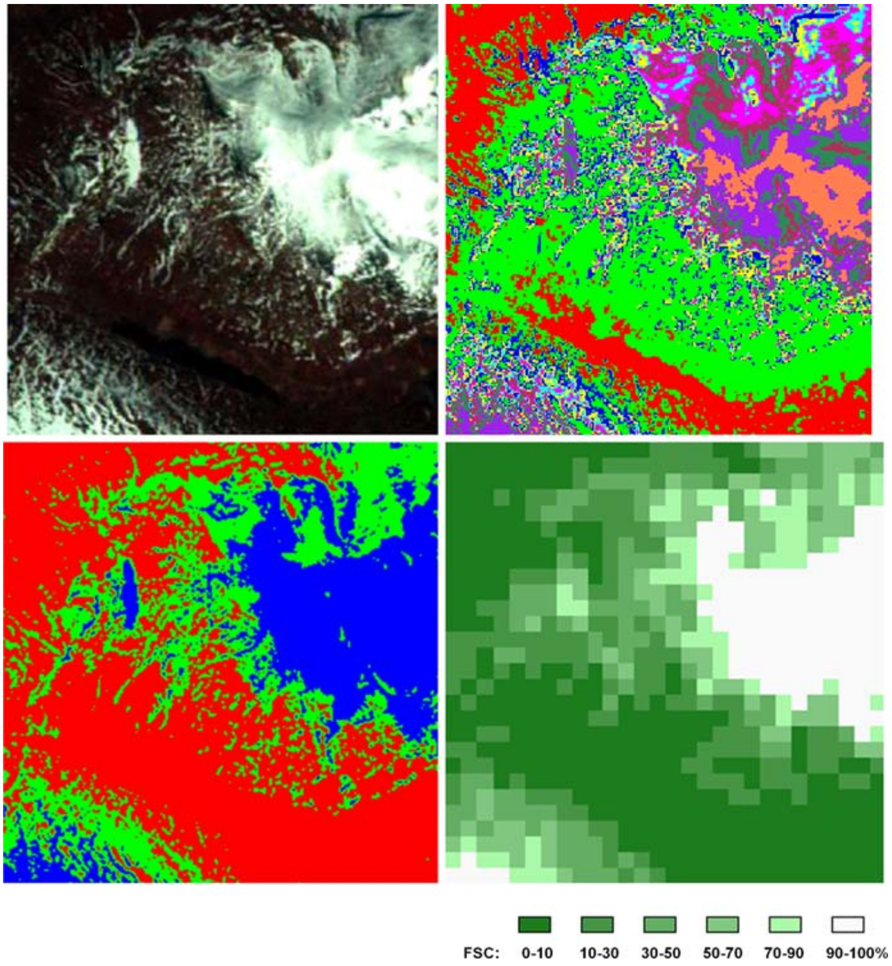

Fig. 2 Developing an accurate snow reference map from a Landsat ETM+ image acquired on 23 May 2004. *Upper left* ETM+ sub-image showing Heimdalshøe (*upper right corner*) and Øvre Heimdalsvatn (*lower left*). *Upper right* The image after unsupervised clustering into 10 classes. *Lower left* Snow cover classification from supervised clustering. *Blue* 100% snow cover; *green* partly snow cover; *red* bare ground. Spatial resolution 25 m. *Lower right* The snow map after resampling to FSC (%) at 250-m spatial resolution. The resolution corresponds to the snow maps made by the time-series multi-sensor algorithm processing MODIS and ASAR satellite data

experiments where algorithm performance could be studied with and without topographic influence simultaneously for, usually, the same snow conditions. This has been very valuable as the topography often significantly affects the algorithm retrieval performance.

Spatial validation data, in most cases snow cover extent mapped from high-resolution data, were converted into lower resolution FSC maps giving precise reference values that could be directly compared with the output of FSC retrieval algorithms. Statistics could then be computed for algorithm performance for various terrain types and orientation measured by slope and aspect. Point measurements, such as snow temperature and snow grain size (SGS), are always more difficult to relate to remote sensing data due to the scale differences. However, sampling along transects or at random positions helped us to determine current spatial variability and, hence, to assist in an assessment of how well local measurements could be scaled up to satellite measurements.

Remote sensing data for retrieval algorithms

Algorithm development using the Heimdalen–Valdresflya site has focused on moderate spatial resolution satellite sensors. These sensors are designed for frequent global monitoring, up to a few times a day. This choice was logical from their application in hydrology, meteorology and climatology. The optical sensors applied were Terra MODIS, Envisat MERIS and AATSR, and NOAA AVHRR. The SAR sensors applied were ERS-1, ERS-2, Radarsat-1 and Envisat ASAR. Two advanced experimental airborne sensors have been flown as well, the DAIS 7915 and the AISA imaging spectrometers.

Methodological foundation of new algorithms

Snow cover retrieval by SAR is based on work that demonstrated the potential of SAR for wet snow detection using ERS and Radarsat standard modes (see, e.g. Koskinen et al., 1999; Nagler & Rott, 2000). Wet snow is detected by utilising the high absorption, and, therefore, low backscatter, of wet snow and then comparing the backscatter with the corresponding pixel of a reference image acquired during dry-snow or snow-free conditions. Dry snow could then be postulated above the mean-wet-snow elevation zone (Malnes & Guneriussen, 2002; Malnes et al., 2004). This methodology has been further improved by taking into account in situ air temperature measurements from meteorological station networks, which were used to derive an interpolated temperature map based on standard 6°C per km altitude lapse rate and a digital elevation model.

Orthe (2003) compared several retrieval algorithms suitable for classification of a time series of Radarsat images. The classification methods were divided into two groups, supervised and unsupervised classification. The classification methods used spatial and temporal contextual information. This information was fused into the classification by using Markov random fields and Markov chains. When utilising temporal and contextual information, the information was transformed into a priori information, which the Bayesian classification rule could use. Markov random fields and Markov chains yielded an overall improvement in the classification accuracy. K-means and Bayesian classification rules gave similar results. They also responded similarly when Markov random fields and Markov chains were applied. The use of the Nagler algorithm (Nagler & Rott, 2000) yielded an overall higher classification error rate than the Bayesian classification rule and K-means.

The new multi-sensor time-series algorithm for FSC builds on independent optical (Solberg & Andersen, 1994) and SAR (Malnes et al., 2004) algorithms and syntheses of the retrieval results from these individual algorithms at the geophysical variable level (in contrast to data fusion at the electromagnetic level).

Furthermore, the Surface Temperature of Snow (STS) algorithm, applied within the time-series multi-sensor retrieval algorithm, developed for SSW, is based on study by Key et al. (1997). A pilot study identified it as one of the best single-view techniques for retrieval of STS for polar atmospheres (Amlien & Solberg, 2003). It can be applied on Terra MODIS as well as NOAA AVHRR data. An algorithm for SGS is also utilised in the SSW algorithm. A normalised grain size index based on Dozier (1989) has been used. MODIS channels 2 and 7 have been used because the index has then been shown to be less sensitive to snow impurities.

Results

The experiments at the Valdresflya–Heimdalen site have resulted in a series of new and improved algorithms for retrieval of snow variables. Building on previous results for retrieval of wet snow cover by SAR, methodology for reliable postulation of dry snow above the mean-wet-snow elevation zone has been developed. The present algorithm uses a −3 dB threshold to discriminate between wet snow and dry snow/bare ground. A finer tuned and variable threshold can be applied if the vegetation cover is known. The results are applied in the time-series multi-sensor retrieval algorithm for snow cover described in the following.

Time-series multi-sensor retrieval of snow cover

This algorithm combines optical data acquired over several days and supplemented with SAR data as frequently as practically possible. SAR data are limited to the melting season because current satellite sensors are only able to retrieve wet snow. Furthermore, current cost regimes for optical and SAR data in practice limit the use of SAR data as optical data are less expensive or free. From practical experience to date, approximately 2–4 SAR image acquisitions per week seem adequate.

The overall multi-sensor time-series algorithm approach can be written as follows:

$$\mathrm{MFSC}_t(x,y) = \mathrm{UFSC}_i(x,y) \qquad (1)$$

for i which gives $\max(\mathrm{conf_{time}}(i)\ \mathrm{conf_{MSCA}}(\mathrm{UFSC}_i(x, y)))\quad i = t, t-1, \ldots, t-n$

where MFSC is the new multi-sensor time-series FSC product, UFSC is a 'time-unit' product (a single-sensor product or a single day product, where the latter includes all observations during day), $conf_{time}(t)$ is a time-dependent confidence function, $conf_{MFSC}$ is the confidence function for the 'time-unit' product, t is the current day and n is the number of days back in the time series ('the time horizon'). In other words, for each pixel (x, y) select the 'best' time unit i from a time series of unit products. 'Best' means the pixel with maximum confidence. Hence, the selection process is controlled by a confidence function.

This confidence function $conf_{time}(i)$ is a decay function of time, i.e. the function reduces confidence as the age of each unit product increases. The function might be linear giving largest confidence to today's observations and no confidence past a given time horizon. Single-sensor products as well as single day products have associated per-pixel confidence values. The confidence values for a day product are the combination of confidence values from a set of confidence functions associated with the single-sensor products where the pixel values have been selected. A single-sensor confidence function is typically related to acquisition geometry, reliability of the decision taken by the retrieval algorithm, etc.

For the sensors and retrieval algorithms applied in the experiments, the optical products yield a snow cover fraction for each 250-m resolution pixel, while the radar products yield the snow cover classified as snow/no-snow for each 100 m resolution pixel. The radar product was resampled to 250 m, resulting in a quasi fractional-snow-cover product for SAR.

The effect of including assumptions about dry snow above the wet-snow zone in the radar product was examined. Using a SAR SCA product to infer dry snow appeared to overestimate the snow cover compared to the optical product. Using SAR SCA based on wet snow underestimated the snow cover compared to the optical product. Attempts were made to reduce the confidence of SAR pixels classified as dry snow, but this did not significantly improve the result.

Based on the experiences from all the runs of the algorithm, a six day time horizon was found optimal for the tested cases. While 3 days resulted in a large fraction of unclassified pixels, 9 days resulted in marginal improvements in coverage over the 6-day product, and too many old observations occurred during periods of rapidly changing snow cover. An example of a snow map generated by the algorithm is shown in Fig. 3.

Experience with the multi-sensor time-series algorithm for FSC showed that the products depend very much on how the initial single-sensor product confidence was set and on the time decay function employed. It appeared that proximity to clouds should give reduced confidence in the optical data minimize the risk of classifying clouds as snow. More important, however, it was to consider how to fuse the SAR and optical products in a better manner. The algorithm would probably give enhanced results if wet snow and dry snow from the SAR product had been handled differently, in particular when the pixels consists of a mixture of wet and dry snow or bare ground.

When optical data are unavailable due to clouds, the use of radar data improves the product by covering larger areas. Owing to the binary character of the radar snow map and the limitation to detecting wet snow only, SAR was weighted lower than optical by an inter-sensor confidence factor. We examined and evaluated various values of this factor and found that values of 0.5 and below clearly reduced the

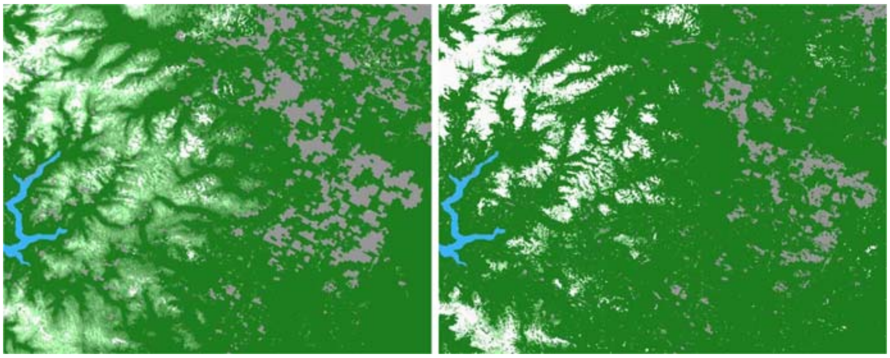

Fig. 3 The day product with and without ASAR on 7 June 2004 covering the Jotunheimen mountains. *Left* MODIS only included. *Right* Both MODIS and ASAR included. This illustrates that the SAR sensor has less ability to determine the snow cover fraction than optical sensors

contribution from the SAR products too much. Using a value close to 1.0 preserved much of the binary pattern from the SAR products. This means that high confidences for SAR had a tendency to override subsequent optical data. Values in the range 0.75–1.0 gave the best overall results.

Using SAR imagery is not as straightforward as optical imagery. In the original 100-m SAR product, the wet snow threshold is binary (wet snow/non-wet snow). Owing to the logarithmic coding of backscatter in SAR imagery, a small fraction of bare soil in a SAR pixel may cancel out a large fraction of snow. Also, the resampling of 100-m products to 250 m generates FSC where bare ground, wet and dry snow and possibly masked pixels are combined into a snow cover fraction.

Time-series multi-sensor retrieval of snow surface wetness

An approach to infer wet snow from a combination of measurements of STS and SGS in a time series of observations has been developed. The temperature observations gave a good indication of where wet snow could be present, but were in themselves not accurate enough to provide very strong evidence of wet snow. However, if a rapid increase in the effective grain size was observed simultaneously with a snow surface temperature of approximately 0°C, then this was a strong indication of a wet snow surface. A simplified version of the algorithm applied is expressed below (pixel indexing has been skipped for clarity; MSSW is time-series multi-sensor SSW):

$$
\begin{aligned}
&\text{if } \mathrm{SGS(today)} - \mathrm{SGS(recently)} > \mathrm{SGStresh\ AND}\\
&\quad -2 < \mathrm{STS(today)} < 1 \text{ then } \mathrm{MSSW} = \mathrm{WET\_SNOW}\\
&\text{else}\\
&\text{if } \mathrm{SGS(today)} < \mathrm{BareGroundSGStresh} \text{ then}\\
&\quad \mathrm{MSSW} = \mathrm{BARE\_GROUND}\\
&\text{else}\\
&\text{if } \mathrm{STS(today)} > 1) \text{ then}\\
&\quad \mathrm{MSSW} = \mathrm{BARE\_GROUND}\\
&\text{else}\\
&\quad \mathrm{MSSW} = \mathrm{DRY\_SNOW}
\end{aligned}
\tag{2}
$$

The algorithm also illustrates how bare ground is inferred from temperature observations above 0°C and a rapidly developing negative gradient for SGS (both due to appearance of bare ground patches at the sub-pixel level).

The 3 days of snow wetness maps for southern Norway based on the algorithm (Fig. 4) illustrate a typical situation with warmer weather entering from the west, and the snow in the mountains becomes wet over a period of a few days.

A combination of snow temperature and SGS was utilised in the algorithm. The calculated SGS index did not give the precise physical size of the snow grains, but gave an indication of the grain size. The value of the SGS index increases with increasing grain size. For a pixel totally covered with snow, the SGS index is a good indication of the grain size. Bare ground gives a low value for the SGS index. This

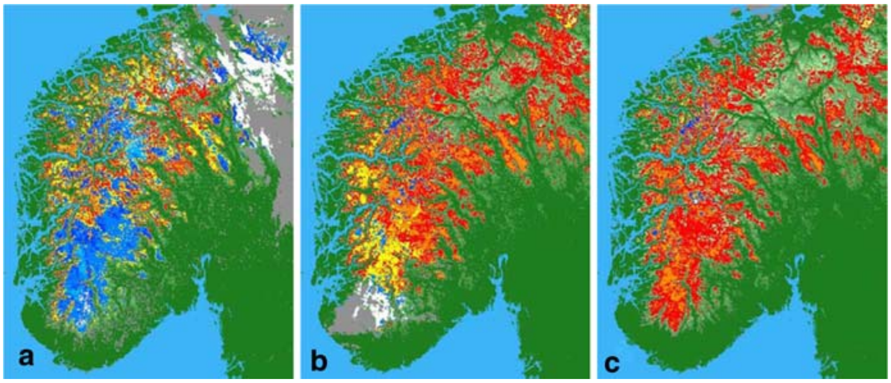

Fig. 4 Snow surface wetness products of southern Norway for 3 days in April 2003. The images show how the mountain regions of southern Norway become warmer over a few days when warmer air masses enter from the west. There are four temperature classes: (1) Dry, cold snow (*white*), (2) dry/moist (*blue/light blue*), (3) moist (*orange/yellow*) and (4) wet (*red*). For classes 2 and 3 *blue* and *orange* means constant grain size and *light blue* and *yellow* means increasing grain size. The figure shows from *left to right*: **a** 16 April; **b** 20 April; and **c** 22 April

means that for a pixel only partly covered with snow, a low SGS index was measured, even for large SGSs. A decreasing value of SGS could mean newly fallen snow or increasing snow-free area.

For STS there was a similar problem. With a snow temperature of 0°C, the snow will start to melt and the temperature will stop increasing. For a pixel only partly covered with snow, the temperature of the snow-free area will create an influence, resulting in measured STS values above 0°C. This would usually mean that the snow is wet, but if the snow-free area is sufficiently large, one can measure an average positive temperature for the pixel even if the snow is cold and dry. Therefore, a good estimate of SSW is valid only for pixels completely covered with snow. An accurate FSC map should be used to restrict the pixels classified. It was assumed that the SSW estimates were reasonably good even if small areas of bare ground were included.

Discussion

Snow cover area

Even though the contrast between snow and snow-free ground is quite high in the visual part of the electromagnetic spectrum, accurate mapping of the snow cover is not straightforward. This is partly due to the situation that the snow fraction at the sub-pixel level is needed to obtain the required level of detail for the snow maps. Combined with the fact that the snow spectrum changes continuously and that the regions to monitor frequently have complex terrain reliefs, this has resulted in a failure to obtain very accurate operational FSC monitoring for larger regions under all snow conditions.

There are two alternative operational or close-to-operational approaches for FSC mapping published, one based on spectral unmixing and the other on the NDSI. The spectral unmixing approach was originally introduced by Nolin & Dozier (1993). A disadvantage of this method is that it is supervised, which makes it difficult to be used in large-scale and operational applications. Rosenthal (1996) proposed a method for unsupervised spectral unmixing, which was further improved with a spectral library approach by Painter et al. (1998). A spectral library of snow, vegetation, rock and soil endmembers was used. The snow endmembers of varying grain size were derived from a radiative transfer model. The other spectra were measured in a laboratory and in the field. An overall RMS error of 4% was obtained from analysing three images acquired by the airborne imaging spectrometer AVIRIS over a mountainous region and comparing them with aerial images.

The spectral unmixing approach has proven to be very accurate when the spectral properties of the endmembers can be determined in advance by field measurements and spectral modelling, as indicated by the example of above of 4% RMS error. Our experiments with the optical part of the time-series multi-sensor algorithm indicate an RMS error of 10–15% under normal conditions. Nevertheless, too much pre-analysis information is required through measurements and modelling for operational use of the spectral unmixing approach. In contrast, the approach used in this study determines input parameters to the retrieval algorithm through the use of a few calibration targets that are analysed automatically.

Salomonson & Appel (2004) tested whether there was enough ‘signal’ in the NDSI to map fractional snow. An overall correlation coefficient of 0.9 and a RMS error of 10% were found for the linear regression result between FSC and NDSI. The algorithm has been validated and implemented as a standard NASA MODIS FSC product, which was launched operationally in December 2006 (Salomonson & Appel, 2006). The algorithm seems to be a competitive approach to the optical part of our FSC algorithm with regard to accuracy and operational utility. A comparative analysis is suggested for future work.

Very few multi-source sensor studies have been published so far, although Tait et al. (2000) provide an example of a true combination of data from two sensors to produce a snow map. NOAA AVHRR data and DMSP SSM/I data were analysed together with climate station data and a digital terrain model in a decision tree produce a continental-scale snow map for North America. However, these results are not directly comparable as a passive microwave sensor (SSM/I) was used instead of SAR, and so neither spectral content nor spatial resolutions are comparable. Nevertheless, our results show that a time-series multi-sensor approach is able to compensate to a large degree for cloud cover by utilising SAR when available and the snow is wet (the multi-sensor component of the algorithm) in addition to previous optical and SAR observations (the time-series component) without compromising much on accuracy.

Snow surface wetness

The ideal approach based on optical data would have been to apply a retrieval algorithm for liquid water contents in the snow, like that proposed by Green & Dozier (1995). However, this would require an imaging spectrometer with optimally located spectral channels for measuring a liquid–water molecular absorption feature. Such sensors are currently not available in satellites, only as experimental sensors in aircrafts. Our aim has been to propose an algorithm that could be used operationally based on satellite data.

The experiments with the snow wetness algorithm have confirmed that the approach of combining STS and SGS, analysed in a time series of observations, can be used to infer wet snow, including giving an early warning of snowmelt start. Air temperature measurements from meteorological stations confirm in general the maps produced. The main problems observed are related to clouds. In some maps, dry and cold snow was more frequently close to clouds. One could imagine that this is because the clouds have kept the sunlight away, hence the snow has not been warmed. However, it might equally be that parts of the clouds have not been detected such that the cloud temperature is partly included. These problems are typically associated with transparent clouds.

Synthetic aperture radar is very sensitive to snow wetness. Using the same technique as in our snow cover algorithm for wet snow, a binary map of wet snow was achieved. Ideally, the amount of liquid water could have been retrieved for the snow surface using a SAR technique. The backscattering from snow is a complicated function of surface parameters (roughness, correlation length and wetness), snow parameters (density, depth, grain size and water content) and soil parameters (surface roughness and moisture) in addition to sensor parameters (frequency, polarisation and incidence angle). If the snow is wet, then the dominating contribution comes from the snow surface due to absorption. In Fily et al. (1997), algorithms were demonstrated for the retrieval of snow wetness from multi-polarisation SAR. For single polarisation SAR (such as ENVISAT ASAR Wide Swath) there are too many parameters involved in the equation to facilitate a full inversion of the problem. Several authors have, however, shown that wet snow can be detected (see Nagler & Rott, 2000), and this approach is in practice the microwave alternative to our optical algorithm.

No comparative study has so far been carried out for the two alternatives of optical and SAR sensors. However, we know from our applications of snow cover retrieval that the SAR algorithm is sensitive to small fractions of bare ground, in particular for rough surfaces like rocks. In practice, wet snow mapping would be limited to full snow cover when using SAR, just as for optical as the emissivity of the snow-free ground is not known when using the STS algorithm and would then most likely give too high temperature estimates.

While the SAR signal is dominated by the dielectric properties of the medium measured and its geometrical properties at the scale of the microwave wavelength, optical sensors are sensitive to reflection, absorption and scattering properties of the snow grains in the top layer of the snow pack. Hence, the sensors are measuring entirely different physical phenomena. In spite of this situation, the results of experiments of combining snow cover retrieved by SAR and optical sensors generally give reasonably consistent results. The SAR-based maps were valuable for updating the multi-sensor time-series products in periods of missing optical observations due to cloud cover. The SAR observations were to a large degree confirmed by subsequent optical observations.

Conclusions

The multi-sensor time-series SCA algorithm has after its introduction been applied in several large-scale experiments and is currently used operationally in the snowmelt season by Kongsberg Satellite Services in Norway, providing snow maps to hydrological users in Norway and Sweden. The snow cover algorithm is evaluated for application in a global climate monitoring system for snow variables. The early warning of the start of snowmelt and the extent of snow cover have the potential to be useful tools in detecting the timing of major hydrological processes in remote areas, such as ice break and the spring flood (Kvambekk & Melvold, 2010), which again are crucial to the seasonal development of lake biological production and food chains (Larsson et al., 1978, 2010; Borgstrøm et al., 2010).

The Heimdalen–Valdresflya site's variable topography provided a relatively unique opportunity for studying algorithm performance with and without topographic influence simultaneously for similar snow conditions. This has been valuable as the topography often significantly affects algorithm retrieval performance. The accessibility of the site has also been important as it could be reached on short notice within a few hours, which made it possible to successfully carry out most field campaigns under cloud-free conditions.

The experiments with the snow wetness algorithm have confirmed that the approach of combining snow surface temperature and SGS, analysed in a time series of observations, can be used to infer wet snow, including giving an early warning of snowmelt start. Air temperature measurements from meteorological stations confirm in general the maps produced. The main problems observed are related to clouds. In some maps, it was observed that dry and cold snow was more frequently close to clouds. These problems are typically associated with transparent clouds. The knowledge of snowmelt processes in the catchment of Øvre Heimdalsvatn and the developed algorithms will be valuable in future research and monitoring lake ecosystems such as Øvre Heimdalsvatn.

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