

MULTI-SENSOR/MULTI-TEMPORAL APPROACHES FOR SNOW COVER AREA MONITORING

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ABSTRACT

The overall idea behind the work presented is to combine the use of optical and SAR sensors and utilise the best features of each sensor when possible in order to map snow cover area (SCA) more frequently and with better spatial coverage than would otherwise be possible. Optical remote sensing sensors are able to map snow cover quite accurately, but are limited by clouds. SAR sensors penetrate the clouds, but current satellite-borne sensors are only able to map wet snow accurately. In this paper we describe the methodology developed and the results of applying this for SCA mapping through the snowmelt season 2004 in South Norway. The results include the use of ENVISAT ASAR and Terra MODIS. Common for all the experiments is that the sensor fusion has taken place at the level of geophysical parameters. A few algorithms for multi-sensor time-series processing have been developed. One approach is to analyse each image individually and combine them into a day product. How each image contributes to the day products is controlled by a pixel-by-pixel confidence value that is computed for each image analysed. The confidence algorithm is able to take into account, e.g., information about observation geometry, probability of clouds, prior information about snow state and reliability of the classification. The time series of day products are then combined into a multi-sensor multi-temporal product. The combination of products is done on a pixel-by-pixel basis and controlled by each individual pixel's confidence and a decay function of time for the product. The "multi-product" should then represent the most likely status of the monitored variable.

INTRODUCTION

The seasonal snow cover is practically limited to the northern hemisphere. Here, the average snow extent during the winter months ranges from 30 to 40 million km². The water equivalent volume of this snow mass ranges from 2000 to 3000 km³. In the mountainous areas and in the whole north of Europe, snowfall is a substantial part of the overall precipitation, e.g., in Finland 27% of the annual average total precipitation is snow. In Norway, about 50% of the precipitation in mountainous areas is snow.

Monitoring of the seasonal snow is important for several purposes. In northern regions, the snow may represent more than half the annual runoff, putting specific demands on the models and other tools employed in managing this water resource. Risk of flooding enhances this demand, both in areas with stable winter coverage, and in areas only occasionally covered with snow. Snow covered ground affects the energy exchange processes developing weather and climate, both locally and in large regions, and is an important element in meteorological and climatological modelling tools. The snow pack itself causes avalanches every year in alpine regions, enforces a high priority road clearing service both in cities and in rural areas, and affects many other aspects of human life.

Optical remote sensing sensors are able to map snow cover quite accurately, but are limited by clouds. Synthetic Aperture Radar (SAR) sensors penetrate the clouds, but current satellite-borne sensors are only able to map wet snow accurately. The research institutes Norwegian Computing Center (NR) and NORUT IT have together developed algorithms for snow variable mapping applying a combined multi-sensor multi-temporal approach. The overall idea is to utilise the best fea-

tures of each sensor when possible in order to map snow variables more frequently and with better spatial coverage than would otherwise be possible.

In this paper we briefly describe the variable retrieval algorithms we use for SAR and optical data, and then describe the multi-sensor multi-temporal approach we have developed followed by a presentation of experiments performed and finally discussion and conclusions.

METHODS

Optical retrieval algorithm

The optical SCA algorithm is based on an empirical reflectance-to-snow-cover model originally proposed for NOAA AVHRR (1) and later refined (2). The algorithm has recently been tailored to MODIS data by NR. It retrieves the snow-cover fraction for each pixel. The model is calibrated by providing two points of a linear function relating observed reflectance (or radiance) to fractional snow-cover area. The calibration is usually done automatically by means of calibration areas. Statistics from the calibration areas are then used to compute calibration points for the linear relationship.

A particular problem for practical use of the snow algorithm is clouds. NR has experimented with several approaches, and the current best cloud detection algorithm is based on K Nearest Neighbour (KNN) classification of MODIS data. In a KNN classifier a pixel, represented by a vector of band values, is assigned the label, which is most prevalent among the K nearest labelled vectors from a reference set. A KNN classifier is an asymptotically optimum (maximum likelihood) classifier as the size of the reference set increases.

SAR retrieval algorithm

Several papers have demonstrated the potential of SAR for wet snow detection using ERS and Radarsat standard modes (see, e.g., 1 and 2). Wet snow was 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. Recently, dry snow has also been inferred by using a $20 \times 20 \text{ km}^2$ moving window and a digital elevation model (DEM). Dry snow is postulated above the mean wet snow elevation within the moving window (5). The methodology has been further improved by taking into account in-situ air temperature measurements from the meteorological station network, which is used to derive an interpolated temperature map based on standard 6°C per km height-laps rate and a DEM (6).

Present algorithms use a -3 dB threshold to discriminate between wet snow and dry snow/bare soil. A more fine-tuned and variable threshold could be applied if the vegetation cover is known.

Multi-sensor time-series algorithm

The basic idea behind the algorithm is to combine optical data over several days and supply with SAR data as frequently as practically possible. SAR data have to be limited to the melting season due to the fact that current satellite sensors are only able to retrieve wet snow. Furthermore, current cost regimes for optical and SAR data might in practice limit the use of SAR data, while optical data are much cheaper (or free). From practical experience so far, approximately 1-3 SAR image acquisitions per week seem adequate.

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

$$MSCA_i(x,y) = USCA_i(x,y) \quad (1)$$

for i which gives $\max(\text{conf}_{time}(i) \text{ conf}_{MSCA}(USCA_i(x,y))) \quad i = t, \dots, t-n$

where $MSCA$ is the new multi-sensor time-series SCA product, $USCA$ is a "time-unit" product (a single-sensor product or a day product), $\text{conf}_{time}(t)$ is a time-dependent confidence function, conf_{MSCA} is the confidence function for the "time-unit" product, t is the current day and n is the number of days in the time series. 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 entirely controlled by the confidence function.

The confidence function $conf_{time}(i)$ is a decay function of time, i.e., a function giving reduced confidence as the age increases of each unit product. The function might be linear giving largest confidence to today’s observations and no confidence above a given time horizon. The two main versions of the multi-sensor time-series algorithm developed so far differ mainly in their way of generating the time-unit products (a one-per-day product or a near-real-time product).

Single-sensor products as well as day products have associated per-pixel confidence values. The confidence values for a day product are the combination of confidence values in the corresponding single-sensor products where pixel values have been selected.

A single-sensor confidence function is typically related to acquisition geometry, trust in the decision taken by the retrieval algorithm, etc. The following single-sensor confidence functions have been found to be relevant:

$$\text{Optical pixel confidence: } conf_{SCA-OPT} = c_s() c_c() c_d() \quad (2)$$

- c_s : Confidence function related to pixel sample ground size (increases with distance to nadir)
- c_c : Confidence function related to cloud probability (clouds may be transparent)
- c_d : Confidence function related to snow age (snow grain size and impurities increases with time and reduces contrast)

$$\text{SAR pixel confidence: } conf_{SCA-SAR} = c_{cl}() c_g() c_t() \quad (3)$$

- c_{cl} : Confidence function related to classification confidence (distance to threshold)
- c_g : Confidence function related to acquisition geometry (snow contrast depends on incidence angle)
- c_t : Confidence function related to air temperature in reference and new image (from meteorological stations)

The confidence values are in the range between 0 and 100. Zero confidence means that no SCA value has been estimated. This refers to water, forest and radar shadowed areas in the SAR products, and to clouds and large view angles ($> 60^\circ$) in the optical products.

The confidence function for day products, day-confidence, $conf_{DSCA}$, is the product of the single-sensor confidence function (for either optical or SAR) multiplied by an inter-sensor confidence factor, $conf_{INTER-OPT}$ and $conf_{INTER-SAR}$. This factor makes it possible to give one sensor different confidence scaling than the other.

For the sensors and retrieval algorithms applied in the experiments in this paper, the optical products yields a snow cover fraction for each 250 m resolution pixel, while the radar products yields the snow cover as a classification into snow/no-snow for each 100 m resolution pixel. The radar product is resampled to 250 m, thus resulting in a quasi fractional-snow-cover product for SAR.

RESULTS

The experiments described in the following have been carried out partly for a test site where several field campaigns have taken place as well as acquisitions of aerial images for snow reference map generation. Additionally, experiments were carried out for South Norway in general where available Landsat TM and ETM+ images have been used for reference when available.

The test site Heimdalen-Valdresflya is located in the Jotunheimen mountain area in the mid of south Norway (9.0° E; 61.4° N). The area is of about 200 km² with an elevation range of 1050-1840 m a.s.l. The area is free of tall vegetation except for some birch in the lowest locations. A digital elevation model (DEM) has been generated for the whole area based on 1:40,000 scale aerial photos acquired under snow-free conditions. Hourly temperature observations were available from the nearby stations at Bygdin (1050 m a.s.l.) and Bitihorn (1607 m a.s.l.).

The time series of image data is from the period 1 March until 30 June 2004. There were in general 1-2 Terra MODIS acquisitions per day. Envisat ASAR Wide Swath (WS) images were ordered from 15 April, in average two days a week (some weeks several more). Before this date, all products are based on MODIS alone.

Two parameters were varied in the experiments:

- The time decay function, $conf_{time}(i)$, was set to 0.30, 0.15, and 0.10, which corresponds to a maximum time horizon of 3, 6 and 9 days after the first day. We also studied the effect of using the day products with 1 day time horizon
- The inter-sensor confidence factors were set to $conf_{INTER-OPT} = 1.0$ and $conf_{INTER-SAR} = 0.75$. We also examined the effect of using results from one sensor only (single-sensor combined day-products)

The results presented in the following are mostly based on the day product approach mentioned above. A more thorough comparison of the two approaches is planned presented later. Also, we were not able to present and discuss the results of all of our experiments in the following as this would make the paper too comprehensive.

We start by looking at a period of products in May 2004 to illustrate how the multi-sensor time-series algorithm works in general. The first day of the period is 9 May and consists of an optical

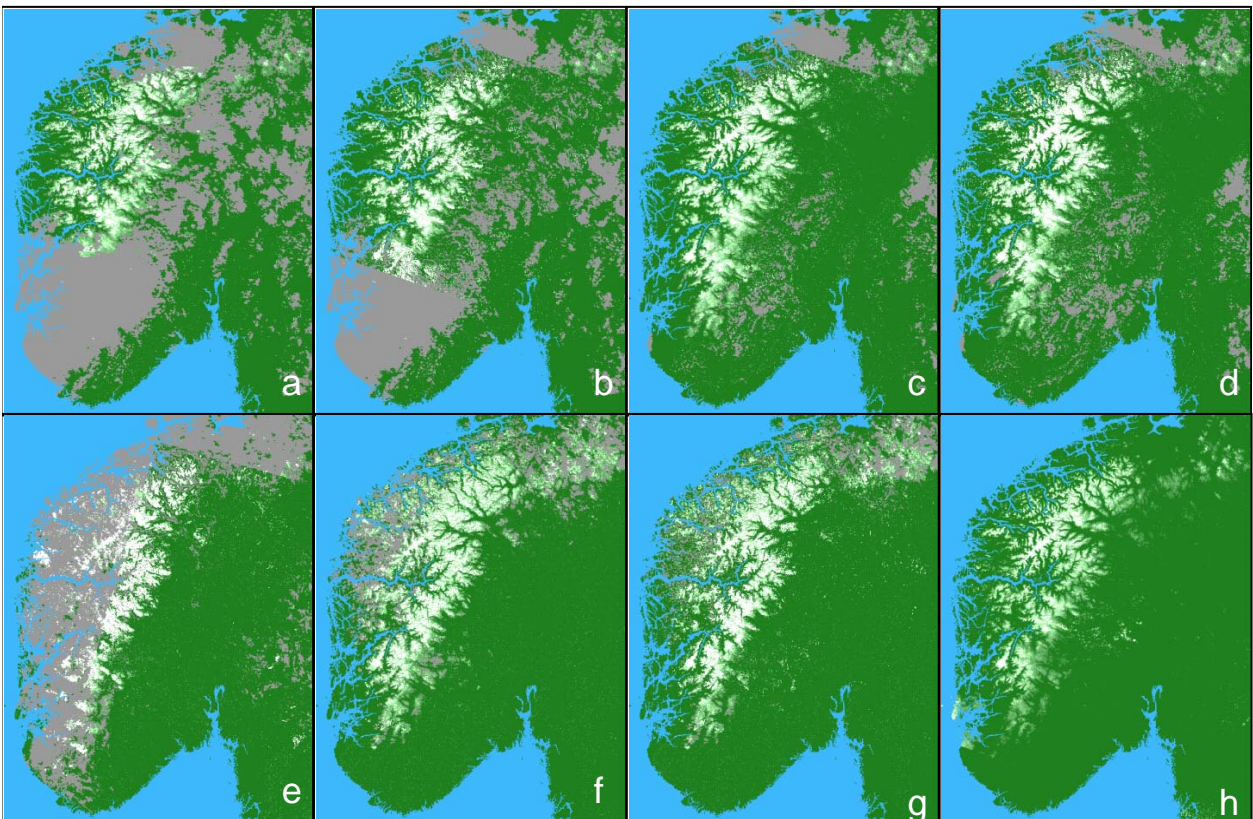


Figure 1. Multi-sensor time-series SCA products from May 2004. Fractional snow cover is shown on a scale from green (snow free), via tones of green to white (100% snow cover). Clouds and other areas of zero confidence are shown in grey. When not specified, MODIS and ASAR have been used as the data sources. From upper left: a) Optical product for 9 May 2004; b) Multi-sensor time-series product for 9 May 2004. The product consists of optical observations as well as SAR observations; c) 10 May; d) 12 May; e) 19 May. Most of the mountain areas are mapped from the SAR data. Optical data with cloud mask errors cause false snow in the west and south; f) 25 May, with inclusion of optical data only; g) 25 May, also with inclusion of SAR data; h) 31 May, single-image product where MERIS has here been used as the data source (without cloud masking).

day product and as well as a SAR product. Being the first day in a time series, the day product corresponds to a situation where there have been no useful observations for a while. This situation might appear if there are several days of full cloud cover with only dry snow present in the SAR products. Figure 1a shows the optical day product and Figure 1b the multi-sensor time-series day product. We see that the mapped area increased by including SAR data, and that the two results appear to agree quite well.

When new day products are added by the multi-sensor time-series algorithm, the mapped area might increase, and the estimated values updated according to the confidence functions. In Figure 1c we see the development of the multi-sensor time-series product the first few days after its initiation. The second day in the time series, 10 May, yielded good optical observations, which updated and confirmed the existing data and increased the mapped area to almost the whole mountain region. The next two days were cloudy. Therefore, there was no day product on 11 May and only a SAR day product on 12 May, see Figure 1d. On 12 May it is clear that the confidence decay function of time has worked on the existing time-series product. In the western part of the map we see that the SAR product has been applied. Note the difference to the east, where the SAR product had zero confidence and the existing multi-sensor time-series product was decayed below the threshold (the grey colour indicating clouds). The reason for zero radar confidence here may be presence of forests. Also note that some locations near the coast in the west have been wrongly classified as snow in the radar product.

The period 13-22 May continued to be dominated by clouds, and the daily time-series had to rely on old products and radar observations. Figure 1e shows the product for 19 May, and almost all the snow-covered mountain areas result from optical data. Some clouds in the western part are misclassified as snow covered. The SAR products have identified a lot of snow cover, but these areas are surrounded by unclassified pixels. We cannot say from the product whether those areas actually are snow covered or not.

The optical SCA product for 23 May updated and verified the multi-sensor time-series product in the east and south. An important difference, when utilising optical products compared to SAR products, is the ability to estimate fractions of snow cover. The radar SCA gives a more binary result, and often yields a patchy appearance, while the optical data gives a more smooth appearance.

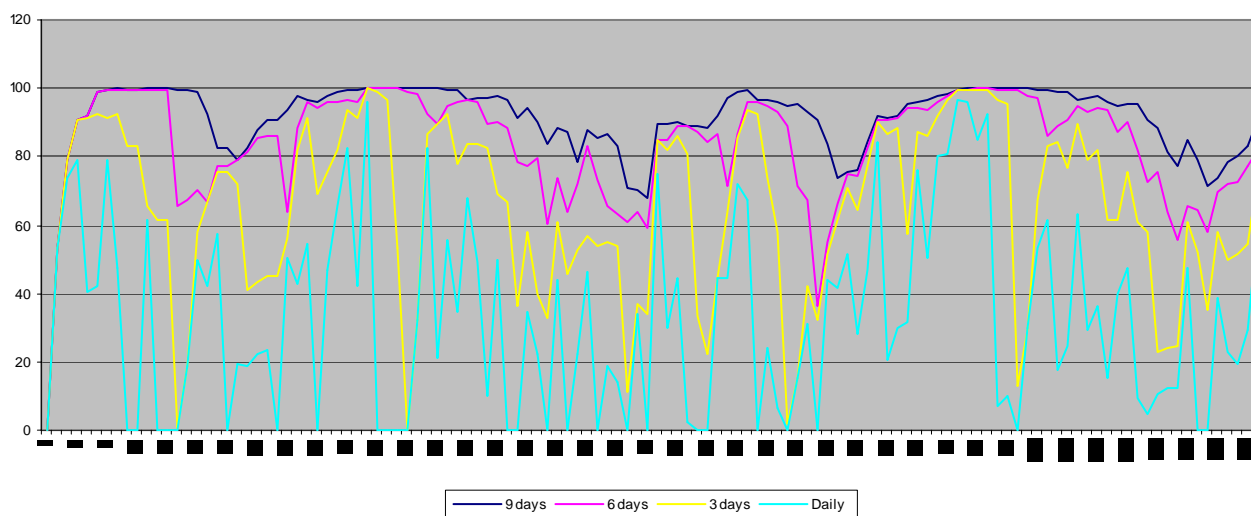


Figure 2. Data coverage in percentage of the total land area for multi sensor products with different time horizons. The inter-sensor confidence factor is 1.0 for both sensors

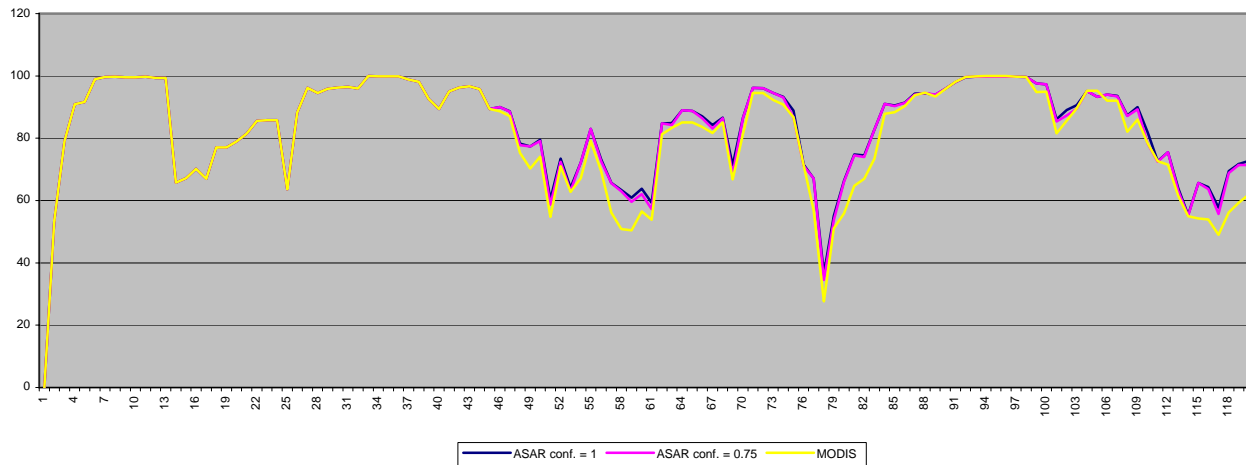


Figure 3. SCA coverage in percentage of the total area for two values of the inter-sensor

The time-series product of 25 May is shown in two different versions, one with optical data only (Figure 1f), and one where also SAR data have been included (Figure 1g). The SAR data improves the classification in the northwest by identifying snow-covered areas as well as snow-free areas. Note that in the eastern part of the radar product some strange patches of snow appear within the snow-free areas.

In Figure 1h we show the last product for this period. From 27 May the sky was mainly cloud free for large parts of the area. The last day product of 31 May used here is based on Envisat MERIS data. Since MERIS does not allow detection of clouds over snow-covered surfaces, it is hard to use this sensor operationally. However, this product indicates that SCA retrieval from MERIS works as well as for MODIS.

A single sensor or day product will not give SCA values for the whole area. This is caused by cloud coverage and radar-shadow effects. One measure of quality of an SCA product is the total area covered with SCA values. We have calculated the area covered in percent of the total land area (South Norway) for day products, single-sensor products and single-sensor time-series products. This has been done for all combinations of confidence parameters.

Table 1. Mean coverage of the land area in percentage for a MODIS time-series product and multi-sensor time-series day products with different time horizons and inter-sensor confidence factors

	1 day	3 days	6 days	9 days
MODIS		61.48	81.21	89.38
conf_{INTER-SAR} = 1.0	33.14	64.68	83.76	91.11
conf_{INTER-SAR} = 0.75	33.14	64.18	83.39	90.92

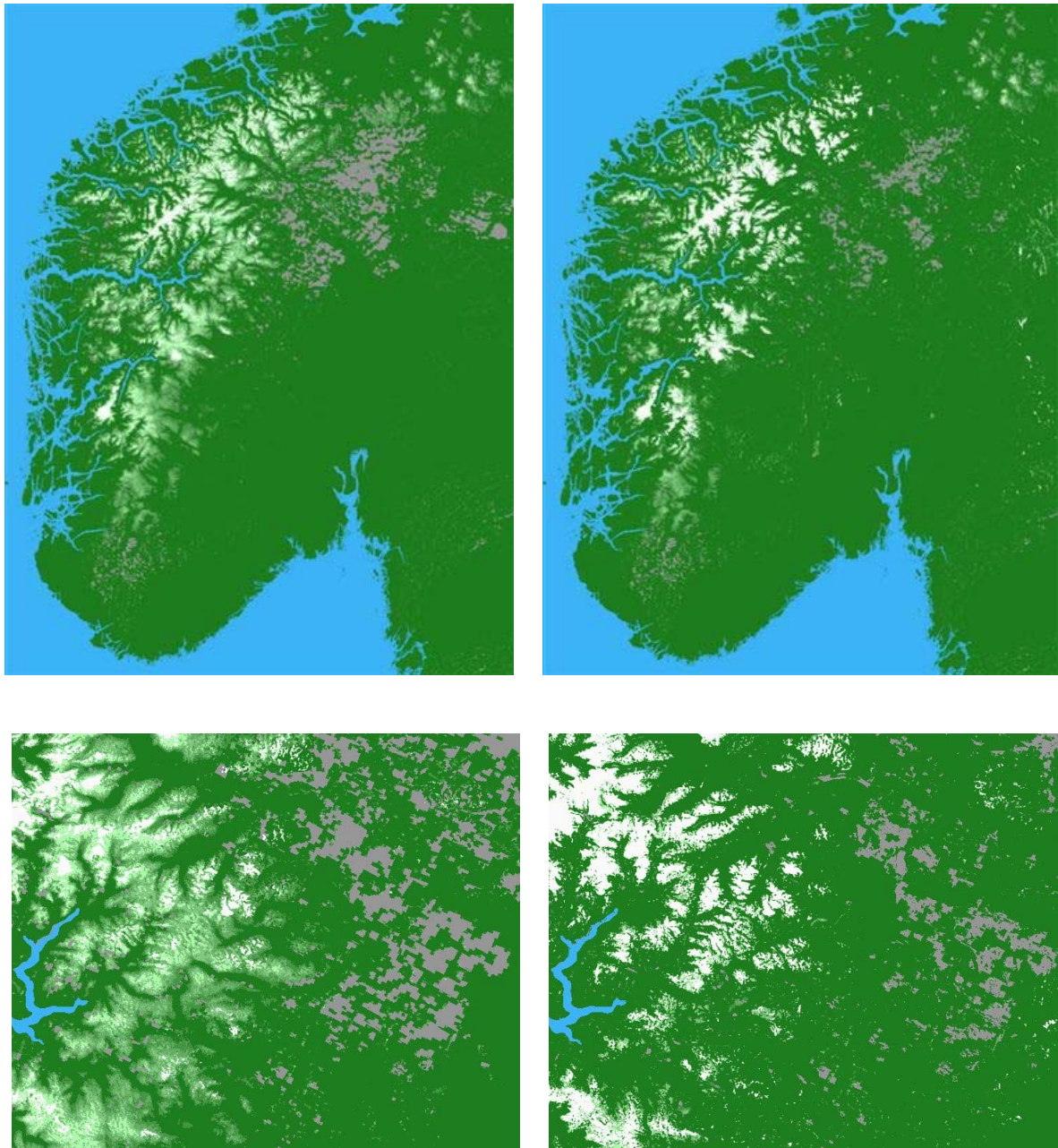


Figure 4. The day product with and without ASAR on 7 June 2004. Left: MODIS only included. Right: Both MODIS and ASAR included. Top: Overview of South Norway. Below: Enlargement of the Jotunheimen area (from northern part of the overview). After the inclusion of ASAR data the SCA tends to approach the extreme values of 0% and 100% and lots of snow seem to have disappeared. In other places the snow cover appears to have increased from partial to complete coverage.

In Figure 2 the area with SCA data in percent of the total area is shown for different multi-sensor time-series products for each day throughout the test period. Both inter-sensor confidence factors are set to 1.0. The plot shows how the coverage varies with the time horizon.

Figure 3 shows the coverage of SCA data for multi-sensor time-series products with two values of the inter-sensor confidence factor for the test period. We see little difference for the values 1.0 and 0.75. Both give a better coverage than a single-sensor MODIS time-series product.

Mean values for the coverage through the test period of 122 days are given in Table 1. Coverage for an ASAR single-sensor time-series product is not calculated because it is not directly comparable to the other alternatives. Forested areas are masked out for SAR. In the SAR product this is shown as zero confidence in the forested areas. The SAR product also gives confidence zero for lakes and for the area inside Sweden. Therefore, the calculated area of SCA values for ASAR will always be much less than for MODIS.

Figure 4 illustrates in more detail the differences between the results of SCA retrieval from optical data and SAR data. Six days time horizon and an inter-product confidence factor of 1.0 were applied. In this time-series multi-sensor product of 7 June 2004, ASAR data has yielded a more binary looking product. Lots of partly snow-covered areas disappear by including ASAR, probably due to backscatter from patches of snow-free ground this late in the snowmelt season.

A multi-sensor time-series product has been compared with a Landsat Thematic Mapper (TM) image from the 23 May. The result is shown in Figure 5. The TM-derived snow area is 2.1% larger. We compared a Landsat RGB image with a field photo taken for validation of TM-derived SCA. From the comparison it appears that the TM SCA product may be a little generous on the snow cover, which is consistent with the slightly larger snow area from TM compared to the multi-sensor time-series products.

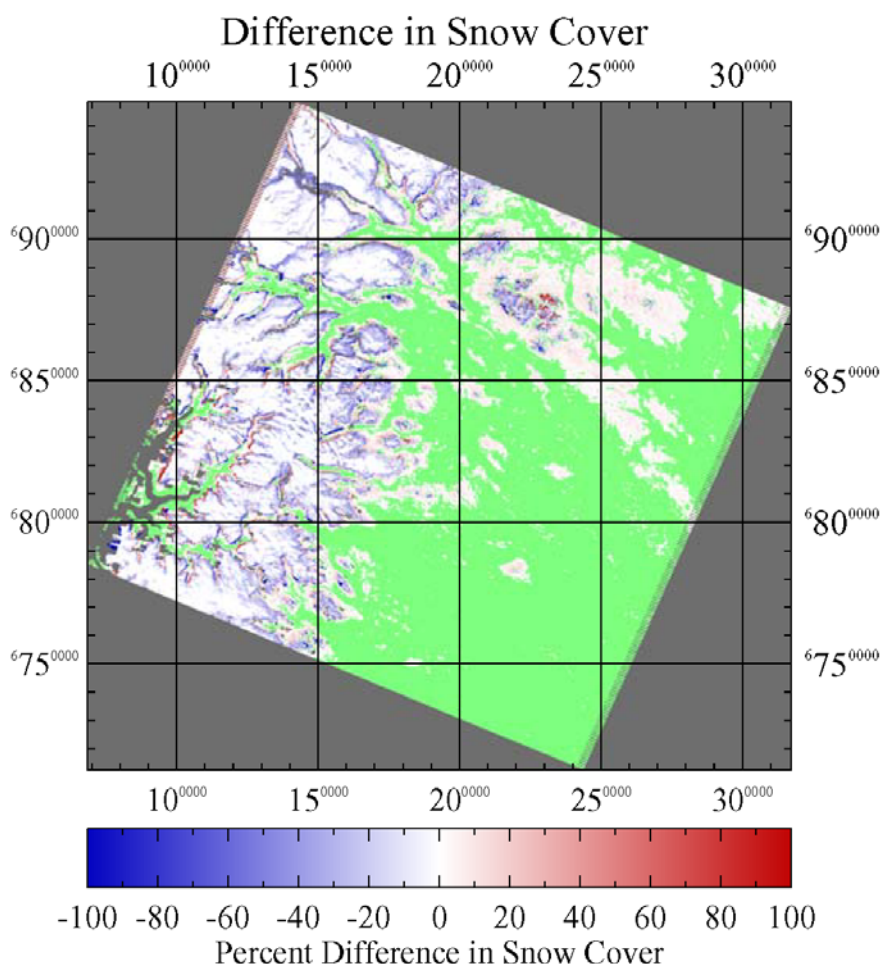


Figure 5. Difference in snow cover between the 23 May multi-sensor time-series product and Landsat TM-derived SCA. Green shows common snow-free areas. The multi-sensor time-series product shows 24.3% snow cover, while the TM product shows 26.4%. Areas where SCA from TM is higher are blue and lower are red.

DISCUSSION AND CONCLUSIONS

The current experience with the multi-sensor time-series algorithm shows that the products depend very much on how the initial single-sensor product confidence is set and on the time decay function. It appears that closeness to clouds should have been given reduced confidence in the optical data in order to reduce the risk of classifying clouds as snow. More important, however, is to consider how to fuse the SAR and optical products better.

When optical data are unavailable due to clouds, the use of radar data improves the product by covering larger areas. Due to the binary character of the radar snow map and the limitation to detect wet snow only, we set the inter-sensor confidence factor for SAR to a lower value than for optical in some of the experiments. We examined and evaluated various inter-sensor confidence factors for SAR, and found that factors of 0.5 and below clearly reduced the contribution from the SAR products too much. Using a value close to 1.0 preserves much of the binary pattern from the SAR products. This means that high confidences for SAR had a tendency to override subsequent optical products. We found that values in the range 0.75-1.0 gave the overall best results.

We examined the effect of including assumptions about dry snow above the wet-snow zone in the radar product. Using a SAR SCA product including also inferred dry snow appeared to overestimate the snow cover compared to the optical product. Using SAR SCA based on wet snow only appeared to underestimate the snow cover compared to the optical product. We also tried to reduce the confidence of SAR pixels classified as dry snow, but this did not improve the result significantly.

Based on the experiences from all the runs of the algorithm we found that a 6 days time horizon was optimal for the cases we tested. While 3 days resulted in a large fraction of unclassified pixels, 9 days resulted in marginal improvements in coverage (compared to 6 days) and too many old observations in periods of rapidly changing SCA.

Some experiments were performed with Envisat MERIS data instead of MODIS. The MERIS-based single-sensor SCA maps seem to be of similar quality as the MODIS-based maps for cloud-free conditions. However, clouds make serious problems over snow-covered surfaces since MERIS does not have the spectral bands needed to separate snow and clouds spectrally. Envisat's AATSR can be used for generating a cloud mask, but it would, unfortunately, only cover a part of the MERIS image. If one limits the use of the MERIS image to the area covered by AATSR, less frequent coverage would be a consequence.

We also tested an approach where the SCA values of the best single-sensor optical and SAR products were combined as a weighted mean of the two. The weights used were proportional to the confidence of the corresponding pixels. The approach did not change the product very much in general. When the SCA values of optical and SAR differed much, the result had a tendency to be worse (one of the values might be an "outlier", then worsening the "good" value).

Other approaches of combining optical and SAR could be considered. Instead of combining the two sensors when making a day product, we could leave the day product idea and combine ASAR with an updated time-series product (which already included the current MODIS day product). However, any approach where we use weighted mean to update the time series will make it difficult to control how long time one observation should be allowed to influence the time series.

A better idea could be to maintain two independent time series, one for each sensor and updated by the "selection-of-best" approach. For each day any relevant algorithm can now be applied in order to retrieve the combined product, without pushing this multi-sensor product forward and influencing the future products. A more general approach would be to store all observations for at least the defined time horizon, and then reanalyse all data for each multi-sensor product that is going to be produced.

The experience with the SAR SCA retrieval algorithm confirms that interpretation of SCA from SAR imagery is more complicated than for optical imagery. For the original 100 m pixel resolution SAR product the wet snow threshold is binary (wet or dry snow). In the SAR imagery a small fraction of bare ground in a pixel may cancel out a large fraction of snow due to the large contribution to the

total backscatter from rocks and vegetation, which tends to emerge early in the snowmelt season. Resampling of 100 m products to 250 m generates fractional snow coverage where bare ground, wet and dry snow, and maybe also mask pixels, are combined into a snow-cover fraction value.

In spite of the abovementioned problems with fusion of optical and SAR products, the results of the study showed that SAR-based snow maps in general were fairly consistent with optical-based snow maps. The SAR-based maps were very useful for updating the multi-sensor time-series products in a period of missing optical observations. The SAR observations were to a large degree confirmed by subsequent optical SCA observations. However, for some locations the SAR wet-snow values had a tendency to underestimate the SCA compared to optical data. When dry snow estimates were included in the radar products, the tendency was the opposite at higher elevations.

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