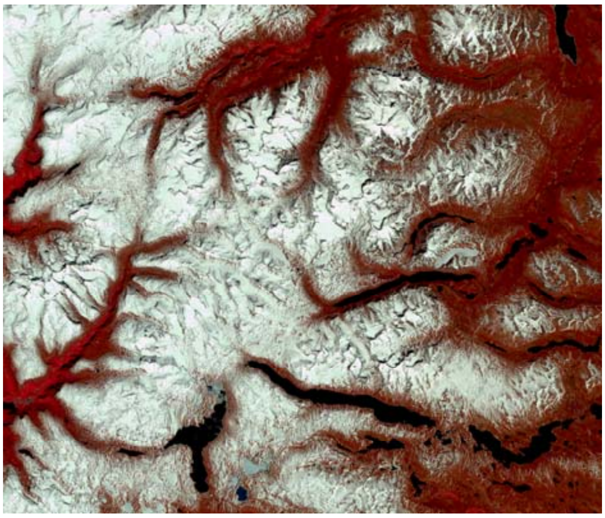
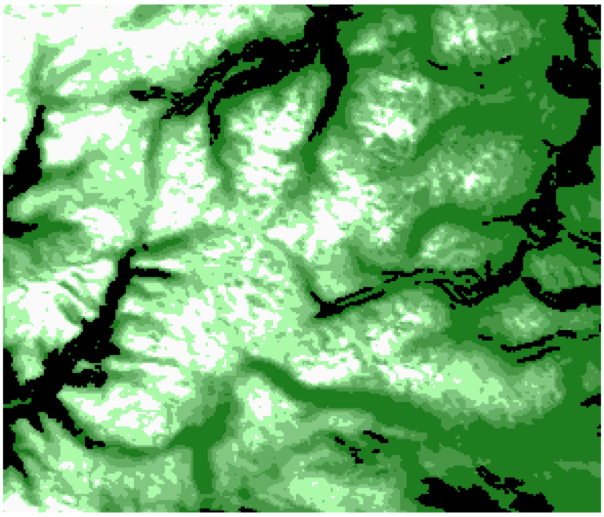
Note

Validation of the NLR fractional snow cover algorithm

Extended report including topographic radiometric correction





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Norsk Regnesentral

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Abstract

This note is a new and extended version of the NR note SAMBA/34/2008/, "Validation of the NLR fractional snow cover algorithm". To cover a larger part of the year, also outside the snowmelt season, two more data sets have been included. In addition, the snow cover algorithm is taking the topography of the test area into account.

Norwegian Computing Center has for many years developed, improved and tested algorithms for fractional snow cover (FSC) retrieval. Maps showing the snow cover for Norway and Sweden based on MODIS images from the Terra satellite have been produced since 2001. It has been known that the algorithm is not perfect. The old version did not take into account the topography, and although it was working well for relatively flat areas, there were errors in the snow estimates in mountainous terrain. A typical error was that it estimated too little snow in areas facing away from the sun. In this note we have tried to validate the algorithm in Jotunheimen, which is a region with a lot of high and steep mountains. Taking the topography into account, the snow cover algorithm should give improved results.

The algorithm is used on MODIS images having a resolution of 250 m. The results have been compared with Landsat images with a resolution of 30 m. For a number of days during the year, we have found Landsat images from various years. The amount of snow has been estimated from these images using unsupervised clustering combined with visual inspection.

The amount of snow estimated from MODIS and Landsat images has been compared for areas outside forests. As expected, the snow cover algorithm gives improved results, taking the topography into account.

There has also been a test of the algorithm inside forests for a scene with 100% snow cover inside the forests, one with absolutely no snow, and one with practically no snow inside the forests.

Keywords	Snow cover, satellite images MODIS
Target group	Snow hydrology, climatology, meteorology
Availability	Open
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Research field	Earth observation
Number of pages	50

Contents

1 Introduction

1.1 The NLR algorithm

Norsk Regnesentral (NR) has for several years produced maps showing the snow cover area (SCA) and fractional snow cover (FSC) for whole Norway or parts of Norway based on images from the MODIS sensor on the Terra Satellite. The images have been downloaded daily from the NASA website. In the estimation of snow cover, the so called NLR algorithm has been used.

This algorithm is using calibration areas. A number of selected areas are used as basis for full snow cover, and another set of areas are used as basis for bare ground. The selected areas are permanent and the measured reflectance values from these areas are used to make threshold values for full snow cover and bare ground. A linear relationship is determined between the two thresholds to retrieve a snow cover percentage per pixel. A closer description of the algorithm can be found in Solberg et al. (2004).

This method gives good results in long periods of the snowmelt season, but it has some weaknesses. The calibration areas for full snow cover are situated at the top of plateau glaciers. This means that the measured reflectance is taken from flat areas. For areas which are nearly flat or have a moderate slope, the snow percentage can be estimated fairly accurate. However, the original method did not take into account the slope or the aspect angle of the landscape. Areas with a slope leaning away from the sun will reflect less light than flat areas, and less the steeper the slope is. As a result the calculated SCA will have too low values. This effect is prominent early in the year when the sun elevation is low. It is expected that the SCA result will be better as the sun rises higher, but for steep slopes leaning towards north, the results will never be perfect.

Taking the sun position and the topography into consideration, it is possible to modify the algorithm in such a way that the underestimation of SCA in areas facing north and overestimation in areas facing south will be corrected. Knowing the angle of steepness and direction of each pixel in the area, it is possible to use the position of the sun and compensate for the varying sun illumination and adjust the measured reflectance values to give a better SCA estimate.

One extra problem occurs with low sun elevation. In a hilly terrain, the mountains will create shadows, and there may be large areas which are not directly illuminated by the sun. The NLR algorithm does not account for this, and so it is expected that the SCA will be underestimated in the shadows.

Early in the season, before melting starts, the snow is dry with a small grain size, and practically all snow has the same reflectance. As the melting starts, the snow will get wet, and get a larger grain size, first at the lower altitudes. The reflectance will be gradually reduced, especially when there become large bare areas. From these areas, sand, dirt and vegetation litter of various kinds will blow into the snow areas and reduce the reflectance. When the snow from the last year has melted, old dirty snow from earlier years appears. The calibration areas, situated at the highest glaciers will still have dry snow, small grain size and no pollution a long time after the melting and pollution has started in the lower areas. This will contribute to an underestimation of SCA.

To sum up: The NLR algorithm used without taking the sun elevation and the topography into account, is expected to underestimate the SCA, especially early in the season because of low sun elevation and late in the season because of snow impurities.

With compensation for the topography, the algorithm, hopefully, should manage to make a satisfying SCA classification in all types of terrain. The results should be as good whether the terrain is flat or steep, and there should be no difference if the terrain is facing south, north, east or west. One of the objectives with this study is to validate the algorithm using terrain compensation, and find the correction parameters which give the best results.

Two MODIS images taken at different times on the same day will give different FSC and SCA results. One reason is because the position of the satellite relative to the observed area changes for each orbit, and so does the position of the sun. Tests have shown that the recorded signals from a specific area can differ quite a lot, and so will the calculated FSC. The best results are achieved when the satellite is close to zenith when observed from the area. Then the recorded pixels cover the smallest areas on the ground. Along the centre line of the recorded image the pixels have a size of 250 x 250 m in band 1 and 2. Towards the edges of the image the pixel size increases, and details are smeared out.

The use of calibration areas may also cause different FSC results. If one or more calibration areas are completely or partly covered with clouds in one image and not in the other, the calibration values will be different, and the FSC results may differ.

1.2 Objective of the study

To get a quantitative assessment of the errors of the SCA retrieval, the results of the SCA calculation from MODIS should be compared to accurate snow maps based on a number of high resolution images from various times in the melting season and for various types of terrain.

1.3 Method

To accurately estimate the SCA, aerial images or satellite images of high resolution could be used. High resolution images covering large areas for a number of dates from one or several years are not easy to find. The best set of such images is probably to be found in the Landsat archives. From these images the SCA has been determined manually using classification tools. Calculated SCA from MODIS has been compared with the reference maps. It is interesting to know the absolute difference between calculated and true SCA, but also to find in what type of terrain the differences are largest and smallest.

1.4 Validation area

A region in Jotunheimen in Southern Norway was selected as validation area. In this region there are large areas without forest, and various types of mountainous terrain. The area was selected such that it could be covered by two different passes of the

Landsat satellites. The borders were finally adjusted so that the area did have no cloud cover in any of the chosen Landsat images. The area is marked in a map in Figure 1.

2 Input images

2.1 Landsat images

2.1.1 Choice of images

We would like to have a set of Landsat images covering Jotunheimen from different times of the year and with different amount of snow cover. As the area was covered by two different passes of the Landsat satellites, we expected to have many scenes to choose between in the Landsat archive. But there are not many scenes in the archive, and many of those have large cloud-covered areas, so we ended up with 8 scenes with a time span from 16 January until 19 October with snow cover from close to maximum to an absolute minimum. We would have wanted to have more scenes of various amounts of snow cover, especially from June and July, but we did not find any usable. The scenes used in the validation are shown in Table 1

Satellite	Track	Scene	Date
Landsat 5	199	17	2004.01.16
Landsat 7	200	17	2003.03.01
Landsat 7	200	17	2003.04.18
Landsat 7	199	17	2000.05.04
Landsat 5	199	17	2004.05.23
Landsat 5	200	17	2004.05.30
Landsat 5	199	17	2003.08.09
Landsat 5	200	17	2003.10.19

Table 1 Landsat images used in the validation

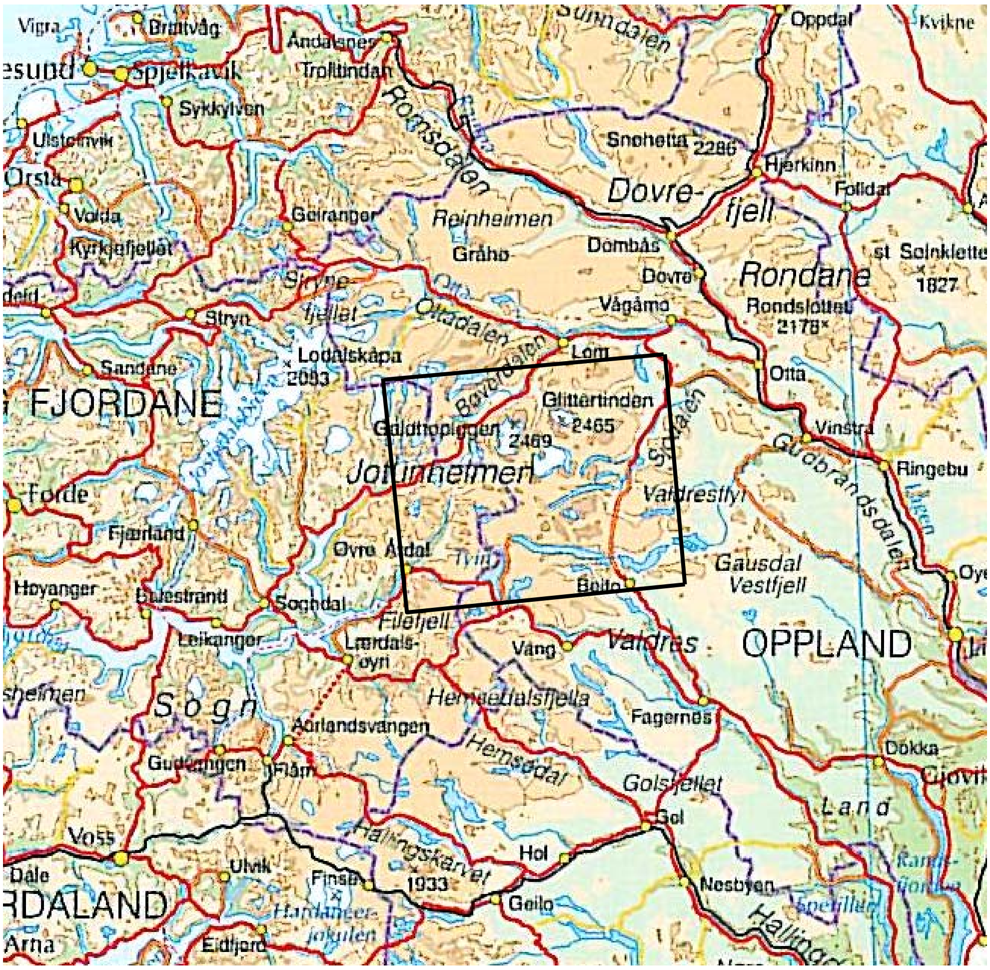
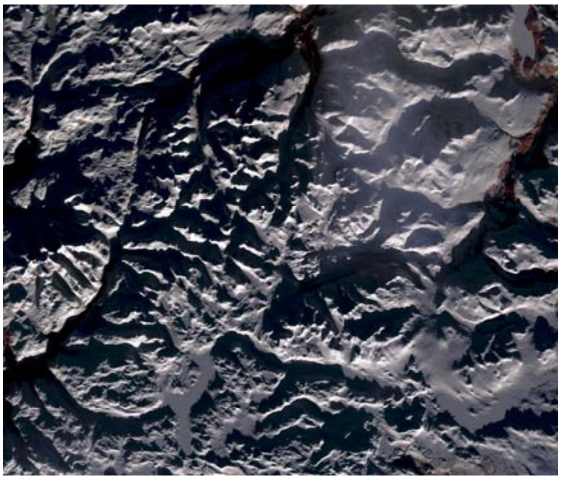


Figure 1 Test area in Jotunheimen

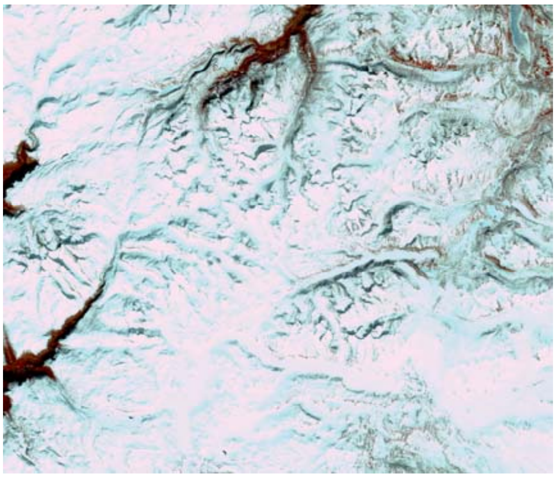
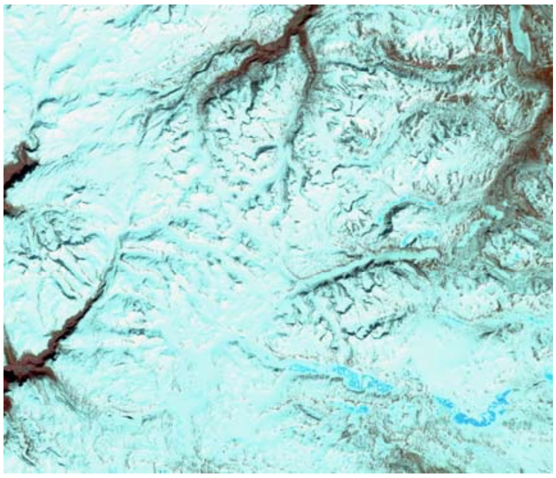
2.1.2 Geocorrection

The images were transformed to UTM zone 33, WGS 84, using the coordinates of a vector water mask and a digital elevation model of 25 m resolution. The correction was done with Erdas Imagine and ENVI. The Landsat images were delivered with a pixel size of 30 × 30 m. To make it easy to compare with MODIS images of 250 m pixel resolution, the images were transformed to 25 m resolution in the correction process.

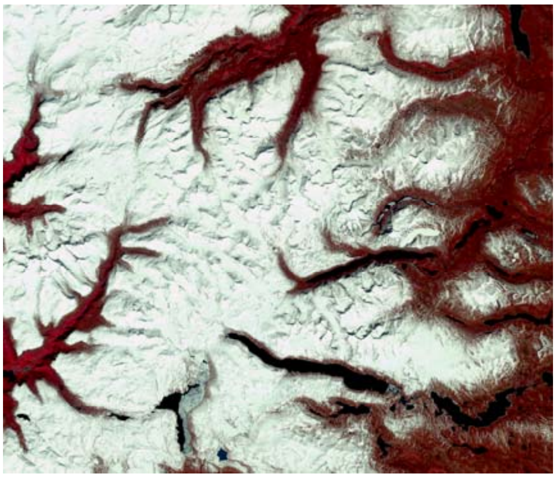
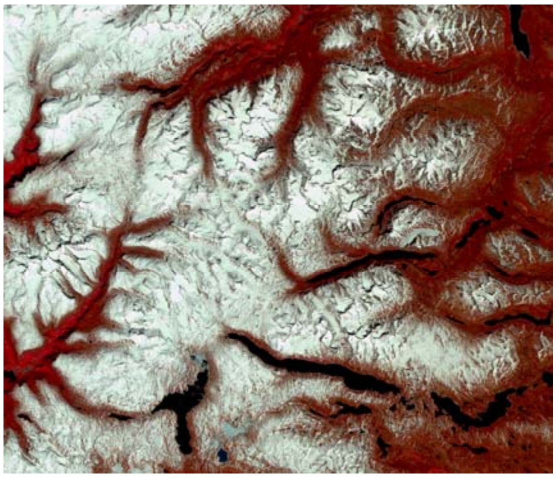
The selected Landsat images are shown in . The images have been geocorrected and cut to the validation area in Jotunheimen.

2004.01.16 2003.03.01

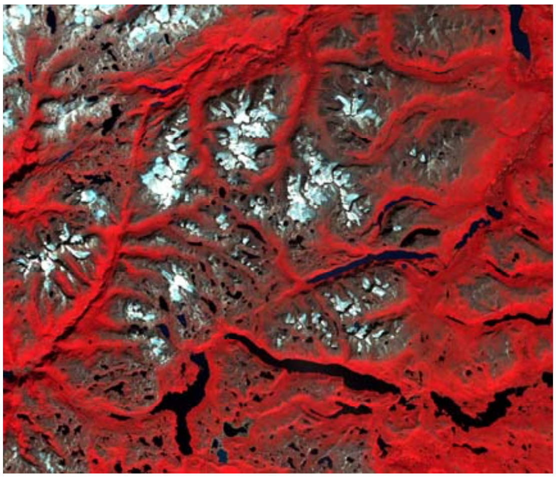
 

2003.04.18 2000.05.04

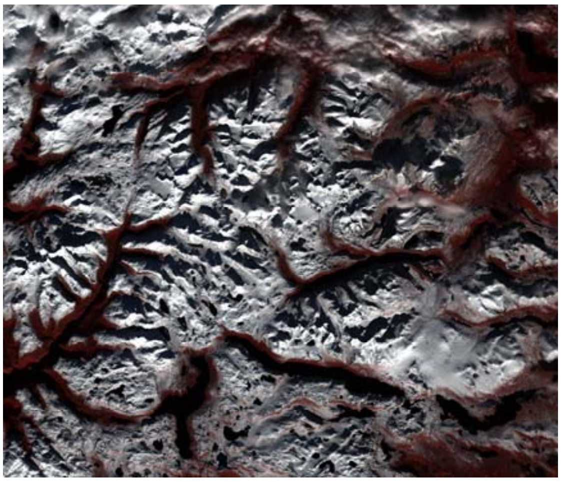
 

2004.05.23 2004.05.30

Figure 2. Selected Landsat scenes. The figure continues on next page.



2003.08.09



2003.10.19

Figure 2 (continued) The selected Landsat images. The images have been geographically corrected and cut to the validation area. Band 4, 3, and 2 are here used as RGB. The red colour is caused by high values in the infrared band 4, due to vegetation.

Comments to the images

2004.01.16: The area is almost completely covered with snow. The sun is low, and there are large shadows of the mountains. This will complicate the estimation of snow cover. There is also a sort of haze over the north-eastern part of the area. There will be no snow cover estimation in this area.

2003.03.01: The area is almost completely covered with snow. The sun is still low, but the shadows are smaller than in the image from January. Still the shadows will have large influence on the snow estimation

2003.04.18: Melting has started, but most of the area is still covered with snow. There are many small areas without snow which give many pixels only partly covered with snow. Areas which seem to be without snow may be forested areas still with some snow on the ground. The effect of shadows has been significantly reduced since the beginning of March.

2000.05.04: There is exceptionally much snow to be in the beginning of May. There are small differences in the mountains from the April image, but one can see that the snow has started disappearing on the large lakes, and the ice is starting to melt.

2004.05.23: A normal situation of snow in the lower parts. In the higher parts it seems somewhere to be more snow than in the image from the beginning of May 2000. There was a short period of cold weather around 23 May and one day with precipitation. This may have resulted in a thin layer of new fallen snow which may have covered areas of bare ground in the higher parts.

2004.05.30: This image is taken one week after the previous one. There have been large changes in the snow cover during this week. The temperature was high this week, and the new snow has melted, leaving large areas of bare land.

2003.08.09: This summer practically all snow from last winter had melted. The few patches of snow were from earlier years and were more gray than white. The snow had also melted on the glaciers, so all the "snow-like" areas in the image are mainly snow-free glaciers. In the areas where the snow from last and earlier winters usually is situated, the rocks now appear light coloured, without lichen, and may look like dirty snow, seen from a satellite (see Figure 3).

Figure 3 Glaciers with some snow, and light coloured rocks nearby

2003.10.19: There is new fallen snow in the higher areas. The sun is low and the shadows will complicate the snow estimation. The areas covered with clouds, in the northern part of the image, will be excluded from snow cover estimation.

2.2 MODIS images

MODIS images from the same days as the Landsat images have been downloaded from the NASA archive. For some of the days there are two images. For the other three there is only one image per day. A list of the images is shown in Table 2 .

The centre line of the images crosses Jotunheimen at passages around 11 UTC. Three of the images used in the study have been taken close to 11, which should give the best possible results. For the images taken around 10, the centre line is in the Baltic sea. For the images taken around 11:40, the centre line is far out in the Atlantic ocean. The images from 2004.05.23 11:40 and 2003.08.09 10:00 have clouds covering parts of Jotunheimen. These were excluded from the study. For 2004.05.30 and the two new dates introduced in this study, 2004.01.16 and 2003.10.19, we have used both images. The two new images are partly covered with clouds.

In Table 2 the MODIS images are listed with date, time and sun position. The position of the sun is calculated as seen from the coordinates 61º 30" north and 8º 30" east, which is close to the centre of the test area. Sun azimuth is given in degrees, relative to south. Positive values mean toward east, and negative toward west.

Date	Time	Sun elevation	Sun azimuth
2004.01.16	10:05	5.64	21.16
	11:40	7.60	-1.04
2003.03.01	11:00	20.48	10.17
2003.04.18	11:00	39.07	8.56
2000.05.04	11:10	44.58	4.30
2004.05.23	10:05	47.01	27.17
2004.05.30	10:10	48.37	26.16
	11:45	50.20	-7.77
200308.09	11:40	44.38	-2.84
2003.10.19	10:10	17.64	15.79
	11:45	18.31	-8.81

Table 2 Selected MODIS images with sun position

As seen from Table 2, the sun elevation varies from about 5 degrees in January to about 50 degrees in end of May. It should be possible to study the influence of sun elevation on SCA calculations. It should also be possible to study the influence of the sun azimuth position. For three days we have two images with the sunlight coming from different directions. This will probably also influence on the estimation of SCA.

3 Classification methods

3.1 Unsupervised clustering

Classification of a satellite image can be done by unsupervised clustering. The result of a clustering is that each pixel gets a class value depending on the characteristics of the pixel. The user can choose which spectral bands should be included and the number of classes. In this case the idea is to choose the bands which separate snow from bare ground in the best way, and a number of classes which makes it possible to have bare ground, full snow cover, and fractional snow cover in different classes.

With ENVI one can choose between isodata and k-nearest-neighbour unsupervised clustering. The user can set a minimum and maximum number of classes, and the program will return the minimum number of classes which fulfil the criteria set by a number of parameters given by the user.

For the Landsat images one can choose between 7 bands. Tests with the selected images show that band 1-4 or in some cases only band 1 and 2, give the best results. Isodata clustering has been selected, and tests have been done with maximum number of classes of 5, 10, 15, and 20. It seems to be necessary with 20 classes to separate full snow cover from fractional snow cover and bare ground in a reliable way.

There are disadvantages with clustering of this type of images. In a mountain region like Jotunheimen the area consists of plains and slopes of different magnitudes and directions. A pixel fully covered with snow in a steep area facing north can get the same class as a pixel without snow or partly snow covered in a slope facing toward the sun, because of the differences in illumination. The problem will be especially noticeable early in the spring when the sun elevation is not high above the horizon. The same problem will arise between pixels in and outside shadows. This indicates that the areas inside and outside shadows should be clustered separately. Outside shadows there will still be the problems with varying sun exposure. Inside the shadows this problem is almost not present, because the shadowed areas are mostly facing north and are covered with snow.

3.2 NDSI

One way to find snow in satellite images is to calculate the normalized difference snow index (NDSI). This method is part of the SNOWMAP approach which is used to produce daily MODIS snow products which can be downloaded over the Internet.

NDSI is defined as the difference of reflectance observed in a visible band, such as TM and ETM band 2 (0.55 µm), and a short-wave infrared band, such as band 5 (1.64 µm) divided by the sum of the two reflectances:

$$NDSI = (b2 - b5)/(b2 + b5)$$

To calculate the NDSI for each pixel of the Landsat image, the reflectance can be calculated by calibrating the image data using calibration data found in the Landsat meta files. For Landsat 5 (TM) the calibration data are given as gain and bias for each band:

$$b = bias + gain \cdot imagedata$$

For Landsat 7 (ETM) the calibration data are given as minimum and maximum radiance (lmin, lmax), and min and max pixel values (qcalmin, qcalmax) for each band. Then we have

$$gain = (lmax - lmin)/(qcalmax - qcalmin)$$
$$b = lmin + gain \cdot (imagedata - qcalmin)$$

For each pixel the reflectance for band 2 and 5, and NDSI must be calculated. High value of NDSI means that the pixel area is covered with snow, low value means no snow. Intermediate values might mean that the pixel is partly covered with snow.

One advantage of using NDSI is that the influence of atmospheric effects and the viewing geometry is reduced compared to the clustering method. This means that you don’t have to bother with the magnitude or direction of the slope of the terrain. You will get approximately the same NDSI value for flat terrain as for a steep slope facing the sun and a slope turning away from the sun if the snow conditions are similar. One disadvantage is that open water gives high NDSI values. Therefore you cannot use NDSI to determine if there is ice on a lake. Another disadvantage is that NDSI gives high values in shadows, so you will get problems by using NDSI directly in shadowed areas.

3.3 Shadow calculation

Both unsupervised clustering and NDSI calculation have problems with the different conditions inside and outside shadows. To get reliable results for estimation of snow covered areas, the calculations should be done separately for the two regions. To be able to do so, the shadows have to be found in each image.

Checking the selected images, it was found that in areas with snow, band 5 (1.55 -1.75 μm), have low pixel values inside shadows. One can find the shadows by thresholding band 5. This works excellent in images with almost complete snow cover. In areas with bare ground, this method cannot be used.

In Figure 4, the shadow map of the image from 2003.03.01 is presented. The shadows have been found as all pixels with values lower than 13 in band 5.

To find the shadows in images with bare ground, a digital elevation model (DEM) can be of great help. It is possible to calculate the position of the shadows from knowledge of the altitude above the sea level for each pixel, and the sun's elevation and azimuth angle. These angles can be found in the metadata for each Landsat image. To find if a certain pixel is inside shadow, you find its geographic position and height above sea level. From this position you draw a line towards the sun. If this line goes higher than the height of all pixels in the DEM along this direction, the pixel is outside shadow. If not, it is inside shadow. This procedure is executed for all pixels in the image. The DEM has to be extended to the south of the selected area to take the mountains just south of the test area into account. There will be some deviations between estimated and real shadows. The DEM is made in a 25 m grid.

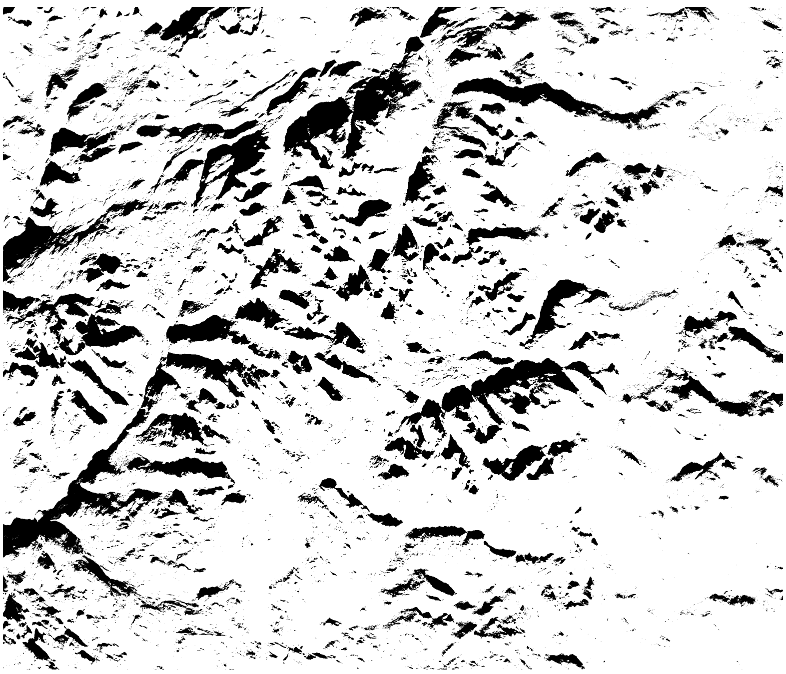


Figure 4 Shadow areas estimated by making a threshold of band 5 for the image from 2003.03.01

With steep mountains, some of the mountain tops will be lacking, and the calculated shadows will be too small. The positions of the pixel values for the DEM are at the corners of the image pixels (not in the centres). This will lead to a small deviation (half a pixel). For a high sun level, these differences will hardly be detectable and probably be less than the errors due to the imperfect geocorrection of the images. Another reason for small deviations is the amount of snow on the mountain summits and in the shadowed areas.

For days with a low sun level, there may larger deviations. For these such images a combination of calculations and clustering can been used.. This a is a tedious work.

3.4 Clouds

In most of the Landsat images there are no clouds in the test area. In the image from 2003.10.19 there are some clouds, especially in the northern parts. The clouds have been manually detected, and the areas covered with clouds have been masked out. In the processing of the MODIS images, clouds will be detected automatically (Koren 2009). The calculation of snow cover will be performed only in cloud free areas. The snow cover may be different in the MODIS and Landsat images, because they have been produced at different times, and the detection methods are different. The comparison of calculated snow cover in the MODIS image with the estimated snow cover in the Landsat image will be done only in areas where there are no clouds in both images. In the Landsat image from 2004.01.16, one can visually see a sort of haze in the north eastern part of the area. This is not detected in the MODIS images by the cloud detection algorithm. The area has been masked out manually, and no comparison has been done inside this area.

3.5 Calculation of snow cover

3.5.1 Input data

- The 8 Landsat images described in Table 1 corrected to UTM zone 33, WGS84, pixel size 25 m, resized to Jotunheimen area.

- Forest mask of South Norway, originally in UTM zone 32, resolution 30 m, resampled to UTM zone 33, 25 m resolution and resized to Jotunheimen area. The original mask is based on the M711 series of topographic maps in scale 1: 50000 from The Norwegian Mapping Authority.

3.5.2 Procedure

The calculation of snow cover was executed by using IDL and ENVI, in batch and interactively.

We have chosen to treat the areas inside and outside shadows differently. Therefore, calculation of shadows has been performed for all Landsat images. For the image from 2003.03.01, which is nearly totally covered with snow, the shadows have been calculated by estimation of a threshold in band 5. For the other images the program built on the DEM has been used. For the images from 2004.01.16 and 2003.10.19, having a very low sun level, a combination of the DEM program and clustering has been used. Cluster classes 1-4 give mostly correct shadows, but in some areas, class 4 is present where the calculated shadow map shows that there should be no shadow. In other areas also class 5 give shadow. Manual adjustments have to be done to get a reliable shadow map. This is a tedious work.

It was decided to use NDSI for calculation of the snow cover outside shadows for all images, mostly because of the reduction of errors due to the variation in size and direction of slopes. In the image from 2003.08.09 there is extremely little snow. Areas normally covered with snow the whole year, were without snow this summer. Such areas look very bright due to lack of lichen and moss, and may be classified as snow in a clustering procedure. Using NDSI, these areas will be classified as bare ground. To find the snow cover, we decided to set two thresholds for the NDSI value. Pixels with NDSI higher than the upper threshold were classified to have full snow cover, and those with NDSI below the lowest threshold were classified as bare ground. The pixels with NDSI between these two limits were classified as partly covered with snow.

Hopefully it would have been possible to use the same thresholds for all images. But it was found necessary to vary the threshold values to be sure to get all areas with full snow cover and to get the smallest patches of snow classified as fractional snow.

To exclude open water from being classified as snow, a clustering was made on the areas outside shadows. Then one or two classes were surely representing water or bare ground. The classified snow map based on NDSI was masked with a bare ground map based on this clustering. The result was a map of areas without snow, but with high NDSI values excluded from the snow areas.

This procedure is demonstrated in Figure 5. A subset of the Jotunheimen area has been chosen, and images from the classification process of 2004.05.23 are shown. In a) the original Landsat image is shown with band 4, 3, and 2 as RGB. You can see three large lakes in different conditions. At the lower border is the lake Gjende completely without ice. In the upper part of the image is Russvatn with some remains of ice, and between these two lakes is Bessvatn which is completely ice covered. In b) the NDSI values are shown in a gray scale with the highest values being white. Image c) is showing the thresholded NDSI image classified into three classes, snow (white), fractional snow (light gray) and bare ground (dark gray). Shadows are marked with black. Here you can see that Gjende and Russvatn are classified as being completely covered with snow. The original image is clustered into 20 classes, and the result is shown in d). Class 1 (red) and 2 (green) are most certain bare ground or open water. (The lighter green colour on Bessvatn is class 14 which represents full snow cover). NDSI overrules the clustering except for open water. In areas where the NDSI shows snow and the clustering gives bare land/open water, bare land/open water is chosen. The NDSI classification and clustering operate only outside the shadows. A clustering inside shadows has to be performed before the final classification is made. The classification result is shown in e) where full snow cover is white, fractional snow cover is light gray, bare ground/open water is dark gray and forest is black.

Inside shadows clustering with 20 classes was carried out for all images. For some images band 1 to 4 was used, and for a couple of images a better result was found with just band 1 and 2. The selection of classes to define full snow, fractional snow cover and bare ground did vary somewhat from image to image. In some cases one class could be determined to be full snow in one part of an image and fractional snow cover in another section. Some compromises had to be made, but the areas in shadows did not cover that large part of the full area (except for the image from 2003.03.01), so the choices did not influence the total result too much.

In calculating the amount of snow, the areas classified as being partly covered with snow, were given 50% snow cover fraction.

After snow classification, the forest mask was used to remove the forest areas from classification.

3.5.3 Choice of parameters

The NDSI thresholds and choice of cluster classes for the images are show in Table 3

	NDSI threshold		Cluster bands	Classes for snow classification		
Date	High	Low		No snow	Fractional	Full
2004.01.16	0.90	0.80	1,2,3,4,5	1,11,13, 15	2,16	Rest
2003.03.01	0.95	0.80	1,2	1,18	2,4,19	Rest
2003.04.18	0.95	0.80	1,2,3,4	1,17	2,3,4,18	Rest
2000.05.04	0.935	0.75	1,2	1,2	3,4,5	Rest
2004.05.23	0.935	0.75	1,2,3,4	1,2	3,4,5	Rest
2004.05.30	0.95	0.75	1,2,3,4	1,2,3	4,5,6	Rest
2003.08.09	0.85	0.75	1,2,3,4	Rest	-	11,12,13,14, 20
2003.10.19	0.95	0.80	1,2,3,4	1,2,3,4,12 13,15,20	5,6,7,16,17	8,9,10,11,14, 18,19

Table 3 Choice of parameter values for snow classification

The choices have been made on a subjective basis, studying 3-band coloured versions of the Landsat images displayed in an ENVI viewer. In addition it was necessary to include personal experience of snow cover in the area. Experience from many excursions with and without skis between March and August during several years has given a solid knowledge of the snow distribution throughout the melting season in the area.

As far as possible the NDSI values and the cluster classes have been chosen to separate the snow classes in the best way. For 2003.08.09 the fractional snow cover class has not been used. The summer 2003 was very special. Practically all snow from the last winter had melted at the end of July. Even the glaciers had extremely little snow left and showed mostly ice. Without the small patches of last year’s snow, the fractional snow cover class was excluded from the 25 m resolution classification. One problem arises with the glaciers without snow. The areas with ice are classified as having full snow cover. The reflection of light from the ice is much lower than from snow, and the MODIS SCA algorithm will not classify these areas as having 100% snow.

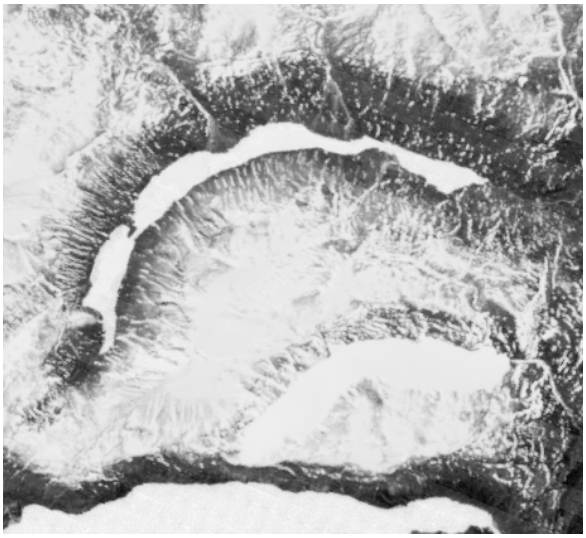
3.5.4 Results

Figure 6 shows the classified Landsat images of 25m resolution. Forest is shown in black, full snow cover in white, fractional snow cover in light gray and bare ground in dark gray.

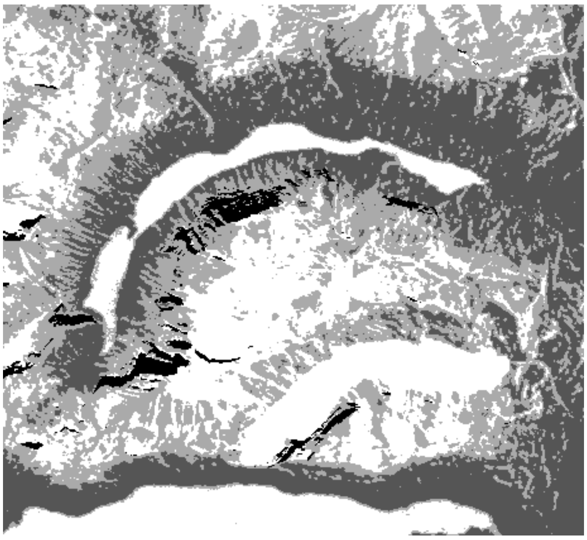
The 'full snow cover' class has been selected to include all pixels which most certainly have a full snow cover. The 'bare ground' class includes all pixels which most certainly have no snow included. The fractional snow cover class will then include all pixels with an amount of snow which probably does not fill the complete pixel area. Here there could be erroneous results. Outside the shadowed areas, a NDSI threshold has been used as the border between full and fractional snow cover. A small change in the threshold value could change the areas of full/fractional snow cover substantially. Inside the shadows there are also problems, but a change in the use of clusters will not have a large influence on the total snow cover area.

The total amount of snow for each day is shown in in section 5.2. The calculations have been executed in three ways, giving three different values for each day. 'Mean' shows the most probable amount of snow based on the assumption that all pixels in the fractional snow cover class have 50 % snow cover. This is of course not correct. The amount of snow in a 'fractional snow cover' pixel can vary between 0 and 100%. To make a minimum limit for the snow cover area, it is assumed that all partly snow covered pixels are completely without snow, and to make a maximum limit it is assumed that they all have 100 % snow. Both assumptions are wrong, but they give a lower and upper limit for the SCA values given in 'Min' and 'Max'.

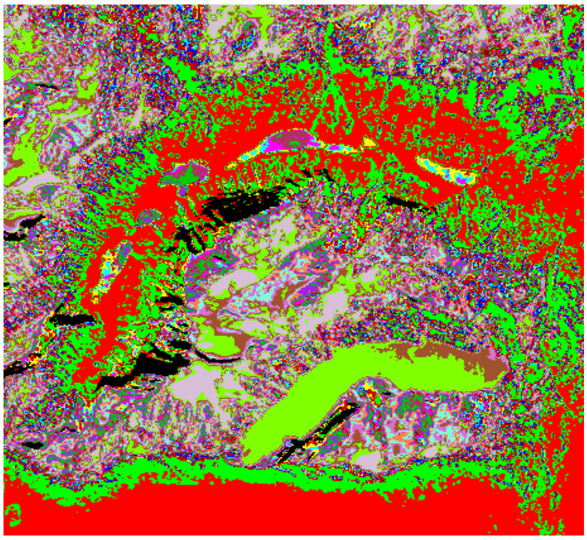
a) Landsat image, band 4, 3, 2



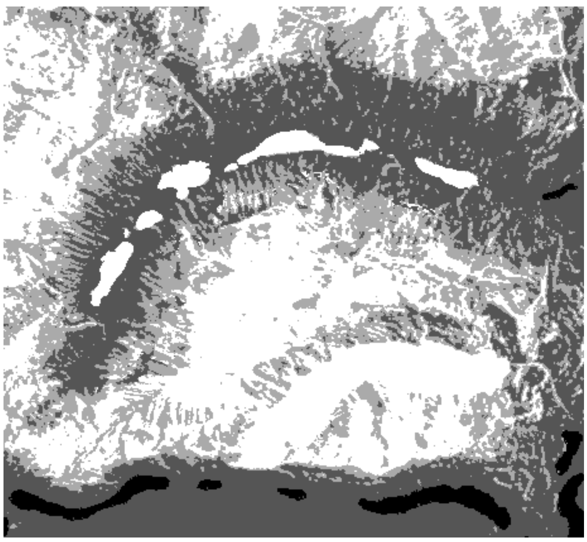
b) NDSI



c) Thresholded NDSI

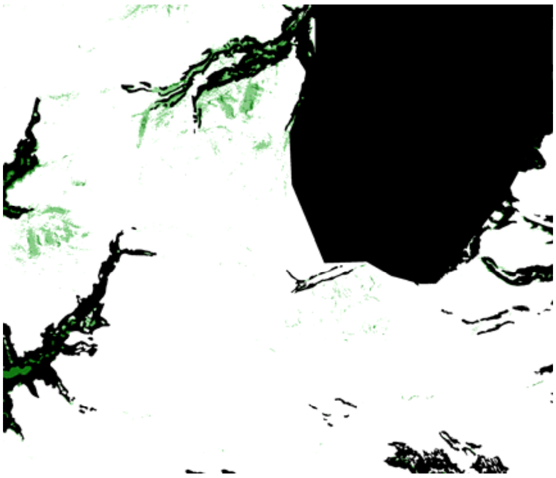


d) 20 clusters outside shadows

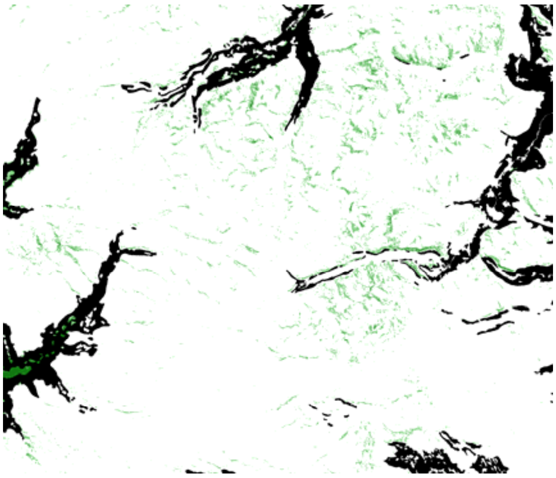


e) Final classification

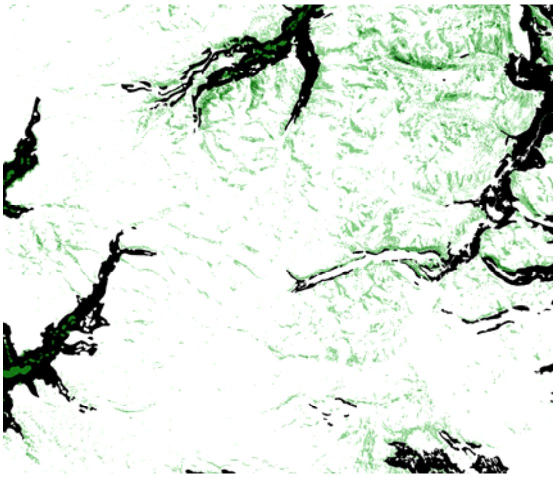
Figure 5 Demonstration of the snow classification procedure for Landsat image from 2004.05.23



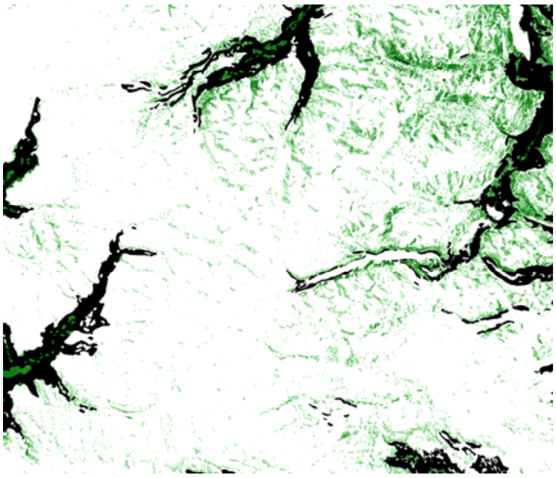
2004.01.16



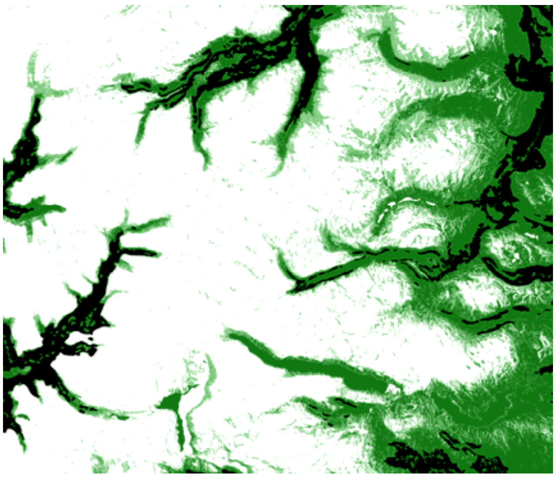
2003.03.01



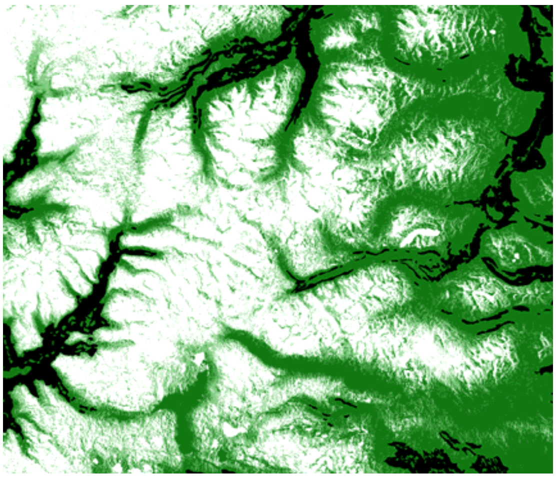
2003.04.18



2000.05.04

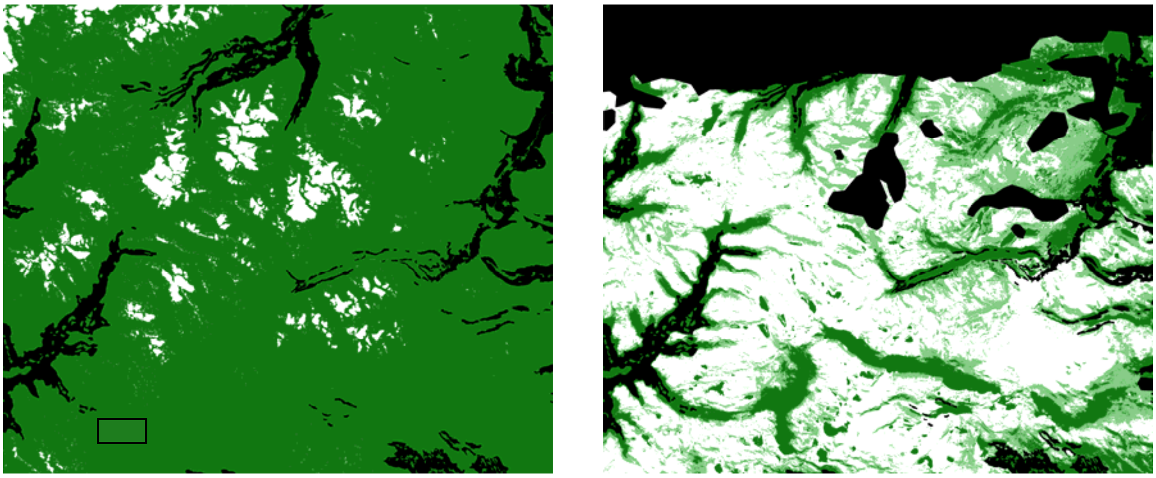


2004.05.23



2004.05.30

Figure 6a Snow classification in Landsat images. The figure continues on next page.
: full snow cover, : fractional snow cover, : bare ground, : forest or clouds



2003.08.09 **2003.10.19**

Figure 6b Snow classification in Landsat images. : full snow cover, : fractional snow cover, : bare ground, : forest or clouds

4 Terrain types

Jotunheimen has been chosen as a test area because of the great variations in the terrain. There are relative flat areas, but also many mountains with steep hill sides and slopes with moderate gradient facing in all directions. It is of great interest to see how well the MODIS SCA algorithm is working in the different types of terrain.

The amount of sunlight reflected by the terrain towards the satellite depends on the material on the surface (snow, water, grass, stone etc.) and also on the angle between the incident sunrays and the surface and on the angle between the view line from the satellite and the surface. If a digital elevation model of the area is available, and if the position of the sun and the satellite is known, it is possible to compensate for the variation of reflected light by the terrain. Then it should be possible to estimate the SCA with the same accuracy for all types of terrain.

Without a terrain compensation it is expected that the SCA results will be best for relatively flat areas, because the calibration data has been fetched from flat areas. For areas facing away from the sun it is expected that the SCA will be underestimated and especially for steep hillsides. For hillsides facing towards the sun it is possible that the amount of snow could be overestimated. If the area is completely covered with snow, the algorithm will not estimate more than 100 % snow, but it is possible that one can get 100 % snow also for hillsides with patches without snow.

In the report from 2008 (Koren 2008), no terrain compensation was included. In this report, a method for compensation has been used. The method is explained in Chapter 5.

To test the dependencies of the SCA result on the topography, Jotunheimen has been divided into different area types. The area has been divided into four classes of steepness. Plain (0 degrees slope angle), flat (less or equal to 10 degrees), moderate (more than 10 and less or equal to 30 degrees), and steep (more than 30 degrees). The area has also been divided into four aspect classes: north, east, south, and west. Each pixel in the resulting SCA maps will belong to one steepness class and one aspect class. The combinations of steepness and aspect result in 13 different classes. There are three classes of steepness for each of the four aspect classes, and then there is the 13^{th} class of plain, which have no aspect direction.

From such knowledge it is possible to find which terrain classes that give best or least good results of the SCA calculations. It is also of interest to see if there are variations depending on the time of the year.

4.1 Method

The division of Jotunheimen into different terrain classes has been done by using a digital elevation model (DEM) with spatial resolution of 25 × 25 m. For each pixel in the DEM, the slope and aspect angles have been calculated. From the slope angle, each pixel has been classified as belonging to one of the classes of steepness. From the aspect angle each pixel has been put into one of the aspect classes. The ideas of how to calculate steepness and aspect appeared by studying Romstad (2001).

The size and direction of the slope angle can be calculated in different ways, giving somewhat different results. Descriptions of different methods can be found in Cadell (2002), Barnsley (2003) and Rainis (2004). Here a method used by ERDAS Imagine has been used. It has been classified as a quadratic surface method.

To calculate the slope for a pixel, a 3 × 3 pixel cell is centred at the pixel as shown in Figure 7.

Z1	Z2	Z3
Z4	Z5	Z6
Z7	Z8	Z9

Figure 7 Pixels used for calculation of slope

Z1 to Z9 are the elevations of the centre pixel (Z5) and its 8 neighbours. With pixel size *cx* in x-direction and *cy* in y-direction the slopes in x- and y-direction are calculated as

$$Sx = ((Z3+Z6+Z9) - (Z1+Z4+Z7))/(3 \cdot cx)$$
$$Sy = ((Z1+Z2+Z3) - (Z7+Z8+Z9))/(3 \cdot cy)$$

The total slope: $S = sqrt(Sx^2 + Sy^2)/2$

In degrees:
$$\text{slope angle } \theta = arctg(S) \cdot 180/\pi$$
$$\text{aspect angle } \varphi = arctg(Sy/Sx) \cdot 180/\pi$$

If Sx = 0 and Sy > 0 then $\varphi = 0$
If Sx = 0 and Sy < 0 then $\varphi = 180$
If Sx = 0 and Sy = 0 then $\varphi = 360$

This will make an aspect angle of 0 degrees towards south and 180 degrees towards north, with positive values along the western side and negative on the eastern side. A plain area has no aspect angle. The value is set to 360 degrees.

These aspect angles are calculated relative to the image north. The images used in this test are in UTM zone 33 projection. For each pixel the angle between image north and geographic north has to be calculated and the aspect angle has to be adjusted relative to geographic north. The values of the aspect angles are then put into one of the four aspect types by the following rules:
North: $\varphi \leq -135$ or $\varphi \geq 135$, $|\varphi| \leq 180$
West: $\varphi < 135$ and $\varphi > 45$
South: $\varphi \geq -45$ and $\varphi \leq 45$
East: $\varphi > -135$ and $\varphi < -45$

To calculate the slopes for pixels with size 250 × 250 m, some adjustments had to be made. Instead of making a 3 × 3 pixel cell of 250 m pixels, the 25 m pixels inside the 250 m pixel are used in the following way.

1,1					6,1					11,1
1,6					6,6					11,6
1,11					6,11					11,11

Figure 8 Use of 25 m pixels to calculate slope for 250 m pixel

In the DEM a 250 m pixel can be constructed of 10 × 10 25 m pixels. Figure 8 shows the row and column numbers of some of the 25 m pixels in a 250 m pixel. To find the slope of such a pixel, we use the elevation values of 25 m pixels at the borders of the pixel in a similar way to using the neighbouring pixels for 25 m resolution in Figure 7.

The slope for the 250 m pixel is calculated in the following way

$$Sx = ((Z(11,1) + Z(11,6) + Z(11,11) - (Z(1,1) + Z(1,6) + Z(1,11))/3 \cdot dx$$
$$Sy = ((Z(1,1) + Z(6,1) + Z(11,1) - (Z(1,11) + Z(6,11) + Z(11,11))/3 \cdot dy$$

where $dx = 5 \cdot cx$ and $dy = 5 \cdot cy$.

From here the calculations are the same as for a 25 m pixel.

It may seem a bit strange to use 25 m pixels which are situated just outside a 250 m pixel to calculate the slope for that pixel. This can be explained in the following way. In the Landsat image the 25 m pixels are organized in a way that the upper left corner of each pixel has coordinates in the UTM projection which are multiples of 25 m both in x and y direction. The corresponding 250 m pixels have upper left corner coordinates which are multiples of 250 m in the UTM system.

The DEM image with 25 m resolution has centre coordinates of each pixel at multiples of 25 m. So the upper left corners of the pixels are situated 12.5 m away in directions north and west from the corners of the Landsat pixels. If we move the DEM pixels 12.5 in both directions, the elevation values will correspond to the elevation of the upper left corners of the Landsat pixels. In a 250 m pixel the centres of pixels in rows and columns no. 1 and 11 from the DEM image will correspond to the outer edges of the 250 m pixels in Landsat or MODIS images.

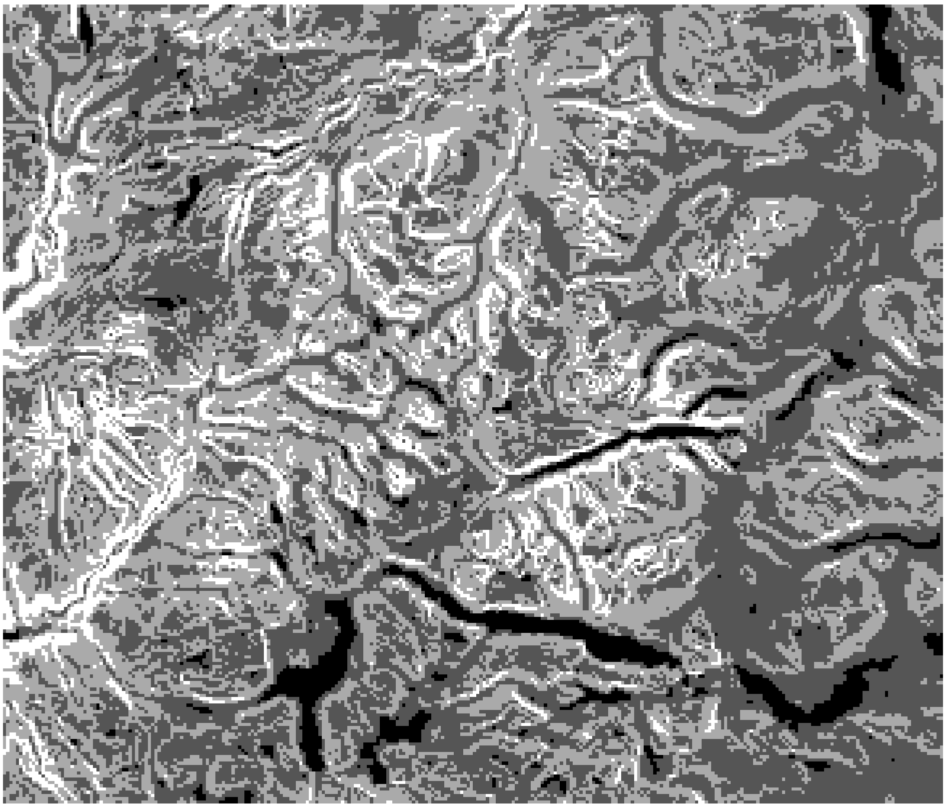


Figure 9 Slope classes in 250 m resolution. Black - plain (water), dark gray - flat areas, light gray - moderate slope gradients, white - steep areas.

There will of course be differences between a terrain type image made from 25 m pixels and 250 m pixels, because of much more details in an image with 25 m resolutions. It will be easy to see differences along the edges of lakes. Small lakes may disappear from the plain class and narrow lakes may be fragmented in the 250 m resolution. But it seems that the overall visual impression is quite similar for images with the two resolutions. Figure 9 shows the slope classes of Jotunheimen in 250 m resolution.

Figure 10 shows the aspect area classes of Jotunheimen in 250 m resolution.

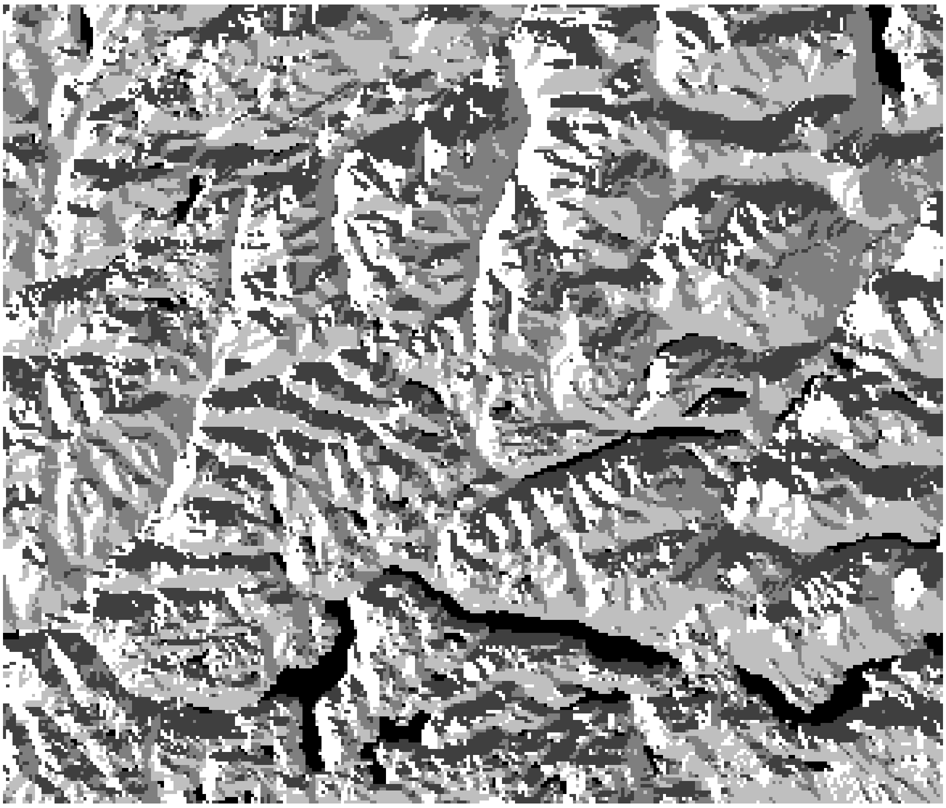


Figure 10 Aspect classes in Jotunheimen, 250 m resolution. Black - plain (lakes), dark gray - north, medium gray - east, light gray - south, white - west.

5 Comparing MODIS and Landsat snow classification

5.1 Input

The MODIS images have been classified in a standard snow product production chain at NR. For each pixel, the fractional snow cover (FSC) has been calculated. The algorithm used is explained in Solberg et al. (2004). In this study, the topography has been taken into account. A DEM with spatial resolution of 25 m has been used, together with the position of the sun in elevation and azimuth. The adjustment of the sun reflectance according to the terrain, has a parameter, C, which has been varied to find a reasonable value, giving the best results. The method is described below.

To see the effect of topographic correction, the FSC has also been calculated without taking the topography into account. This was also done in the initial study, Koren (2008). Because of some changes in the production chain, these calculations had to be repeated. In the process of geocorrection, using the former program, it was a risk that the corrected pixels along the border of a calibration area partly might contain areas outside the calibration area, which could have less than 100 % snow cover. This could lead to a too low threshold for 100 % snow, and the calculated FSC could be too high. In the last version, this has been accounted for. Pixels along the borders of the calibration areas have been excluded, such that all calibration pixels are situated completely inside the calibration areas. This generally leads to lower FSC values, as can be seen by comparing the values from this study with the values from the initial study.

The result maps have a resolution of 250 m and show the snow coverage in percent per pixel. The input to this classification is MODIS L1B images of 1 km and 250 m resolution. The 250 m images are used for snow classification and the 1 km images for cloud classification. A description of the cloud classification can be found in Koren (2009). The images have been transformed to UTM zone 33 projection by programs made at NR, included in the production chain.

In this validation the study area has been chosen such that there were no clouds in the initial images (used in Koren (2008)), covering the area. Introducing new images, there are some clouds present. Areas which are covered with clouds in the Landsat or/and the MODIS image, have been excluded from SCA calculations.

The classified Landsat images have been transformed to 250 m resolution by an aggregation of 25 m pixels. Each 250 m pixel shows the snow cover in percent. In this calculation it is assumed that the areas classified as partly snow have 50 % snow cover. The calculated snow cover in percent is hopefully not far from the real value.

If we let the partly snow covered areas get the values 0 and 100 % snow cover, we can find minimum and maximum limits for the snow cover fraction. This has not been done for 250 m resolution, but the values for 25 m resolution can be found in Table 5.

A forest mask of resolution 250 m has been made from the 25 m resolution mask by aggregation. All 250 m pixels containing at least one 25 m forest pixel have been classified as forest. The total area without forest will be somewhat larger with resolution 25 m than with 250 m.

The total area with forest included: 4526 km^2
Area of forest mask with 25 m resolution: 378.01 km^2
Area of forest mask with 250 m resolution: 532.44 km^2
Area without forest with 25 m resolution: 4147. 99 km^2
Area without forest with 250 m resolution: 3993.56 km^2

The comparison of estimated snow from Landsat and MODIS images of 250 m resolution has been performed for the area without forest.

5.2 Topography compensation

To compensate for the influence of the terrain, one has to know the inclination of the terrain and the position of the sun, to calculate the sun incident angle in relation to the normal on each inclined pixel. From the DEM with 25 m spatial resolution, the topographic slope angle (*ts*) for each 250 m pixel has been calculated. In Kobayashi et al. (2009) a comparative study of radiometric correction methods for optical remote sensing imagery has been done.

A common method used for correction is the cosine correction method

$$LH = LT \cos(sz)/\cos(i)$$

where *LH* is the calculated radiance for a horizontal surface, *LT* is the observed radiance over a sloped terrain, *sz* is the sun zenith angle, and *i* is the sun incident angle in relation to the normal on an inclined pixel.

$$\cos(i) = \cos(sz)\cos(ts) + \sin(sz)\sin(ts)\cos(ta - sa)$$

where *ta* is the terrain surface aspect angle and *sa* is the sun aspect angle from the north.

To simulate the effects of the atmospheric upwelling path radiance and the downward sky diffuse irradiance, a parameter *C* is introduced. (Teillet et al. 1982)

$$LH = LT (\cos(sz) + C)/(\cos(i) + C)$$

Meyer et al. (1993) noted that the incorporation of the C-parameter in the formulation tends to significantly reduce the overcorrection of data, especially for slopes facing away from the sun, as compared to the traditional cosine correction approaches.

Tests have shown that introducing a terrain compensation in the NLR algorithm gives much better results in the SCA estimations, especially for low sun elevations. The correction factor *C*, has been varied to find the best value. For two of the MODIS images, 2003.03.01 11:00 and 2004.05.30 10:10 we have calculated SCA with a number of different values of *C*. 2003.03.01 has a low sun elevation (20.5 degrees) and much snow, while 2004.05.30 has an elevation of 48.4 degrees and snow only in the higher areas. The value of *C* has been varied from 0.005 to 0.5. One measure of quality of the SCA calculation is the RMS error, calculated by comparing the MODIS and Landsat SCA image pixel by pixel.

From

Table 4 one can see that using terrain compensation gives better result with all C-values than no compensation. For low sun elevation, the results vary quite a bit, with lowest RMS error for *C*=0.05. For high sun elevation, the results are almost independent of the C-values. This is for the total RMS error. There may be larger differences if one looks at steep and flat areas, or different aspect directions

Topographic correction factor	RMS error		Correlation	
	2003.03.01	2004.05.30	2003.03.01	2004.05.30
None	45.711	17.409	0.104	0.926
0.005	20.382	15.570	0.562	0.939
0.01	19.532	15.559	0.560	0.939
0.05	19.349	15.479	0.536	0.941
0.10	21.094	15.427	0.511	0.942
0.15	24.599	15.413	0.456	0.943
0.50	37.478	15.630	0.240	0.944

Table 4 RMS error and correlation for the MODIS images from 2003.03.01 11:00 and 2004.05.30 10:10 for different topographic correction factors.

As a reasonable overall measure, we have chosen to use the RMS error to select the value 0.05 as the correction factor to be used for all images. Figure 11 shows the calculated MODIS SCA maps for 2003.03.01 11:00 without and with topographic correction. With a correction factor $C = 0.05$, a lot more snow has been found.

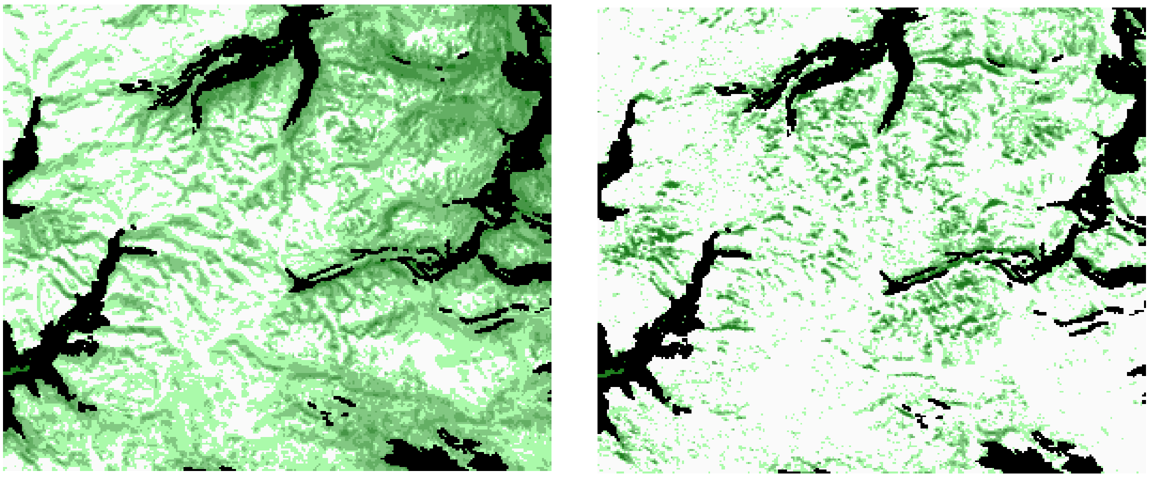


Figure 11 MODIS SCA maps for 2003.03.01 11:00.To the left: no topographic correction. To the right: topographic correction with C = 0.05. Colours as explained in Figure 12.

5.3 Results

5.3.1 Total area

Figures 12-14 show the classified Landsat and MODIS images with 250 m resolution. Forest and clouds are shown in black. Snow cover is shown in percent with white for 100 % snow and nuances of green for fractional snow cover with darker colour for less snow. Only one MODIS image is selected for each day. For 2004.01.16, the area with haze found in the Landsat image, is shown in black. In the MODIS image no clouds were detected, but the haze area is excluded from the SCA calculations. For 2003.10.19, the clouds found in the MODIS image from 10:10 are added to the clouds detected in the Landsat image. A topographic correction factor C=0.05 has been used.

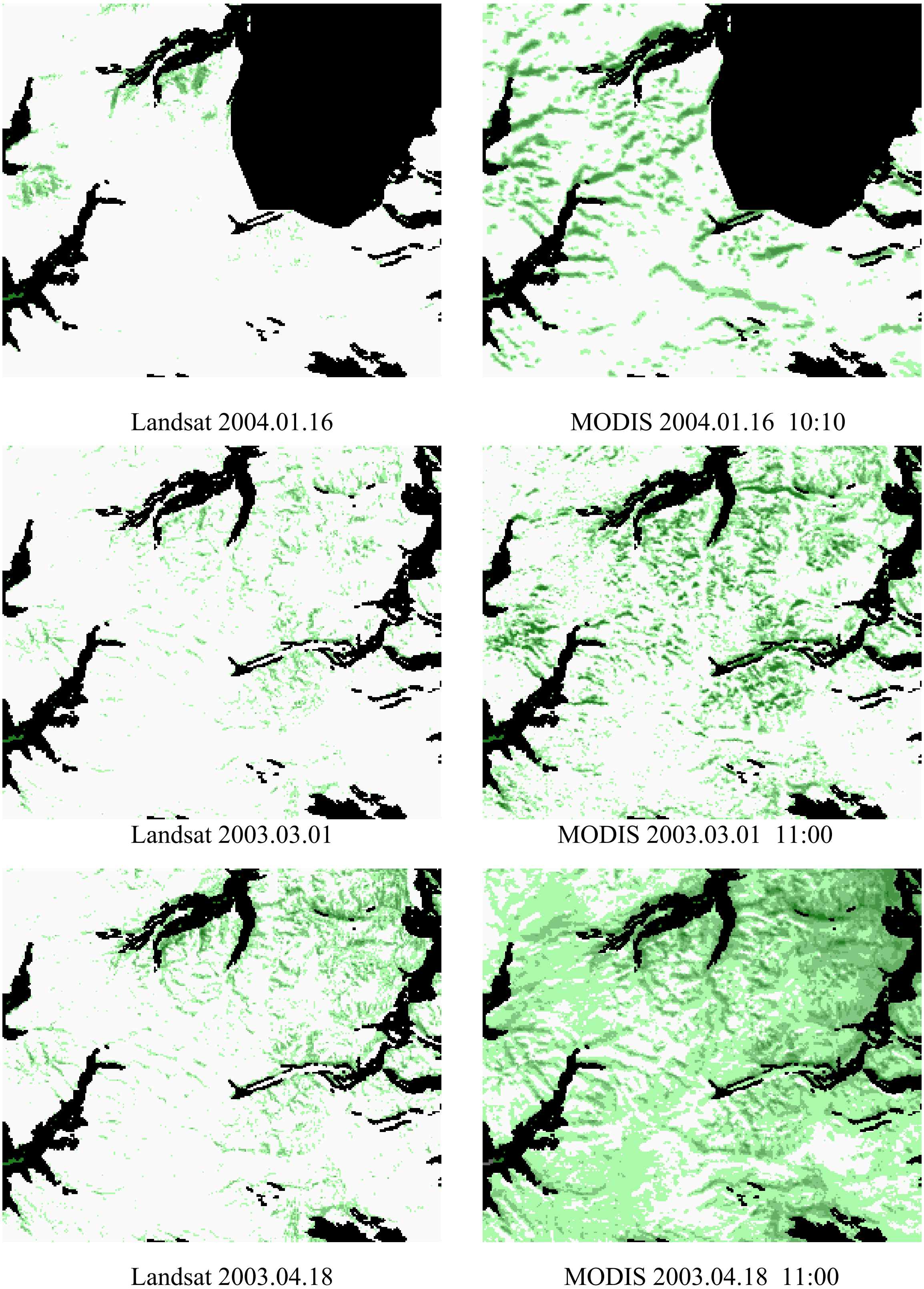


Figure 12 SCA with 250 m resolution from Landsat and MODIS images for corresponding dates. Forest is marked in black. The SCA is given in percent snow cover per pixel.

0-10% 10-30% 30-50% 50-70% 70-90% 90-100%

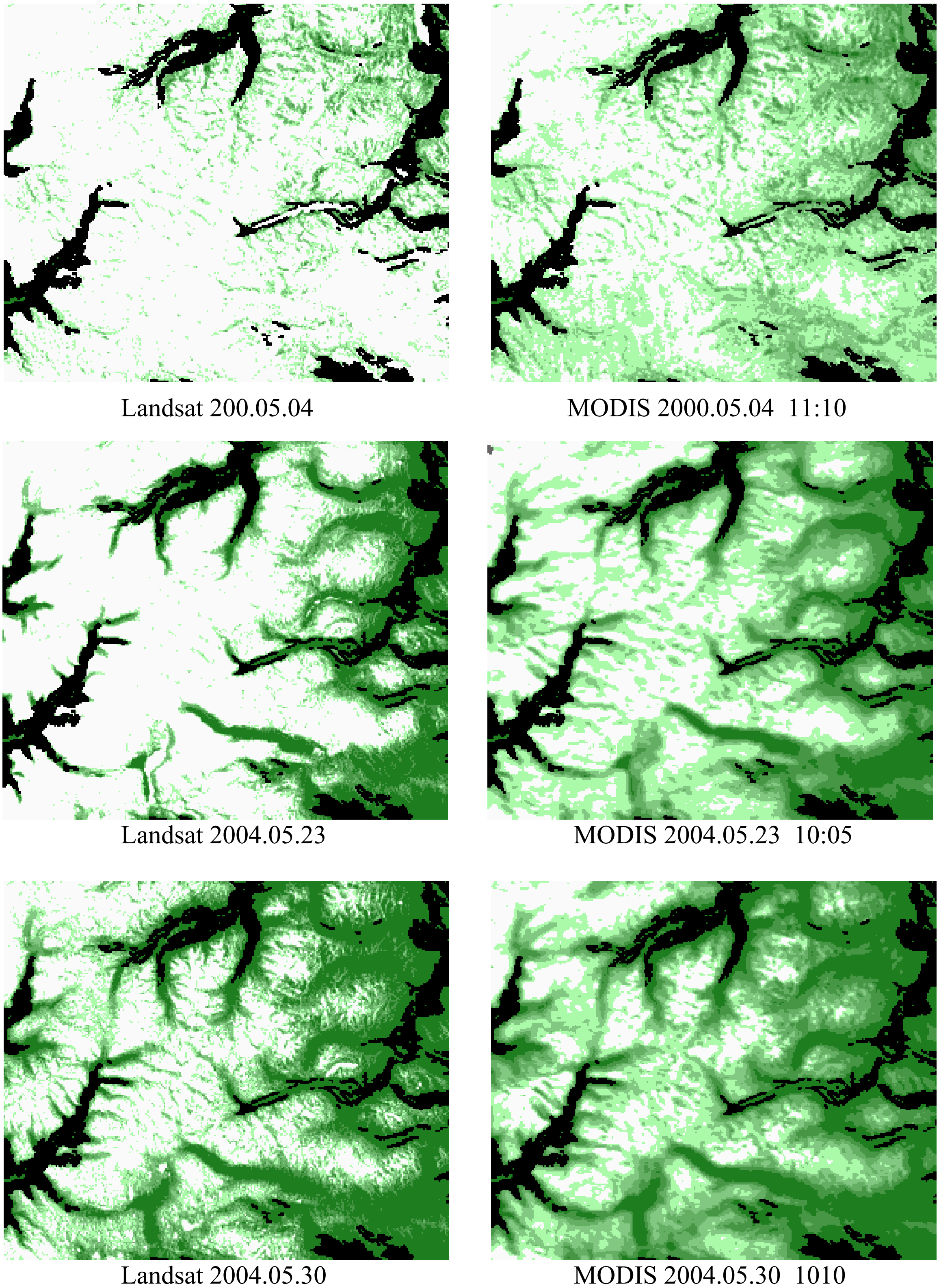


Figure 13 SCA with 250 m resolution from Landsat and MODIS images for corresponding dates. Forest is marked in black. The SCA is given in percent snow cover per pixel.

0-10% 10-30% 30-50% 50-70% 70-90% 90-100%

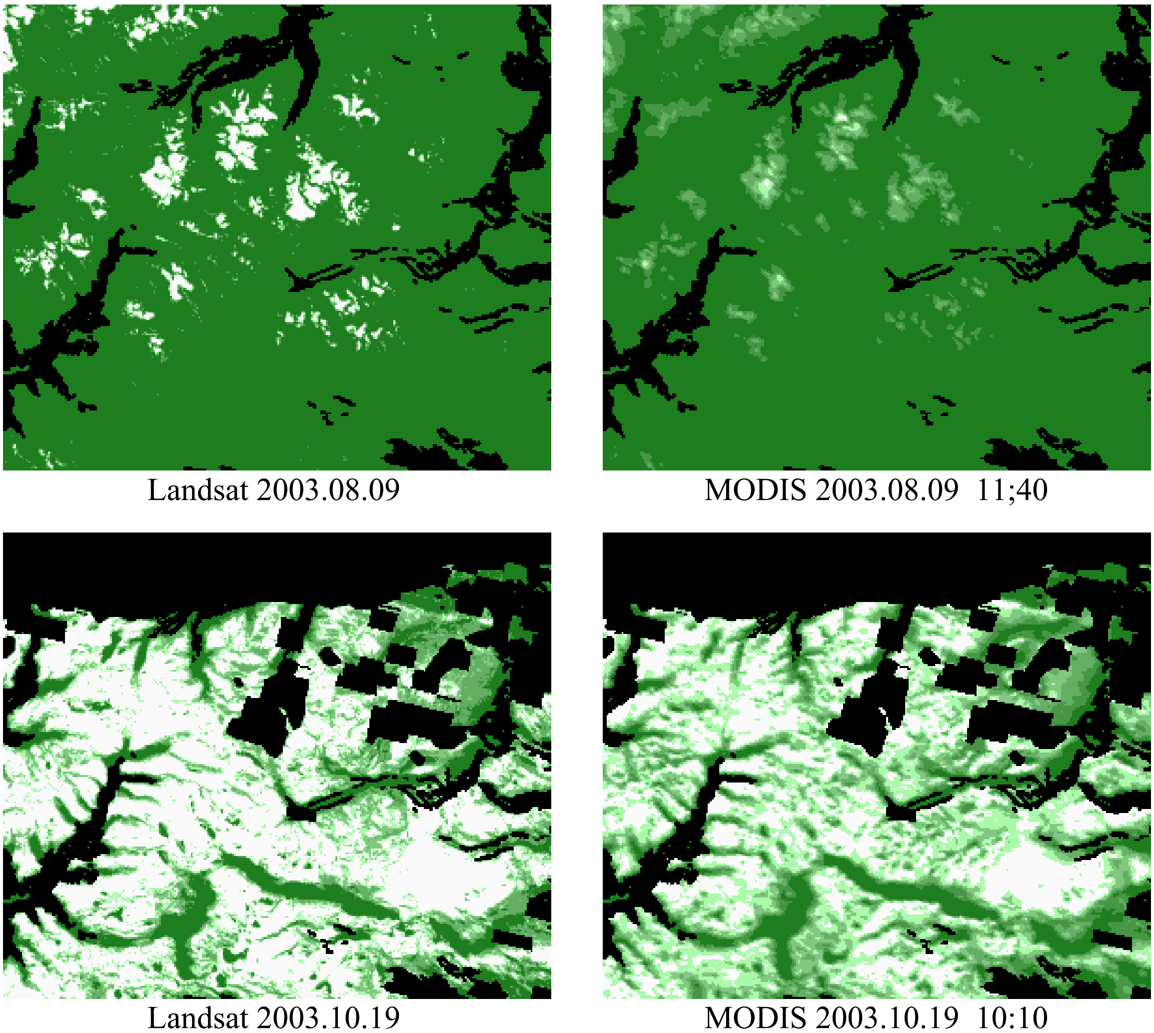


Figure 14 SCA with 250 m resolution from Landsat and MODIS images for corresponding dates. Forest is marked in black. The SCA is given in percent snow cover per pixel.

0-10% 10-30% 30-50% 50-70% 70-90% 90-100%

In Table 5 the total amount of classified snow covered area (SCA) outside forested areas is shown for all Landsat and MODIS images in km² and %. For Landsat the calculated SCA is shown for aggregation to 250 m pixels, where it is assumed that pixels classified as fractional snow cover, have 50 % snow cover. Min, Mean and Max show the SCA value, when classified fractional snow cover is set to 0, 50 and 100 % respectively, with 25 m resolution. One will see that the amount of snow estimated from the Landsat images is different for 25 and 250 m resolution. The area of SCA for 250 m should be close to the mean value for 25 m. There are, however, differences because of the different sizes of the forest masks in the two resolutions. The 250 m forest mask is larger. The MODIS result should in first hand be compared to the Landsat 250 m result.

MODIS				Landsat SCA			
Date and time	**SCA Uncorr**	**SCA Corr**		**250 m**	**Min**	**Mean**	**Max**
2004.01.16	1973.12	2842.10	km²	3052.85	3106.84	3149.50	3192.14
10:05	63.8	91.9	%	98.7	96.6	97.9	99.3
2004.01.16	2119.14	2937.62	km²	3052.85	3106.84	3149.50	3192.14
11:40	68.5	95.0	%	98.7	96.6	97.9	99.3
2003.03.01	2789.00	3538.13	km²	3905.22	3957.61	4047.26	4136.92
11:00	69.8	88.6	%	97.8	95.4	97.6	99.3
2003.04.18	2860.00	3100.23	km²	3767.58	3672.56	3888.94	4105.32
11:00	71.6	77.6	%	94.3	88.5	93.8	99.0
2000.05.04	2954.20	3163.01	km²	3681.10	3537.64	3786.28	4034.91
11:10	74.0	79.2	%	92.2	85.3	91.3	97.3
2004.05.23	2540.12	2682.09	km²	2966.44	2696.24	2976.29	3275.09
10:05	63.6	67.2	%	74.3	65.0	71.2	78.5
2004.05.30	1859.98	1918.97	km²	2199.04	1729.34	2195.96	2662.57
10:10	46.6	48.1	%	55.1	41.7	52.9	64.2
2004.05.30	1657.53	1633.86	km²	2199.04	1729.34	2195.96	2662.57
11:45	41.5	40.91	%	55.1	41.7	52.9	64.2
2003.08.09	126.47	149.46	km²	256.19	242.09	255.11	268.13
11:40	3.2	3.7	%	6.4	5.8	6.2	6.5
2003.10.19	1834.97	1975.84	km²	2181.41	1839.61	2277.77	2715.93
10:10	59.2	63.7	%	70.3	54.2	67.2	80.1
2003.10.19	1651.15	1676.86	km²	1955.30	1839.61	2277.77	2715.93
11:45	60.1	60.8	%	70.9	54.2	67.2	80.1

Table 5 Calculated SCA from MODIS and Landsat images for the whole test area. The % values are relative to the area without forest and clouds. MODIS SCA is calculated without and with topographic correction,C=0.05

For three of the dates the fractional and total snow cover have been calculated for two acquisitions. In Table 5 one can see that there is a large difference in retrieved total SCA. The difference may have more than one reason. The position of the satellite has changed, and the terrain is seen from a different angle. Even if the sun had been at the same position in both cases, the estimated SCA would have been different. But the sun has also changed position. The elevation has changed a bit, but the azimuth has changed more than 20 degrees, and the illumination on the terrain is quite different. For flat terrain, these changes in position should not mean much, but for a mountainous area, the input to the satellite will be quite different. The distribution of the snow according to steepness and aspect directions will also have influence. Most of these changes should have been adjusted for by the algorithm for terrain compensation, but we still see large differences.

Figure 15 shows a subset of the fractional snow cover map for the two images from 2004.05.30. The early image has generally a higher value of FSC for most of the pixels. In the further comparisons the image from 10:10 has been used.

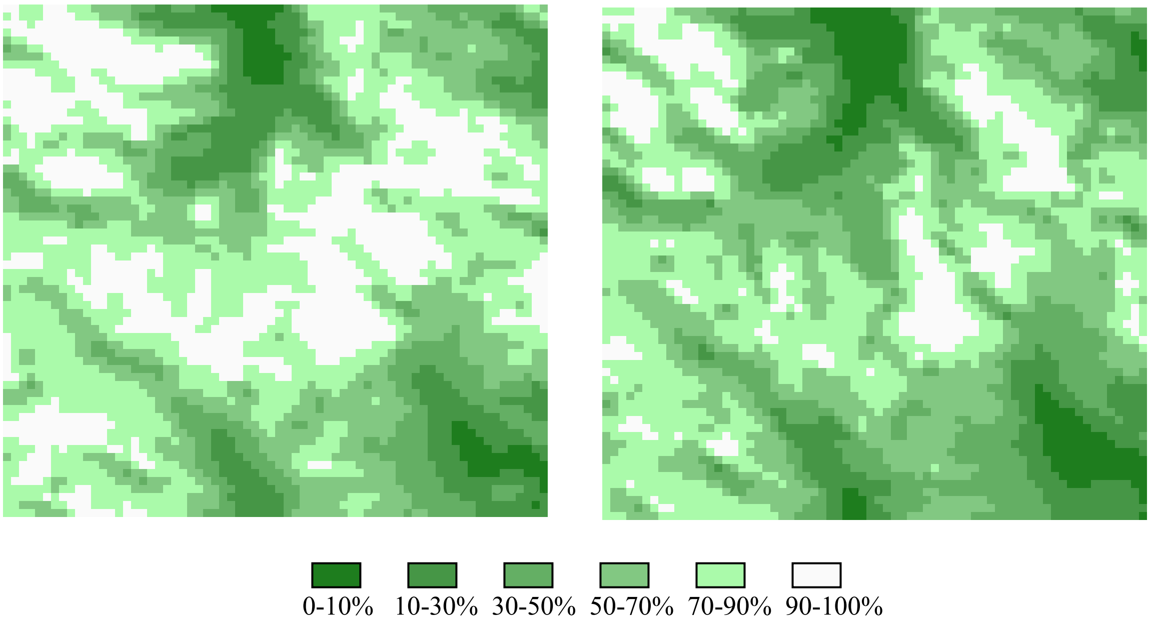


Figure 15 Fractional snow cover in percent for a subset of two MODIS acquisitions from 2004.05.30, left at 10:10 and right at 11:45

Table 5 also shows that there are large differences also for the two images taken at 2004.01.16 and 2003.10.19. For 2004.01.16, the late image shows somewhat more snow, while the early image shows snow for the 2004.05.30. Other examples of double acquisitions show that there seems to be estimated more snow in the early images in Jotunheimen. Closer studies have to be carried out to find a good explanation why.

For 2003.10.19 the total amount of snow is larger for the early image, but the percent of total area is higher for the last image. This is because the amount of clouds is larger in the last image.The total area is the area without forest and clouds. The calculations for 2004.01.16 can not be fully trusted, as will be explained later.

In Table 6 the differences in total SCA area are shown for all images. A perfect SCA algorithm should give MODIS SCA close to the Landsat SCA. One can see that the MODIS SCA is well below 100 % of Landsat SCA for all images. However, there is a significant improvement of the results when topographic correction has been included. The total SCA increases, and the increase is largest for low sun elevations. For 2004.05.30 11:45 the corrected SCA is lower than the uncorrected.

Another measure of SCA quality is the RMS error. In Table 7, the RMS deviation (RMSD) and correlation of the SCA maps calculated from MODIS images, using the SCA maps made from the Landsat images as reference. A bias has been calculated as the mean difference between the values of SCA for the Landsat and MODIS images.

$$\text{bias} = \text{MEAN}(\text{SCA}(\text{Landsat}) - \text{SCA}(\text{MODIS}))$$

This bias is subtracted from the difference (error) when calculating the unbiased RMSD. One can see the same tendency as in the total SCA calculations. The RMS error decreases and the correlation increases when topographic correction has been included.

Date and time	SCA MODIS relative to Landsat in %		SCA difference in km²	
	Uncorr	Corr	Uncorr	Corr
2004.01.16 10:05	64.6	93.1	1079.73	210.75
2004.01.16 11:40	69.4	96.2	933.70	115.23
2003.03.01 11:00	71.4	90.6	1115.97	367.07
2003.04.18 11:00	75.9	82.3	907.43	667.35
2000.05.04 11:10	80.3	85.9	726.90	518.09
2004.05.23 10:05	85.6	90.4	426.32	284.35
2004.05.30 10:10	84.6	87.3	339.06	280.07
2004.05.30 11:45	75.4	74.3	541.51	565.18
2003.08.09 11:40	49.3	58.3	129.72	106.73
2003.10.19 10:10	84.1	90.6	346.44	205.57
2003.10.19 11:45	75.7	85.8	530.26	278.44

Table 6 Differences in SCA results from MODIS and Landsat images without and with topographic correction (*C* = 0.05)

Date and time	RMSD (%FSC)		Correlation (% FSC)		Bias (%FSC)		Unbiased RMSD	
	Uncorr	**Corr**	**Uncorr**	**Corr**	**Uncorr**	**Corr**	**Uncorr**	**Corr**
2003.03.01 11:00	45.71	19.35	0.10	0.54	27.95	9.19	36.17	17.03
2003.04.18 11:00	28.59	20.15	0.58	0.78	22.73	16.72	17.34	11.25
2000.05.04 11:10	24.29	17.45	0.68	0.81	18.20	12.97	16.08	11.67
2004.05.23 10:05	18.14	13.86	0.92	0.95	10.65	7.09	14.69	11.90
2004.05.30 10:10	17.41	15.48	0.93	0.94	8.49	7.01	15.20	13.80
2004.05.30 11:45	21.23	20.19	0.91	0.94	13.56	14.15	16.33	14.40
2003.08.09 11:40	14.82	13.57	0.84	0.87	3.25	2.67	14.46	13.30
2003.10.19 10:10	30.94	20.67	0.64	0.83	11.17	6.63	28.86	19.57
2003.10.19 11:45	32.70	21.99	0.63	0.84	10.84	10.09	30.85	19.53

Table 7 RMS deviaiton and correlation of MODIS SCA images compared to the corresponding Landsat images, without and with topographic correction (*C* = 0.05)

In Table7 the images from 2004.01.16 have been excluded. Although the calculated SCA values seem reasonable (Table 5 and 6), there are uncertainties in the calculations for this day. This is explained in section 5.3.2.

5.3.2 Discussion

The NLR algorithm uses data from calibration areas to determine an upper and lower limit for the input signal. Signals below the lower limit are interpreted as bare areas (no snow), signals above the upper limit mean 100 % snow, and signals between the limits are interpreted as a certain % of snow calculated on a linear basis. The calibration areas for no snow are selected in forested areas at low altitudes. In January these areas are usually covered with snow. Outside the winter season there is a large difference between the upper and lower limit, and it is possible to find a reasonable scale for snow cover from 0 to 100 %.The calculations for 2004.01.16 showed that the two limits were very close, probably because of snow in the “no snow” area. This can result in areas with snow to be classified as “no snow”, and the 0-100 % scale will not be reliable. The NLR algorithm, as used in these calculations, is not suitable for the winter season. One reason is the selection of calibration areas, another reason is the low sun elevation. In mountainous areas, the mountains create large shadows. Although one is trying to compensate for the topography, the shadows have not been taken into account. To do so, a fine DEM is needed. For each scene the position of the sun has to be known. Then the shadowed areas can be found, and a modified NLR-algorithm has to be used to find the SCA inside the shadows.

Comparing Table 5 and Table 6 we find that MODIS generally gives less snow than the estimates from the Landsat images. In most cases the MODIS estimate is even below the minimum value calculated from the Landsat image.

Comparing the results with the corresponding results from Koren (2008), one will find that the new calculations give lower SCA values. This is caused by the change of treatment of the calibration areas, as explained in section 5.1.

It is easy to observe that the topographic compensation improves the calculated SCA values. As expected, the improvement is largest for dates with low sun elevation. Without compensation the best results were achieved for the images taken in May. With compensation the results are more equal throughout the year. Without terrain compensation, the calculated SCA could increase from March till May, although the actual amount of snow was decreasing. With compensation, a more realistic development of the snow cover should be found. However, with a very low sun elevation, the effect of shadows can still be of great importance.

2004.01.16
Although there are large uncertainties in the calibration values, the calculated SCA is close to Landsat values. The effect of shadows is large and one would expect not so good results. Without terrain compensation the SCA values are very low, because of sun elevation of 5.6 – 7.6 degrees and large shadows. There may have been some overcompensation in the SCA calculations with this low sun elevation. There is a large difference in the SCA values for the two MODIS images taken with time difference of about 100 minutes. Opposite to other examples of two acquisitions on the same day, the late image shows largest SCA.

2003.03.01
The result of the topographic compensation is remarkable. The SCA relative to the Landsat estimate increases from 71.4 to 90.6 %. The sun elevation is only 20.5 degrees, so the shadows have a large negative influence on the result.

2003.04.18
MODIS SCA is only 82.3 % of Landsat SCA. Although the result has improved by using terrain compensation, it is still low. From the Landsat image the main area seems to be completely covered with snow. Comparing the two results in Figure 12, the MODIS SCA image shows very small areas with full snow cover. This is difficult to explain. There is still the effect of low sun elevation (39 degrees), but there must be other reasons for the MODIS algorithm to mainly show SCA well below 100 %. There could be some special values for the calibration areas this day, which could

make some offset in the SCA scale. This has not been checked. The weather in Jotunheimen had been fine and cold for some time before the 18 April. The snow had been dry, but at the 16th the temperature started to increase and the snow started to be wet also at higher altitudes. Although there were many small snow-free areas, there were very few large areas without snow, and there were no signs of pollution which could have reduced the snow reflectance.

2000.05.04
There was exceptionally much snow for the time of the year in Jotunheimen. The Landsat image shows large areas with full snow cover, and nearly as much snow as for 2003.04.18. MODIS shows very little bare ground and many more pixels with 100% snow than 2003.04.18. The effect of sun elevation (44.5 degrees) is smaller, but still present. MODIS SCA increases from 80.3 to 85.9 % of Landsat SCA with topographic compensation. One effect which reduces MODIS SCA compared to Landsat, is the disappearance of snow on the lakes. On some of the lakes the snow had melted and the ice was visible. Ice has less reflectance than snow and will let MODIS interpret it as partly snow cover, while it is classified as full snow cover in the Landsat image. Figure 13 shows that generally MODIS SCA has lower values than Landsat all over the area.

2004.05.23
As for 2003.04.18 and 2000.05.04, the MODIS image shows lower SCA values than the Landsat image. The effect of sun elevation is almost eliminated at this time of the year. Only small areas covered by shadows. There seems to be a layer of newly fallen snow in the higher parts, and the snow is probably still dry. The effect of ice on the lakes is still present. The total MODIS SCA increases from 85.6 to 90.4 % of the Landsat SCA with topographic compensation. This value could be increased if the lakes were removed from the calculation.

2004.05.30
Even if the images are taken only one week later than the previous ones, a huge amount of snow had disappeared. This is due to a thin layer of new snow a week before, which did melt during a period of warm weather. The total MODIS SCA is now 87.3 % of Landsat SCA for the 10:10 image, which is somewhat less than the result for 2004.05.23. There are still some small areas of ice on the lakes.

The image taken at 11:45 gives only 74.3 % of Landsat SCA, which is lower than the value found without terrain compensation .The difference between the two images is large. Some of this is caused by the different positions of the satellite. There is also a difference in calibration values which gives a higher limit for 100 % snow in the 11:45 image.

2003.08.09
Although the absolute difference in total SCA is lowest for this day, the relative difference is largest, as the total MODIS SCA is only 58.3 % of the Landsat SCA. This is easy to explain. The areas classified as snow in the Landsat images are mostly snow-free glaciers. These will be classified as partly snow covered in the MODIS image, and the total amount of snow will be much lower. There are, however, also areas where the classification is bare ground in the Landsat, and fractional snow cover in the MODIS image. These are areas where there normally is snow throughout the

whole summer, but were it has melted this year. Here there are very light-coloured rocks without moss and lichen. These will have a high reflectance and may be classified as fractional snow cover in the MODIS image (see Figure 3).

2003.10.19

As for 2004.01.16 and 2004.05.30 there is a large difference in the SCA calculated from the two MODIS images. The result for 10:10 is 90.6 %, and is the best (equal to 2003.03.01) if we exclude the images from 2004.01.16. As for 2004.05.30, the early image gives the highest SCA. This is also seen in a number of cases outside this study.

5.3.3 Terrain types

In Table 8 the estimated SCA from MODIS is given as percentage of the corresponding SCA from Landsat for areas of different degree of steepness. In the rest of this study only the scene from 10:10 has been used for 2004.05.30 and 2003.10.19.

For the plain areas, which actually are lakes, one should not expect the terrain compensation to have any influence. Table 8 shows very small differences except for 2003.08.09 and 2003.10.19 where there are large differences in the relative SCA %. For these days, there is no ice on the lakes and the SCA values should be close to 0. However, with 250 m resolution there may be a few pixels near the lakes which have snow and which are being classified as plain by the terrain classification program. The program for terrain compensation, however, could find that the slope angle is different from 0 and so the calculated SCA for these pixels could be different with or without terrain compensation. As there are very few such pixels, the relative difference in SCA could be large. Therefore, the results for plain areas for these two images can not be considered valuable. The best result occurs for 2003.03.01 where all lakes are covered with new, dry snow. For the other dates, the snow on the lakes gradually disappears. Ice with lower reflectance than snow is present and makes the results less good later in the season.

Area type, steepness								
Date	**Plain**		**Low steepness**		**Moderate steepness**		**Steep**	
	Uncorr	**Corr**	**Uncorr**	**Corr**	**Uncorr**	**Corr**	**Uncorr**	**Corr**
2003.03.01	93.2	94.3	81.5	92.9	62.6	88.9	56.4	86.2
2003.04.18	82.3	83.5	80.3.	82.7	73.3	81.5	63.5	84.1
2000.05.04	73.8	74.6	83.6	85.8	79.2	86.5	71.8	89.6
2004.05.23	76.0	76.7	89.0	91.0	84.3	90.1	80.7	92.9
2004.05.30	73.0	71.0	86.3	85.1	83.9	87.8	83.1	98.0
2003.08.09	100.0	45.5	53.8	54.0	47.2	56.0	42.2	94.0
2003.10.19	122.4	107.9	86.1	84.9	81.0	92.7	53.8	109.0

Table 8 SCA MODIS relative to SCA Landsat in %, according to area steepness, without and with topographic correction (*C* = 0.05)

Without terrain compensation the best results are found in the flat areas (slope of max 10 degrees) areas, as expected. The MODIS SCA lies between 84.9 and 92.9 %. For moderate and steep slopes the results get better with increasing sun elevation.

With terrain compensation, the difference in the results for flat, moderate and steep almost disappears. Most of the images get the highest SCA values for the steep areas. This could mean a too large compensation, but the differences are quite small. 2004.05.30 10:10 and 2003.10.19 10:10 have the largest differences, and highest values for steep areas.

Date	Sun elevation	Sun azimuth	Area aspect							
			North		East		South		West	
			Uncorr	Corr	Uncorr	Corr	Uncorr	Corr	Uncorr	Corr
2003.03.01	20.48	10.17	31.9	88.9	78.3	90.7	100.2	91.6	73.7	90.7
2003.04.18	39.07	8.56	59.9	84.1	76.6	81.6	90.4	77.0	76.3	82.4
2000.05.04	44.58	4.30	66.0	86.4	81.0	86.4	93.1	85.9	82.8	87.1
2004.05.23	47.01	27.17	74.8	91.5	87.3	88.0	96.3	93.8	85.9	93.8
2004.05.30	48.37	26.16	72.0	88.9	84.0	82.0	97.5	95.5	88.2	95.5
2003.08.09	44.38	-2.84	32.4	59.7	44.7	52.9	92.7	62.8	67.8	68.7
2003.10.19	17.64	15.79	53.8	95.7	87.0	85.0	118.3	87.7	86.7	92.0

Table 9 SCA MODIS relative to SCA Landsat in %, according to area aspect, without and with topographic correction (*C* = 0.05)

In Table 9 the relation between SCA from MODIS and Landsat is shown for areas of different aspect directions.

Without correction for terrain the MODIS SCA values for the areas facing north are very low, but get better as the sun elevation increases. For the areas facing south the MODIS SCA is close to the Landsat value. For the areas facing east and west, the results could be expected to be somewhat lower than for the south direction. For 2004.05.23 and 2004.05.30 the azimuth position of the sun is as much as 27.16 and 26.15 degrees east of south, and one could expect higher values for the areas facing east, but the results are quite equal for east and west. The azimuth position of the sun is close to south for the rest of the MODIS images, and there should be no significant difference in incoming sunlight for areas facing east and west. 2003.08.09 is the only image where the sun has an azimuth position west of south, but so close to south that it cannot explain the large difference between areas facing west and east.

With terrain compensation, the differences between calculated SCA for the aspect directions have been reduced. The largest difference is for 2003.08.09 with 52.9 % for east and 68.7 % for west, while the smallest difference is for 2000.05.04 with 85.9 % for south and 87.1 % for west. As expected, using correction for the terrain, the SCA values for north have been increased, and the values for south have been decreased, in some cases significantly. For east and west the increase is smaller. In two cases there has been a small reduction with terrain compensation for east.

In Table 10 the MODIS SCA relative to Landsat SCA in percent is shown for combinations of the area aspect and steepness.

For all dates except 2003.08.09 the results are as expected. For areas facing south, MODIS SCA is increasing with steepness as expected, and in all images the amount of snow is overestimated in steep slopes. The values for flat areas lie between 91.5 and 98.3 % compared to Landsat SCA.

		Area aspect							
Date	Stepness	North		East		South		West	
		Uncorr	Corr	Uncorr	Corr	Uncorr	Corr	Uncorr	Corr
2003.03.01 11:00	Flat	58.1	89.2	87.2	93.3	97.1	95.2	85.2	94.1
	Moderate	12.6	86.9	74.0	89.3	100.9	90.6	67.5	88.9
	Steep	3.4	101.2	54.3	84.6	115.4	74.7	52.4	84.0
2003.04.18 11:00	Flat	72.2	84.5	79.9	81.4	87.6	81.1	81.6	84.0
	Moderate	53.1	88.4	75.9	81.5	91.8	74.5	73.9	81.2
	Steep	30.8	103.2	63.6	83.4	98.4	67.1	62.2	81.9
2000.05.04 11:10	Flat	76.1	84.8	83.8	85.7	89.4	85.9	85.5	87.2
	Moderate	60.5	86.1	80.9	87.1	95.3	86.3	81.6	86.8
	Steep	40.6	99.6	67.9	86.8	102.0	83.7	75.3	88.8
2004.05.23 10:05	Flat	83.4	87.2	90.0	89.7	94.1	90.7	88.7	92.4
	Moderate	70.9	80.4	86.7	87.2	97.0	88.9	84.4	93.6
	Steep	59.7	89.1	79.0	85.0	101.8	90.0	82.9	100.5
2004.05.30 10:10	Flat	80.5	85.8	87.2	83.9	91.4	83.8	86.5	87.3
	Moderate	68.5	89.3	83.3	80.9	100.2	85.7	87.3	96.5
	Steep	55.3	100.2	75.2	79.7	112.6	90.8	103.0	131.6
2003.08.09 11:40	Flat	45.5	54.2	48.3	48.8	74.0	59.1	67.9	64.3
	Moderate	27.3	55.5	42.7	50.7	102.4	64.2	66.5	68.0
	Steep	13.7	102.4	39.7	84.9	167.7	84.0	79.0	108.8
2003.10.19 10:10	Flat	68.7	84.1	91.2	85.3	102.5	85.1	86.8	85.6
	Moderate	43.2	101.0	85.8	84.6	125.8	88.6	84.9	93.4
	Steep	35.7	30.4	72.3	85.9	171.9	98.4	98.9	121.6

Table 10 MODIS SCA in % of Landsat SCA for combinations of aspect and steepness, without and with topographic correction (C = 0.05)

For areas facing north, MODIS SCA compared to Landsat is lower than for the other directions. The value decreases strongly with increasing steepness, more than for the other directions. For flat areas the SCA is increasing from 69.1 % for 2003.03.01 to 87.0 % for 2004.05.23.

Areas facing east and west show quite equal results. The relative SCA decreases with increasing steepness, but not as much as for north. The value for flat areas varies between 84.4 and 94.3 % for east and 88.0 and 93.3 % for west. The lowest value is in both cases for 2003.04.18. The highest value is for 2004.05.23 for east and 2000.05.04 for west.

One special case occurs for 2004.05.30 where the relative SCA has a high value for steep areas facing west. There is no evident reason why there should be that large difference between east and west for this particular date.

6 Snow in forests

6.1 Introduction

The NLR algorithm is developed for estimation of snow in open areas. In this study we are testing how it is working in forested areas. One problem with detection of snow in forests is that the trees are partly covering the ground. For deciduous trees, the leaves are absent in the winter time and the snow on the ground can be observed between the branches. However, the branches are partly covering the ground and it is difficult to estimate the exact fractional snow cover on the ground. The coniferous trees (most of them) keep the needles through the winter, and it is nearly impossible to see the ground just beneath the trees. Close after a snowfall, the branches will be partly or completely covered with snow, and from above the snow covered area will seem to be nearly 100 %. When the snow on the branches has fallen off or melted, the snow covered area as seen from above will be significantly reduced although the snow cover on the ground still may be 100 %. Deciduous trees may also have snow on the branches, and the smaller branches may be completely white when they are covered by ice crystals.

This means that even with the ground completely covered with snow, the impression of the forest from above will vary according to the amount of snow on the trees. Accordingly, there are great problems of estimating the fractional snow cover in the forests. The NLR algorithm is not developed for estimation of snow cover in forests. Anyway, in this report we will try to see if the algorithm could be used to detect if there is snow or not, without trying to estimate the fractional snow cover. If the algorithm finds at least 1 % snow in a pixel, the pixel is classified to contain snow. If not, the pixel is classified as bare land.

The test is done in an area east of the Jotunheimen area, for dates with complete snow cover in the forests or without snow in the forests. We have chosen among the MODIS scenes used in the tests for Jotunheimen. The Landsat images do not cover the complete forest test area, so we cannot use them to confirm whether there is snow or not. The amount of snow is found by observations from meteorological stations in the area. The depth of snow is measured and the fractional snow cover in the vicinity is given by a number from 0 to 4 where 0 is no snow and 4 is complete snow cover. From such observations throughout the test area, three MODIS scenes were selected.

2003.03.01 11:00 : All stations had complete snow cover
2004.05.30 10:10 : All stations had no snow
2003.08.09 : 1140 : No snow assumed. Snow observations have not been done at the stations. Landsat images and on site observations show that here is no snow except on the glaciers.

6.2 Vegetation maps

To find the areas covered with forest, we have used a vegetation map from NORUT (Johansen 2009). The map has a pixel size of 30 m, and the map content is divided in 26 classes. In addition to the vegetation, there are classes for water, snow, buildings and unclassified areas (Johansen et al. 2009). The map is shown in figure 16. There are 8 different forest classes. They are all shown in green in the map. On the map the meteorological stations are marked as red circles.

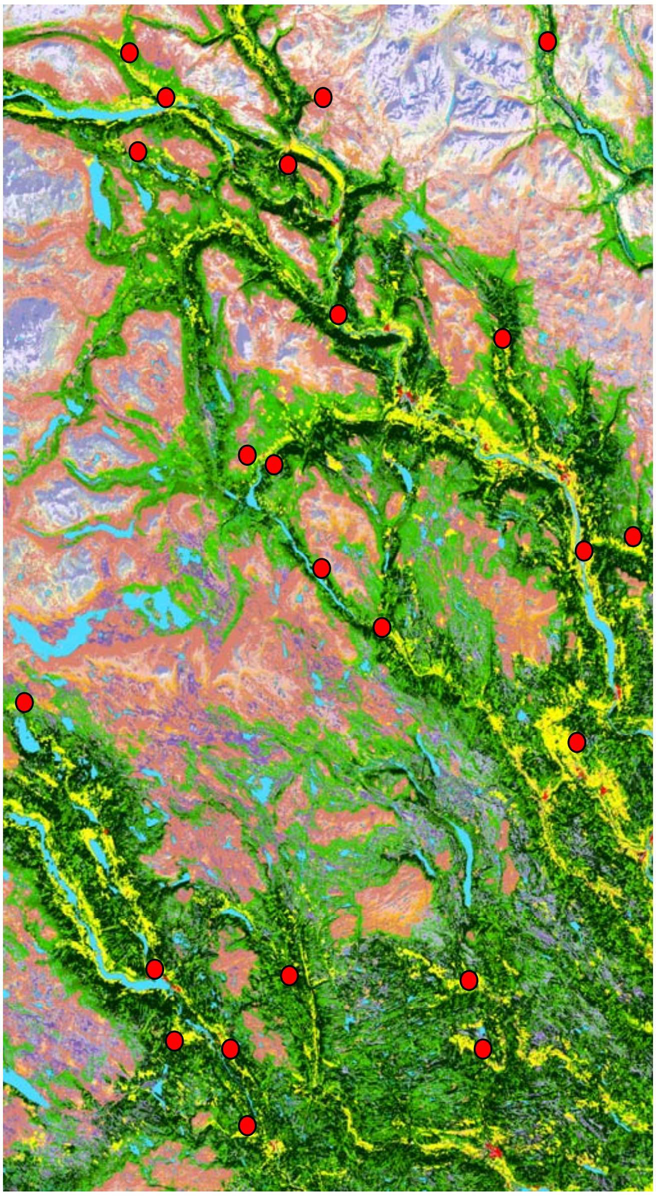


Figure 16 Vegetation map with 25 m resolution. Forests in green. Meteorological stations as red circles

For testing of the NLR algorithm on MODIS images, the forest map had to be resampled to 250 m resolution, the same as the MODIS images. We have also chosen to reduce the number of forest classes to two: coniferous and deciduous forests. In the map there are five classes of different types of deciduous forest. They are combined to one class. There are three classes of coniferous forests. One of these consists of open coniferous forest and mixed forest. We have chosen to combine these classes to one coniferous forest class. This means that there will be some deciduous trees in this class.

To make a forest map of 250 m resolution we have tried a number of methods. The original map was first resampled to 25 m resolution, to make the conversion easier. Each 250 m pixel will then be created from one hundred 25 m pixels. One way to do this is to find which vegetation class is in majority within the new pixel, and choose this as the class for the pixel. We have to combine the non forest classes to one before counting. We also have to combine the forest classes, and then choose the class with the majority of pixels. In addition we have used the nearest neighbour (NN) algorithm of ENVI to find the best class values. Comparing the 250 m map with the 25 m map we found that the NN algorithm gave the best results when looking at the percentage of each forest class for the complete area. The result of this aggregation is shown to the left in figure 17.

Along the borders between forests and open areas, there will be 250 m pixels classified as forest which may contain a large part of open land, and pixels classified as open land which may have a large part of forest inside. In forest pixels containing more or less open land, more snow will be visible and the classification of snow will be influenced of the content of open land. To get the best evaluation of classification of snow in the forests, we have created a forest map where each 250 m forest pixel contains only 25 m forest pixels. This map is shown to the right in figure 17. Comparing the two maps in this figure, one can see that the deciduous forests close to the mountain area are scattered and contains large areas of open land.

Table 11 shows the areas of the forest types for the original vegetation map with 25 m resolution, the map aggregated to 250 m resolution using ENVI's NN algorithm, and the map with 250 m pixels containing 100 % forest.

Resolution	Forest type	Area (pixels)	Area km²	Area %
25 m	Coniferous	5472768	3420.5	30.16
	Deciduous	3291903	2057.4	18.14
250 m NN aggr.	Coniferous	54681	3417.6	30.14
	Deciduous	32971	2060.7	18.17
250 m 100 % forest	Coniferous	29666	1854.1	16.35
	Deciduous	7713	482.1	4.25

Table 11 Forest area in maps with different resolutions. The forest area in the maps with 250 m resolution have been found by NN aggregation and by demanding 100 % 25 m forest pixels in each 250 m pixel. The % value is relative to the total study area of 11340 km²

From the table one can see that the NN aggregation gives forest areas close to the original areas. The original vegetation map was made by selecting the majority class inside each pixel. As the forested area is about the same in the aggregated map, it is reasonable to assume that each 250 m forest pixel contains at least 50 % forest. The areas are significantly reduced when 100 % forest inside each pixel is demanded. The coniferous forest area is reduced to nearly the half and the deciduous area is reduced to below one quarter of the original area. This means that the forests are containing many open areas. In the areas near the tree elevation limit, there are mostly deciduous forest, and the trees often appears in small groups with open land between.

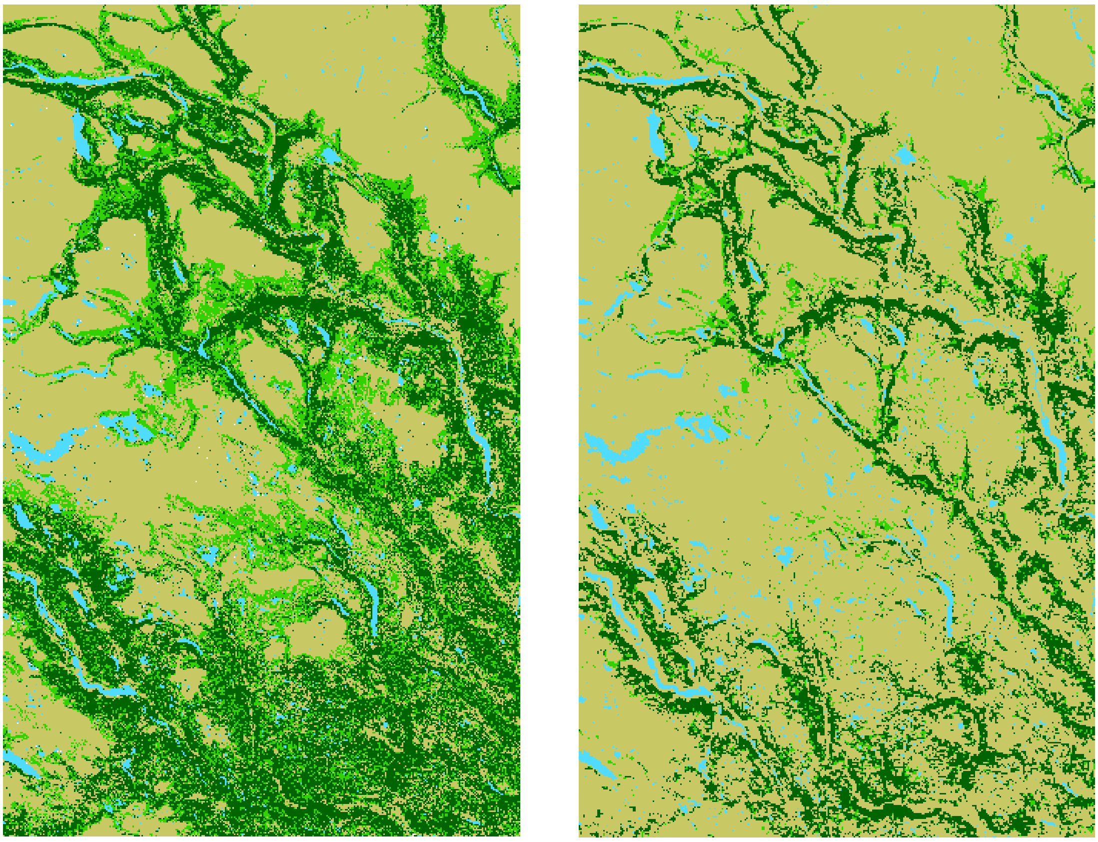


Figure 17 Forest maps with 250 m resolution. Coniferous forest in dark green, deciduous forest in medium green. The yellowish background is open areas. To the left: Each forest pixel is created by NN aggregation of 25 m pixels. To the right: Each forest pixel contains 100 % forest pixels of 25 m.

6.3 Results

Figure 18 shows where snow is detected in the forests for the MODIS images from 2003.03.01, 2004.05.30 and 2003.08.09. Forest without snow is shown in dark green. In the maps deciduous and coniferous forests are combined to one forest map. To see how the snow in the forests is related to the snow in open land, the open areas with snow are shown in orange and without snow in medium green. Be aware that in open land the classes shown are snow or no snow as in the forests, not the fractional snow cover. In the map from 2003.03.01, there is close to 100 % in the open areas, as shown. For 2004.05.30, however, there is not so much snow in the open areas, except in the highest areas. The map gives the impression of more snow than there actually is. But it illustrates that there may be snow close to some of the forest borders, and so there also may be some snow inside the forests near these borders. Clouds are shown in black. The maps have been created with topographic correction with $C = 0.05$.

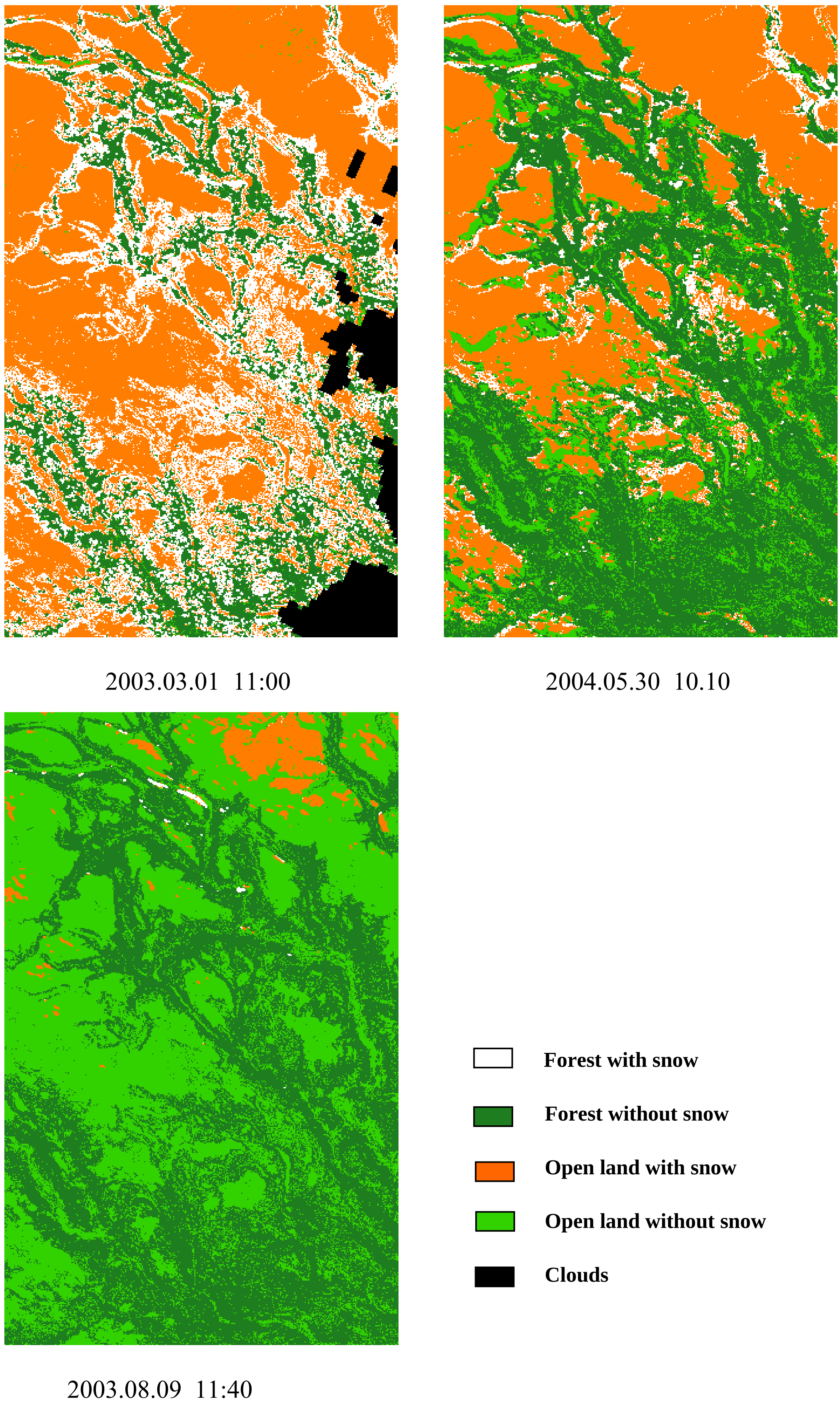


Figure 18 Snow in forests. 250 m resolution, NN aggregation.

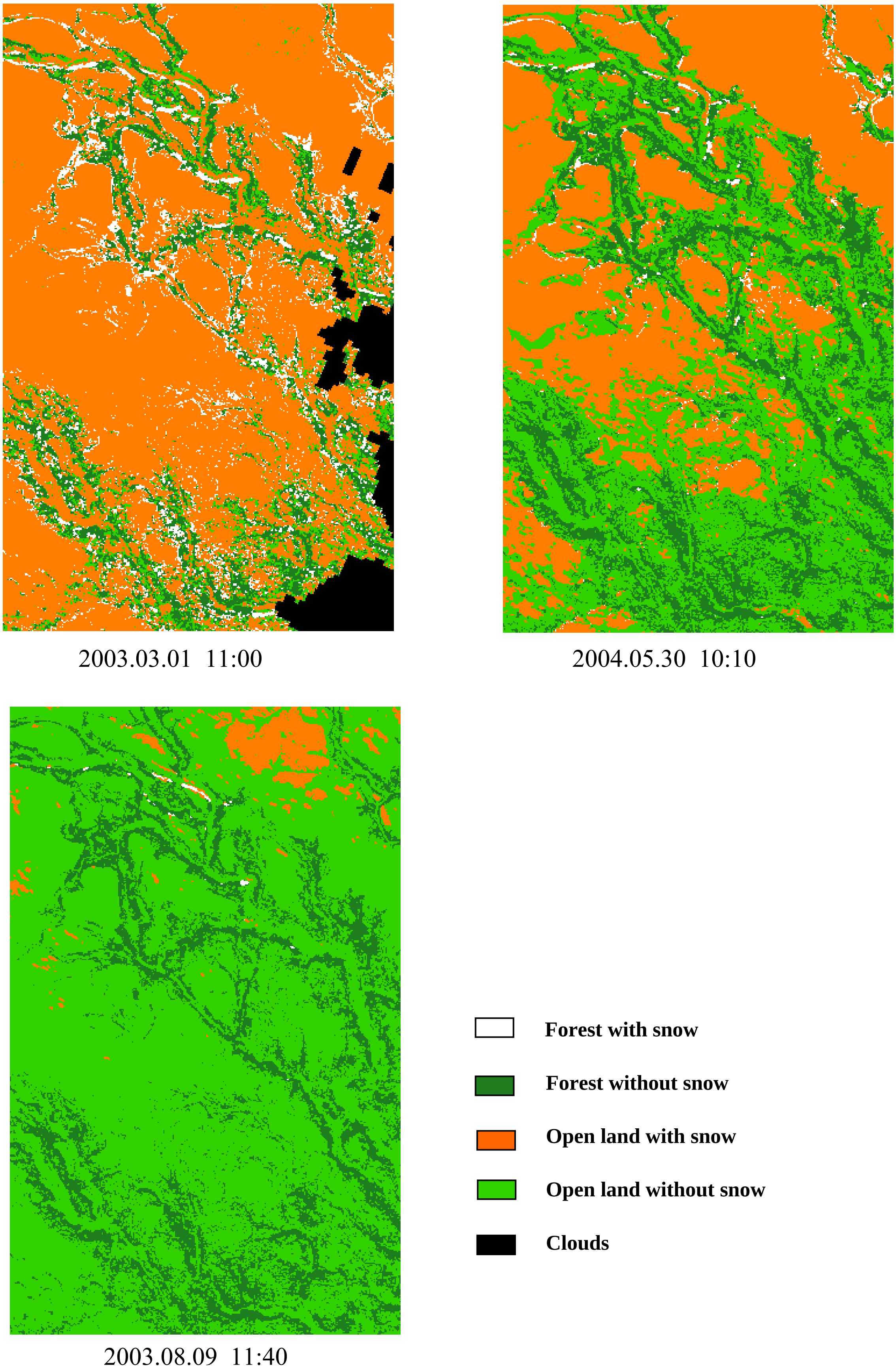


Figure 19 Snow in forests. 100 % forest in each forest pixel.

Table 12 shows the amount of detected snow. For each of the three test scenes, the calculations have been done for NN aggregation and for 100 % forest in each forest pixel. Separate calculations have been done for topographic correction with *C* = 0.05 for deciduous and coniferous forest. For the total forest area, the calculations also have been done without topographic correction. The amount of detected snow is shown in number of pixels and in percent of the forest area not covered with clouds.

		All forest uncorr.		**All forest corr.**		**Coniferous**		**Deciduous**	
Date	**Aggr.**	**Pixels**	**%**	**Pixels**	**%**	**Pixels**	**%**	**Pixels**	**%**
2003.03.01	NN	45067	55.7	50696	62.7	24900	50.2	25796	82.4
2003.03.01	100 %	10949	31.9	14325	41.7	8294	30.7	6031	82.0
2004.05.30	NN	11311	12.9	10776	12.3	3869	7.1	6907	20.9
2004.05.30	100 %			2119	5.7	1214	4.1	905	11.7
2003.08.09	NN	44	0.05	330	0.38	276	0.5	54	0.16
2003.08.09	100%			202	0.5	198	0.7	4	0.05

Table 12 Detected amount of snow in the forests for the three test scenes. The 250 m forest pixels have been created by NN aggregation and by 100 % 25 m forest pixels.

6.4 Discussion

2003.03.01 11:00

Figures 18 and 19, and table 12 show that there are large areas in the forests where no snow has been found, although the observations from the meteorological stations should indicate that there is a full snow cover in all the forest areas. The main reason for the lack of classified snow lies in the used calibration areas. The calibration areas for bare land are forest areas in different parts of Norway and Sweden. In the beginning of March there will be snow in some of these areas (if not in all). This means that the threshold for bare land will be too high, and snow in other forests may be classified as bare land. This will also effect the classification in open areas, but not as much as in the forests.

From table 12 one can see that the topographic correction improves the snow classification for 2003.03.01 when the sun elevation is low. For the other dates with high sun elevation, there are minor differences in the amount of detected snow. As expected it is easier to detect the snow in deciduous, 82.4 %, than in coniferous forests, 50.2 %. When restricting the forest to 100 % forest pixels, the snow detected in coniferous forest is significantly reduced (to 30.7 %). This is probably because there is a reduction of open areas. For deciduous forest, however, there is practically no change. This means that the reduction of open areas does not have a significant influence on the result. The NLR algorithm is working quite well in deciduous forests. The results are not very different from the results in open area, see table 5 and 6.

When there are possibilities of snow in the calibration areas for bare land, there will be errors in the classification results for snow, in the forests, but also in the open areas. A better selection of calibration areas for bare land is needed.

2004.05.30 10:10
The observations from the meteorological stations indicate that there is no snow in the forests. However, there are few stations at high levels above the sea. As seen in figures 18 and 19, and figure 2 some snow has been found in the higher levels, especially in open areas. Figure 18 shows that the snow detected in the forests is situated close to the open areas at levels high above the sea. The Landsat image shows some snow in these areas, so the detection of snow here is probably correct. Table 12 shows that more snow is detected in deciduous than in coniferous forest. This is as expected because it is easier to detect the snow, and because close to the tree limit, there are mostly deciduous trees, and so there actually is more snow left from the winter.

For 100 % forest pixels less snow is detected also for the deciduous forest. While for 2003.03.01 11:00 there was no significant reduction, here the amount of snow has been reduced from 20.9 to 11.7 %. The 100 % forest areas are situated at lower areas, further away from the open areas (see figures 18 and 19), and so there is actually less snow here than in the areas close to the tree limit.

2003.08.09 11:40
At this time of the year there is no snow in the forests. This particular year there was almost no snow even at the highest levels in the summer. Table 11 show that there has been detected a few pixels with snow in the forests. In figure 18 one can see that in most of the area, no snow has been detected. This is correct. But in the northern part of the map one can see a few isolated areas with snow. This is due to some error, but it is difficult to tell how these errors have occurred. The areas with snow are steep hillsides with coniferous forest facing north. The error could be due to errors in the geometric correction of the MODIS image. Just north of the hillsides there is flat land with high signal values, and this could have been detected as snow, but looking at the corrected MODIS image, the signals at the area where snow has been found, are lower than around. The snow could have been detected due to topographic over-correction. In the SCA image without topographic correction, there is no snow in this area. An error in the elevation model could cause an error in the topographic correction. However, the elevation model looks all right in this area. Although the signal values are low compared to the surrounding area, the topographic correction is the most probable cause of this error. One should make a detailed study of the calculation, by studying how the program is running, step by step for this image.

7 Conclusions

The aim of the study was to make comparisons between snow estimates made by the NLR algorithm used on MODIS images and estimates by clustering and visual interpretations of Landsat images. Primarily the study was done for the melting season from March till August in the Jotunheimen region (Koren, 2008). There were found no usable Landsat images from June and July. This makes the study incomplete.

The image from August was from 2003, which was a very special year with respect to snow in the summer season. The results of the snow estimates can not be used as documentation of the qualities of the algorithm for a normal year. Thus, the valuable results of that study were limited to the time period March – May. This means that the effect of snow impurities late in the melting season has not been studied.

In this study it was intended to cover the whole year also outside the melting season, and so images from January and October were included. This means that we also should be able to evaluate the algorithm for the winter season with almost 100 % snow cover, dry snow and low sun elevation, and for late autumn with new fallen snow on the higher mountains.

The studies were done with and without topographic correction in the NRL algorithm.

The results of the study can be summarized in the following points:

- The algorithm underestimates the amount of snow under most conditions, also when using topographic correction.

- Using topographic correction improves the results for all dates, especially for images with low sun elevation. In all cases but one, the total snow cover area increases with topographic correction.

- The value of the parameter, C, used in topographic correction was set to 0.05. Varying the value between 0.01 and 0.15 seems to have little influence on the results.

- Using topographic correction improves the results especially for areas facing north and south. In most cases there are only small differences in the results for the four aspect directions.

- Comparing the results for flat, moderate and steep slopes, there seem to be slightly better results for steep areas in most of the cases.

- In the times with low sun elevation, from late autumn till early spring, there will be large areas covered with cast shadows. This has not been taken into account in the present algorithm. One should expect underestimation of the amount of snow. Using the DEM and the sun position, it is possible to estimate the shadowed areas and adjust the calculations for these. This will need extra calculations for cast shadow finding, and a special algorithm for snow inside shadows.

- The estimated amount of snow varies throughout the day due to variation in satellite positions and calibration values.

- The NLR-algorithm is far from perfect in coniferous forests. However, it is not developed for forested areas. In forests without open areas, little snow has been found even if there is 100 % snow cover in the forests.

- In deciduous forests, the snow detection is far better than in coniferous forests. The algorithm seems to produce usable results even in forests without large open areas.

- Due to the choice of calibration areas, the present algorithm does not give reliable results in the winter because there may be snow in the calibration areas for bare ground. The threshold for bare ground will be too high, and too little snow will be detected. This will especially affect forested areas. If an area with forest having 100 % snow cover is used as a calibration area for bare ground, similar forested areas with 100 % snow can be classified as having no snow. The open areas with snow usually reflect more light and will be classified as having snow. The calibration method should be changed.

- Incorrect snow detection has been found in certain areas, especially for the scene from 2003.08.09. The most probable cause of these errors is an over-correction of low signals in steep hillsides facing north. Should be studied closer.

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