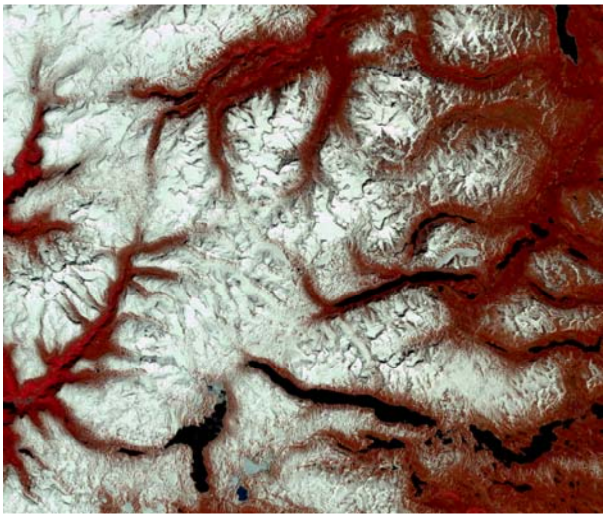
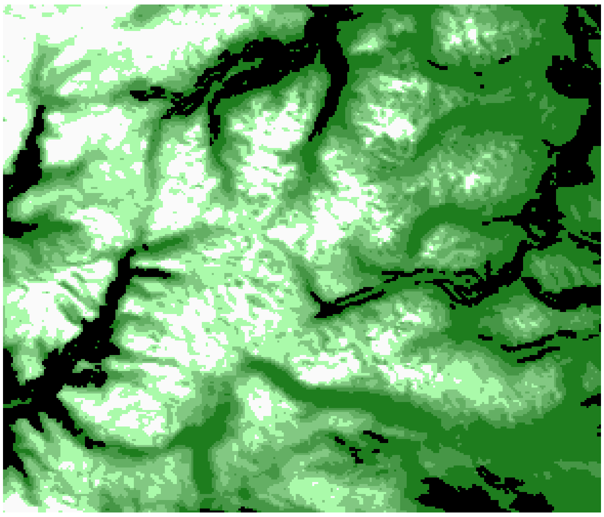
Validation of the NLR fractional snow cover algorithm





Note

Note no SAMBA/34/08

Authors Hans Koren

Date September 2008

Norsk Regnesentral

Norsk Regnesentral (Norwegian Computing Center, NR) is a private, independent, non-profit foundation established in 1952. NR carries out contract research and development projects in the areas of information and communication technology and applied statistical modeling. The clients are a broad range of industrial, commercial and public service organizations in the national as well as the international market. Our scientific and technical capabilities are further developed in co-operation with The Research Council of Norway and key customers. The results of our projects may take the form of reports, software, prototypes, and short courses. A proof of the confidence and appreciation our clients have for us is given by the fact that most of our new contracts are signed with previous customers.

Norsk Regnesentral
Norwegian Computing Center
Postboks 114, Blindern
NO-0314 Oslo, Norway

Besøksadresse
Office address
Gaustadalléen 23
NO-0373 Oslo, Norway

Telefon · telephone
(+47) 22 85 25 00
Telefaks · telefax
(+47) 22 69 76 60

Internett · internet
www.nr.no
E-post · e-mail
nr@nr.no

Title	**Validation of the NLR fractional snow cover algorithm**
Authors	**Hans Koren**
Date	September
Year	2008
Publication number	SAMBA/34/08

Abstract

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. It does not take into account the topography, and although it is working well for relatively flat areas, there are errors in the snow estimates in mountainous terrain. A typical error is that it estimates 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.

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 in the snowmelt season, between 1 March and 9 August, 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. We have found that the algorithm works better with high sun elevation, especially for areas facing away from the sun. The amount of snow is underestimated in all areas, except for slopes with moderate or steep gradients facing the sun. For such regions we find overestimation for all tested dates. The estimated total snow area varies from 74.1 % to 89.4 % from beginning of March to end of May, relative to Landsat estimates. For relatively flat areas (gradients not more than 10 degrees), the corresponding results are 85.6 % to 92.9 %.

Keywords	Snow cover, satellite images MODIS
Target group	Snow hydrology, climatology, meteorology
Availability	Open
Project number	830100
Research field	Earth observation
Number of pages	34

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 method does 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.

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 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.

Two MODIS images taken at different times of 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 of the observed 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.

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.

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 6 scenes with a time span from 1 March till 9 August, 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 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

Table 1 Landsat images used in the validation

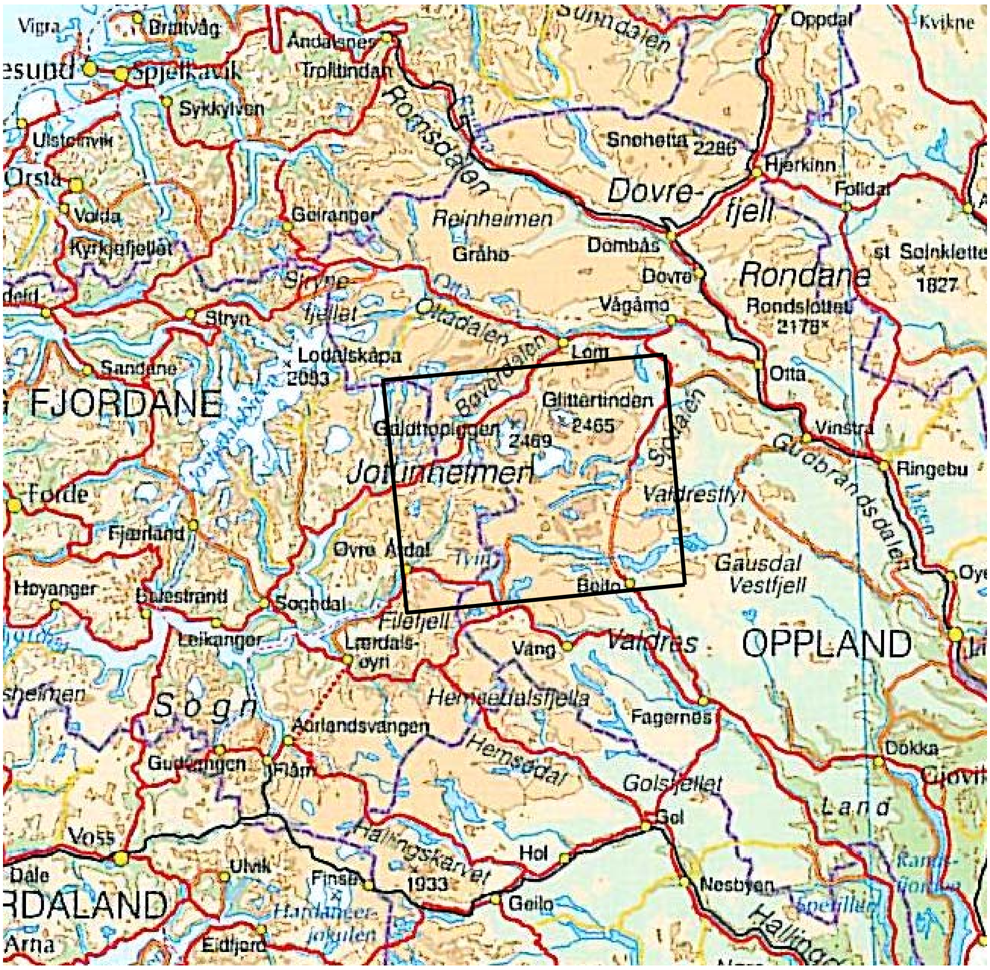


Figure 1 Test area in Jotunheimen

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. 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 Figure 2. The images have been geocorrected and cut to the validation area in Jotunheimen.

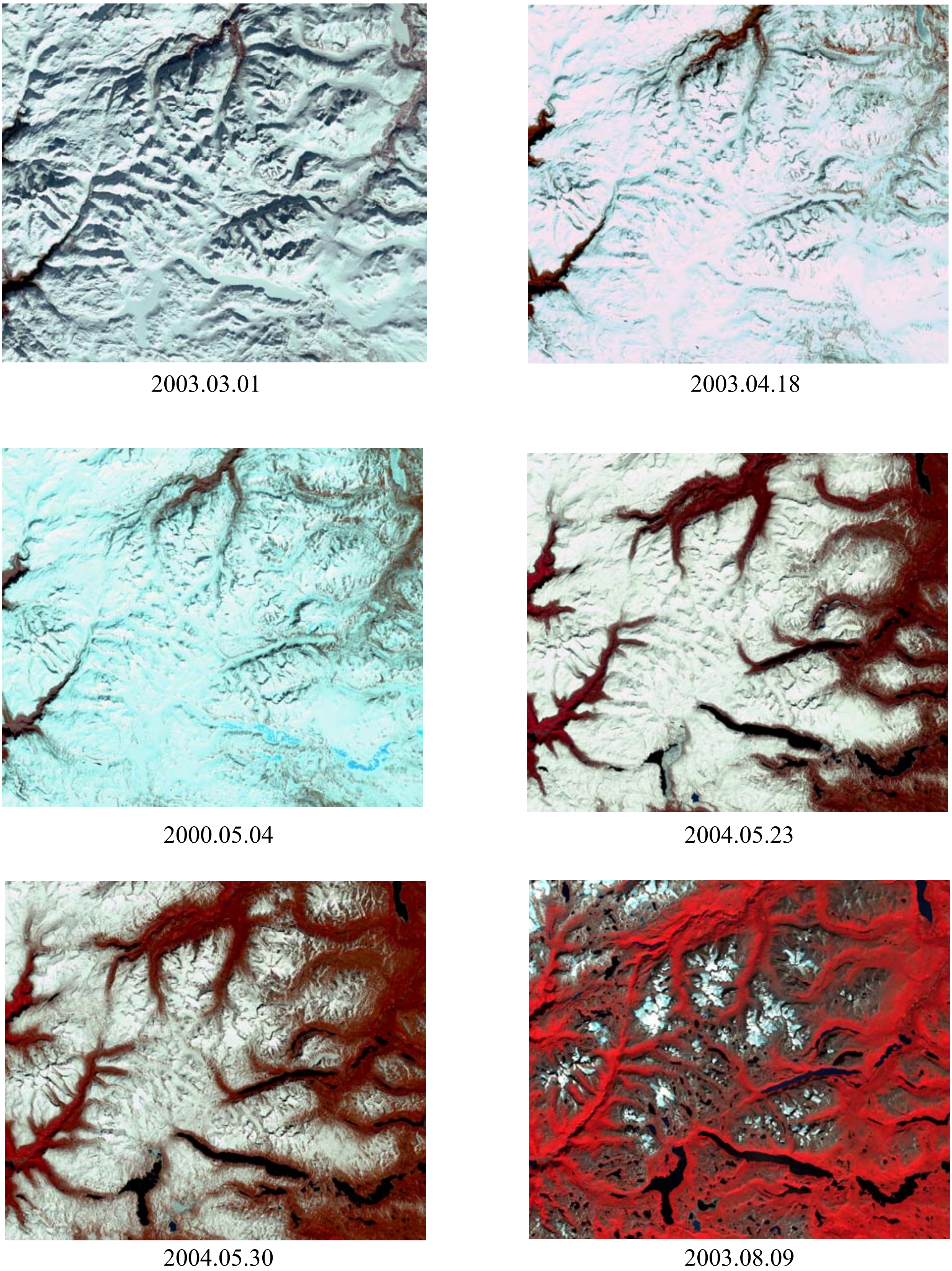


Figure 2 The selected Landsat images. The images have been geographically corrected and cut to the validation area. Band 4, 3, and 2 are here used as RGB. The red colour is caused by high values in the infrared band 4, due to vegetation.

Comments to the images

2003.03.01: 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.

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 difference sin 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

2.2 MODIS images

MODIS images from the same days as the Landsat images have been downloaded from the NASA archive. For three 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.

Date	Time
2003.03.01	11:00
2003.04.18	11:00
2000.05.04	11:10
2004.05.23	10:05
	11:40
2004.05.30	10:10
	11:45
2003.08.09	10:00
	11:40

Table 2 Selected MODIS images

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. The two images from 2003.04.30 were used to show the difference in SCA retrieval during one day.

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:

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

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

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

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.

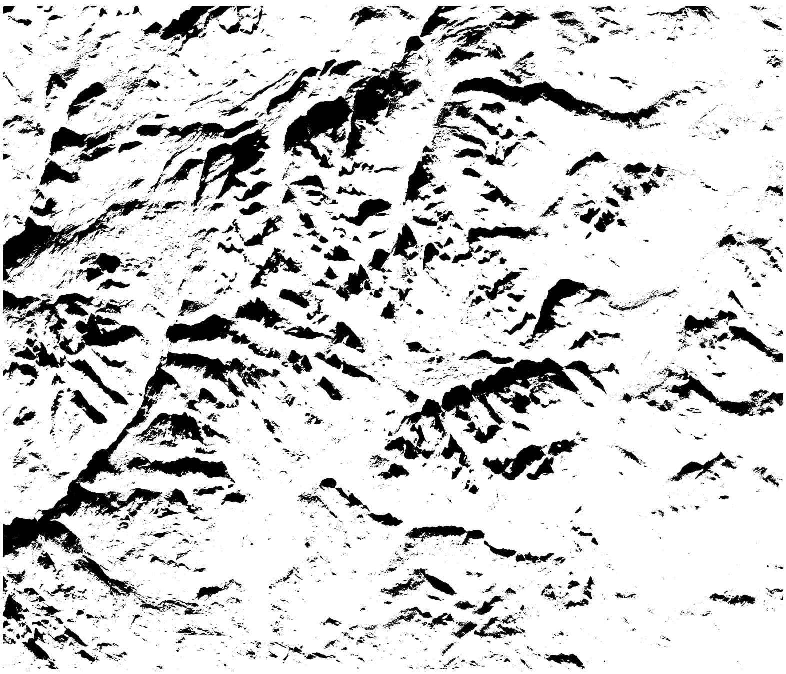


Figure 4 Shadow areas estimated by making a threshold of band 5 for the image from 2003.03.01

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). 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.

3.4 Calculation of snow cover

3.4.1 Input data

- The 6 Landsat images described in Table 1, corrected to UTM zone 32, 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.

3.4.2 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.

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.

3.4.3 Choice of parameters

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

	NDSI threshold		Cluster	Classes for snow classification		
Date	**High**	**Low**	**bands**	**No snow**	**Fractional**	**Full**
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

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.

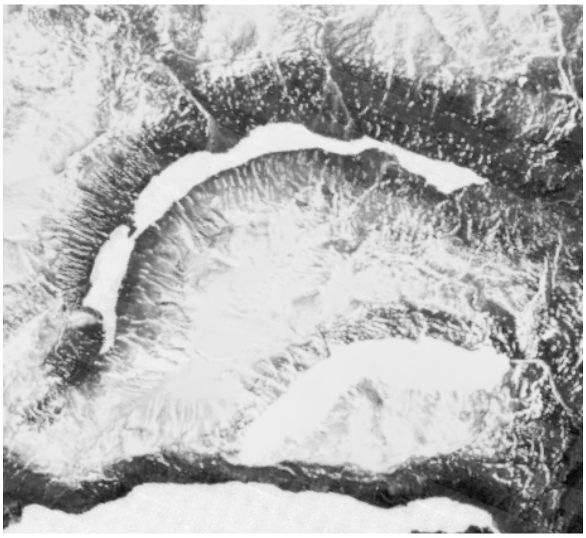
3.4.4 Results

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.

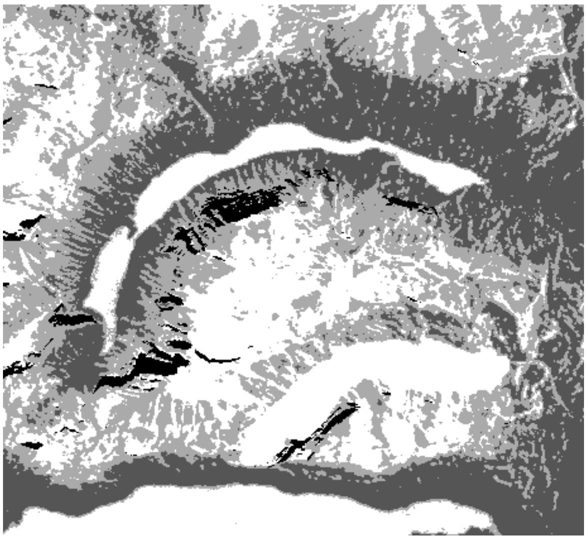
The 'full snow cover' class has been selected to include all pixels which most certainly have a full snow cover. The 'bare ground' class includes all pixels which most certainly have no snow included. The fractional snow cover class will then include all pixels with an amount of snow which probably does 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 Table 4 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'.

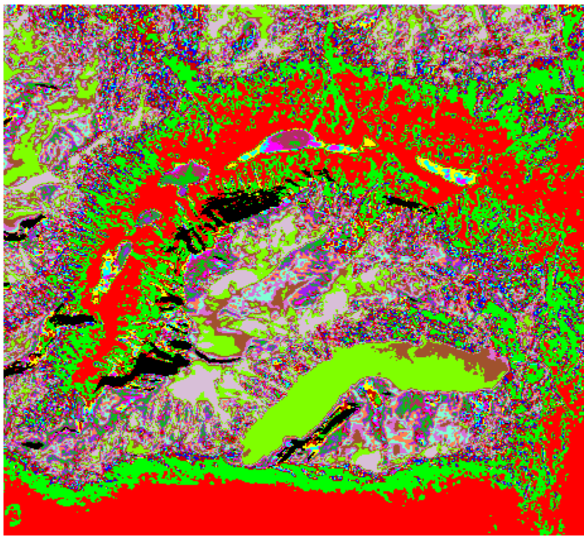
a) Landsat image, band 4, 3, 2



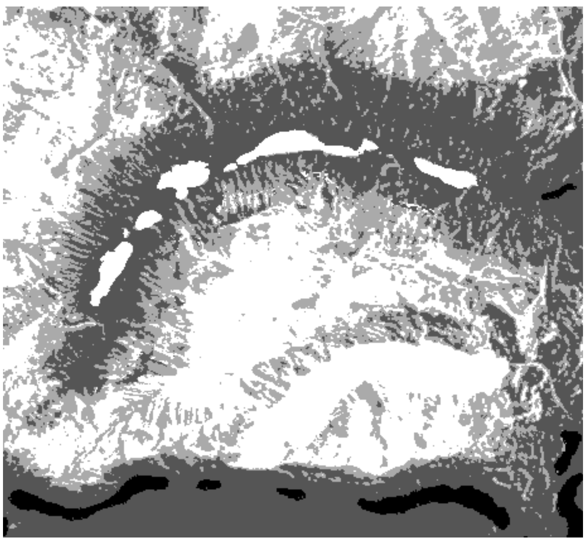
b) NDSI



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

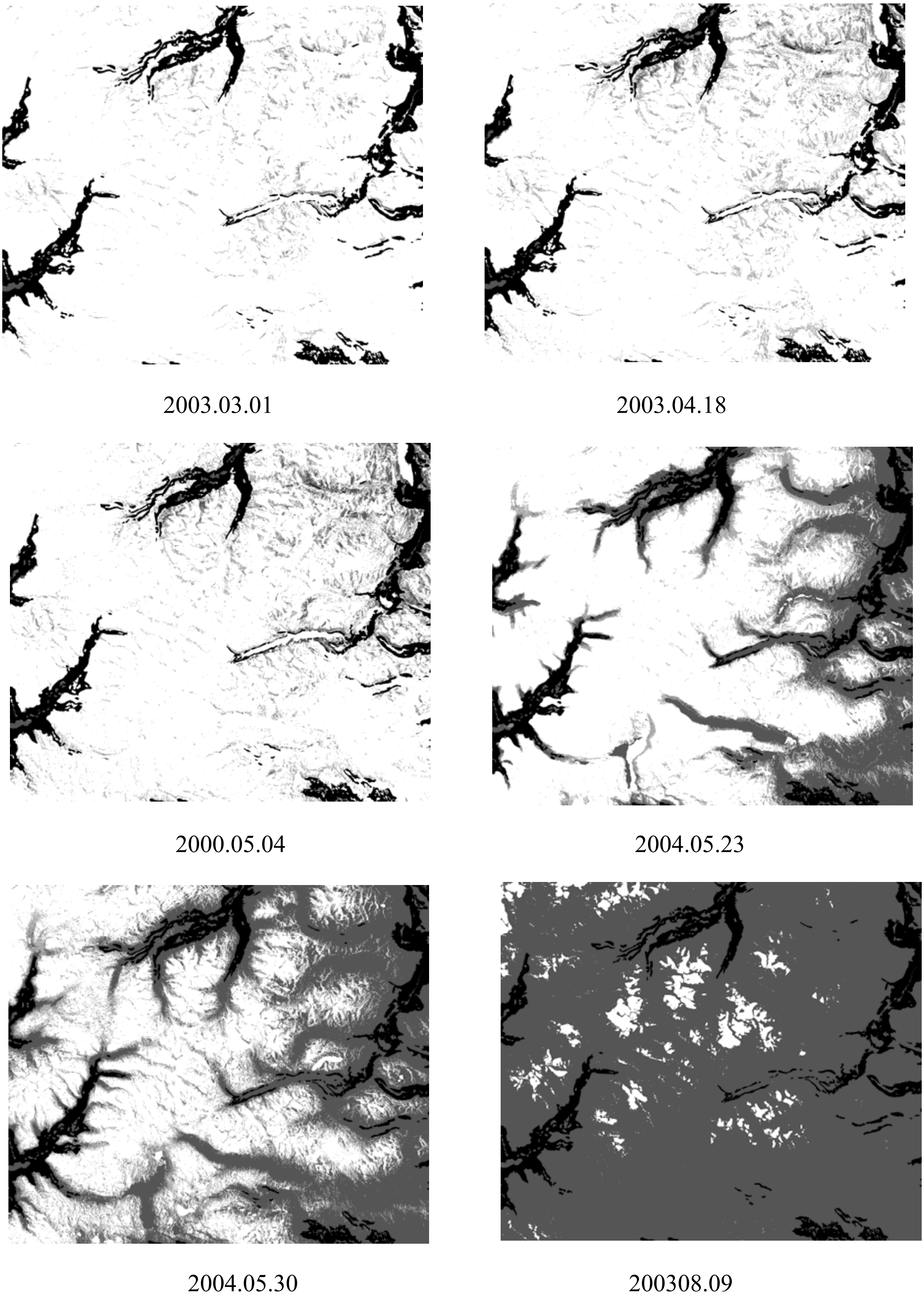


Figure 6 Snow classification in Landsat images. White: full snow cover, Light gray: fractional snow cover, Dark gray: bare ground, Black: forest

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.

In the existing SCA algorithm no such terrain compensations have been included. It is therefore 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.

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:
slope angle $\theta = arctg(S) \cdot 180/\pi$
aspect angle $\varphi = arctg(Sy/Sx) \cdot 180/\pi$

If Sx = 0 and Sy > 0 then φ = 0
If Sx = 0 and Sy < 0 then φ = 180
If Sx = 0 and Sy = 0 then φ = 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: φ ≤ -135 or φ ≥135, |φ| ≤180
West: φ < 135 and φ > 45
South: φ ≥ -45 and φ ≤ 45
East: φ > -135 and φ < -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.

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.

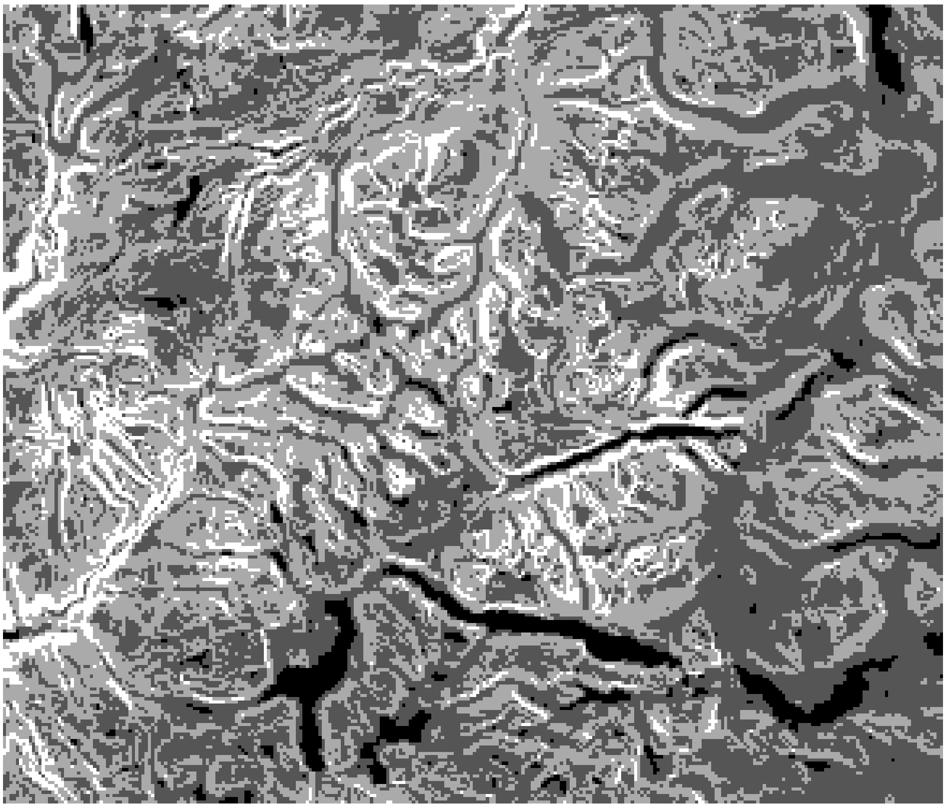


Figure 9 Slope classes in 250 m resolution. Black - plain (water), dark gray - flat areas, light gray - moderate slope gradients, white - steep areas.

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

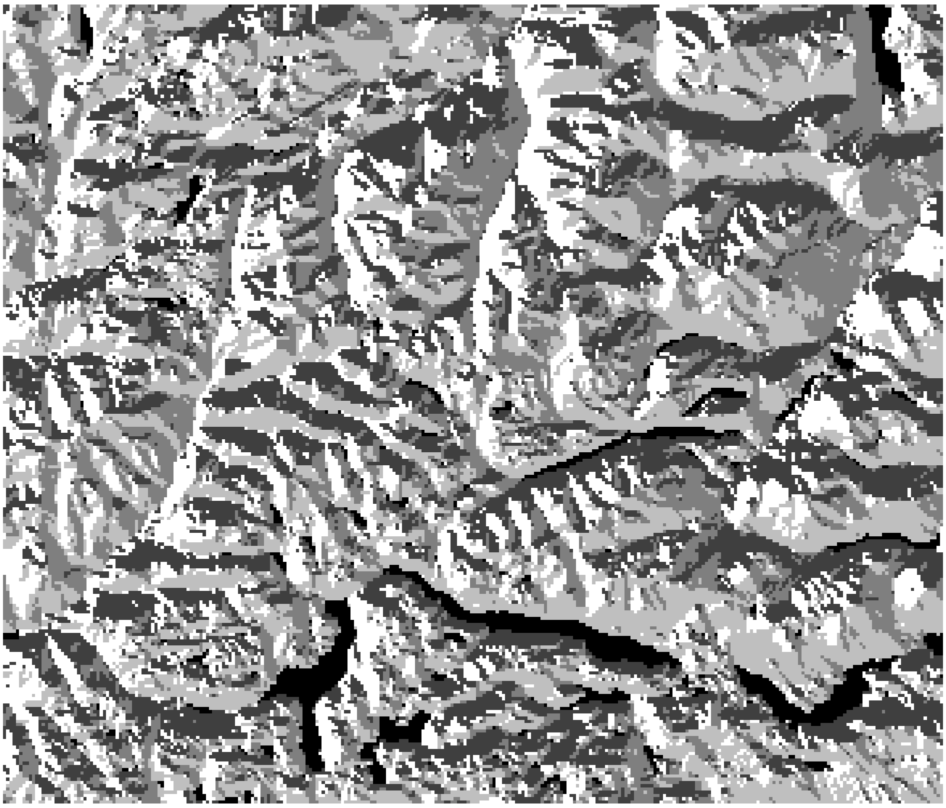


Figure 10 Aspect classes in Jotunheimen, 250 m resolution. Black - plain (lakes), dark gray - north, medium gray - east, light gray - south, white - west.

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. The algorithm used is explained in Solberg et al. (2004). The resulting 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 1km images for cloud classification. A description of the cloud classification can be found in Solberg et al. (2004). The images have been transformed to UTM zone 33 projection by the MODIS Swath Reprojection Tool, downloaded from the web. Description can be found at http://gcmd.nasa.gov/records/MODIS_Swath_Reprojection_Tool.html

In this validation the study area has been chosen such that there are no clouds in the images covering the area.

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 4.

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: 378.00625 km^2
Area of forest mask with 250 m resolution: 532.4375 km^2
Area without forest with 25 m resolution: 4147. 99375 km^2
Area without forest with 250 m resolution: 3993.5625 km^2

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

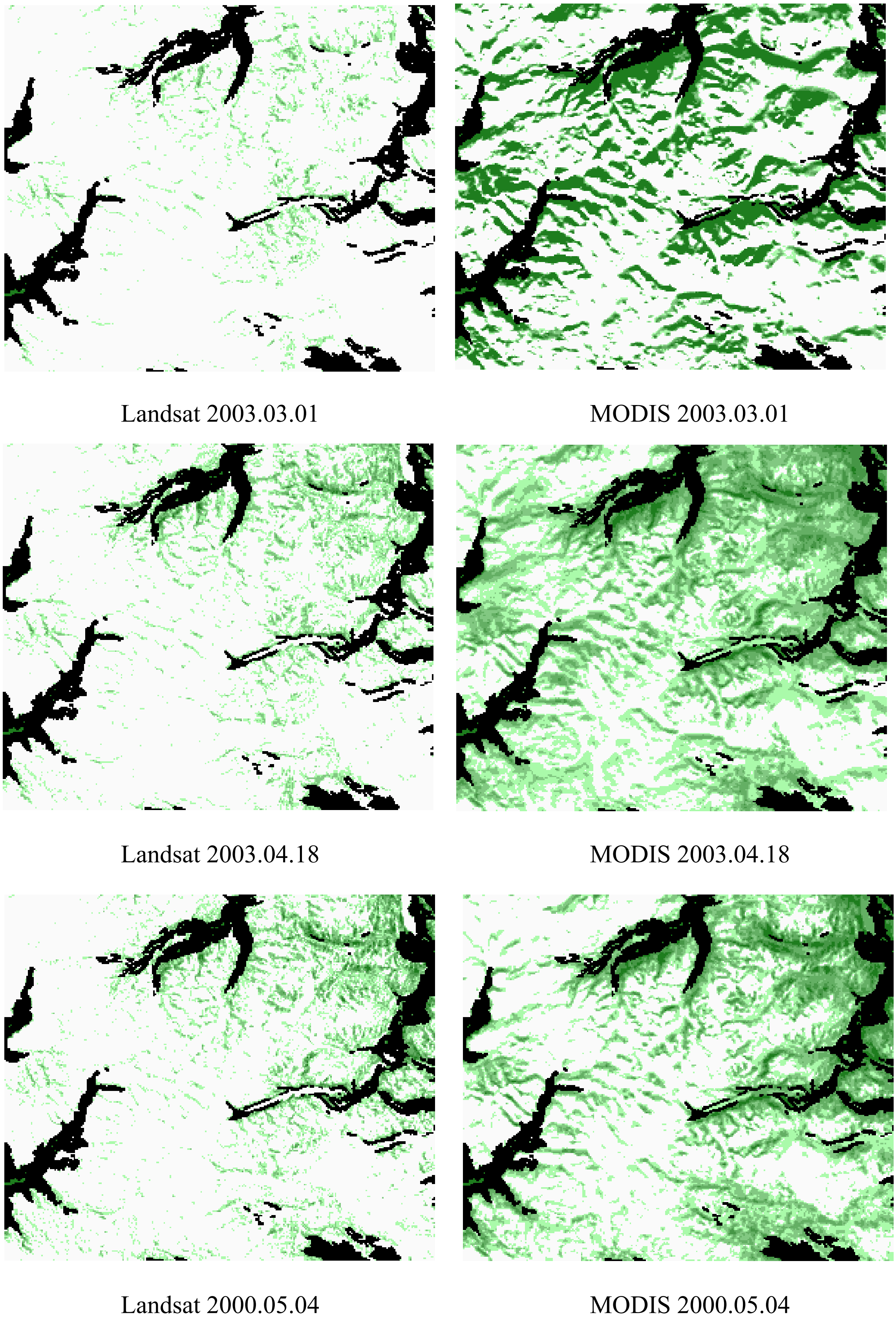
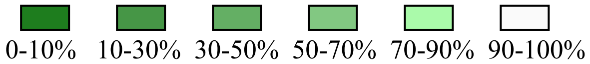


Figure 11 SCA with 250 m resolution from Landsat and MODIS images for corresponding dates. Forest is marked in black. The SCA is given in percent snow cover per pixel.



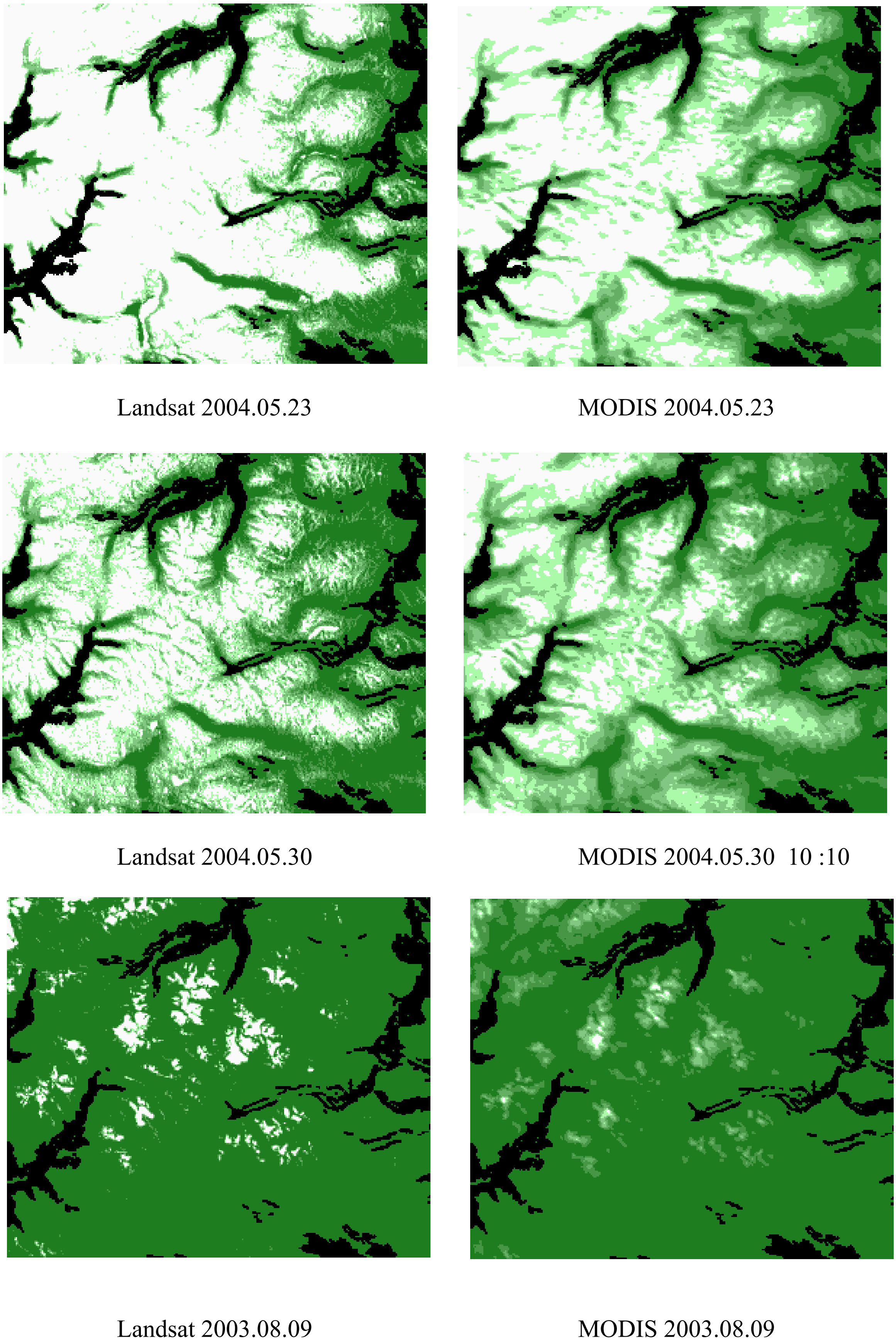


Figure 12 SCA with 250 m resolution from Landsat and MODIS images for corresponding dates. Forest is marked in black. The SCA is given in percent snow cover per pixel.

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

5.2 Results

5.2.1 Total area

Figure 11 and Figure 12 show the classified Landsat and MODIS images with 250 m resolution. Forest is 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.

In Table 4 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**		**250 m**	**Min**	**Mean**	**Max**
2003.03.01 - 1100	2895.16	km²	3913.92	3957.61	4047.26	4136.92
	72.5	%	97.8	95.4	97.6	99.3
2003.04.18 - 1100	3026.86	km²	3775.98	3672.56	3888.94	4105.32
	75.8	%	94.3	88.5	93.8	99.0
2000.05.04 - 1110	3197.90	km²	3689.31	3537.64	3786.28	4034.91
	80.1	%	92.2	85.3	91.3	97.3
2004.05.23 - 1005	2651.95	km²	2973.05	2696.24	2976.29	3275.09
	66.4	%	74.3	65.0	71.2	78.5
2004.05.30 - 1010	1938,37	km²	2203.94	1729.34	2195.96	2662.57
	48.5	%	55.1	41.7	52.9	64.2
2004.05.30 - 1145	1678.68	km²	2203.94	1729.34	2195.96	2662.57
	42.0	%	55.1	41.7	52.9	64.2
2003.08.09 - 1140	193.44	km²	256.76	242.09	255.11	268.13
	4.8	%	6.4	5.8	6.2	6.5

Table 4 Calculated SCA from MODIS and Landsat images for the whole test area. The % values are relative to the area without forest.

For 2004.05.30 the fractional and total snow cover have been calculated for two images. In Table 4 one can see that there is a large difference in retrieved total SCA. For the late image the total SCA is only 86.6 % of the result for the early image.

Figure 13 shows a subset of the fractional snow cover map for the two images. 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.

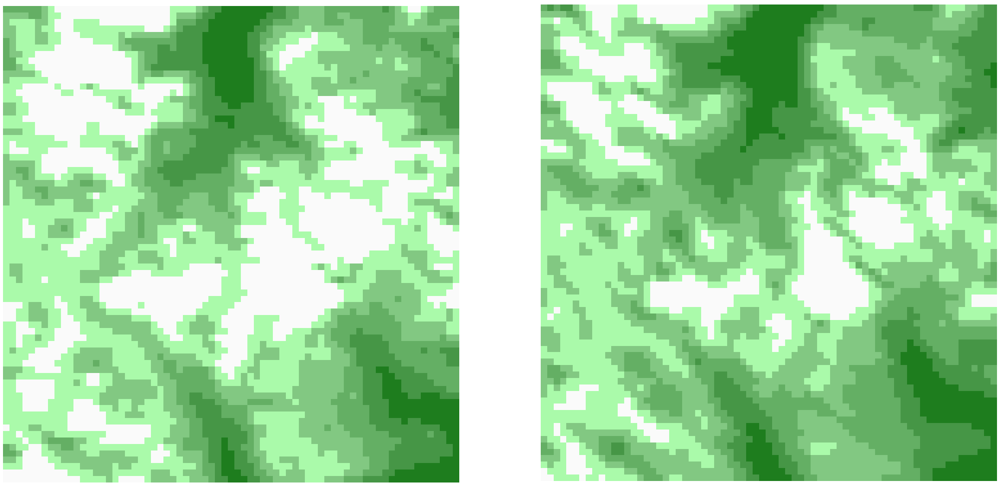


Figure 13 Fractional snow cover in percent for two MODIS images from 2004.05.30

In Table 5 the differences in total SCA area are shown for all 6 dates. The differences in area of estimated bare ground and full snow cover for MODIS and Landsat are shown in Table 6.

Date and time	SCA MODIS relative to Landsat in %	SCA difference in km²	SCA difference in % of total area
2003.03.01 - 1100	74.1	1010.05	25.29
2003.04.18 - 1100	80.3	740.72	18.55
2000.05.04 - 1110	86.9	483.20	12.10
2004.05.23 - 1005	89.4	314.49	7.87
2004.05.30 - 1010	88.3	260.68	6.53
2003.08.09 - 1140	75.5	62.75	1.57

Table 5 Differences in SCA results from MODIS and Landsat images.

Date	MODIS		Landsat	
	0 %	100 %	0 %	100 %
2003.03.01	11038	28160	30	50980
2003.04.18	154	12991	43	40600
2000.05.04	281	26060	54	36780
2004.05.23	2232	16426	4831	32431
2004.05.30	6097	5530	8818	9957
2003.08.09	40866	57	54366	1776

Table 6 Number of pixels with estimated 0 % and 100 % snow cover for all images

5.2.2 Discussion

Comparing Table 4 and Table 5 we find that MODIS generally gives less snow than the estimates from the Landsat images. In all cases except 2004.05.30, the MODIS estimate is even below the minimum value calculated from the Landsat image.

The difference between Landsat and MODIS SCA is largest in the beginning of the season and is decreasing by time. Although the absolute difference is smallest at the end of the season, the relative difference is largest for 2003.08.09.

For the first three dates, 2003.03.01, 2003.04.18, and 2000.05.04 the Landsat estimates show a decreasing SCA, while the calculated MODIS SCA is increasing. This effect is due to increasing sun elevation. In this period the sun elevation at the acquisition time is increasing from 19.7 to 43.7 degrees. The areas facing towards north will get less shadows and more sunlight. There will be more reflected light towards the satellite, and the SCA algorithm will detect a higher percent of snow cover. Even if the total snow cover is actually decreasing, the MODIS SCA algorithm may find it to be increasing.

2003.03.01

Table 5shows that the total amount of MODIS SCA is only 74.1 % of the estimated SCA from Landsat. A low value is expected at this time of the year with a low sun elevation and large areas in the shadow. In Figure 11 it can be seen that the MODIS SCA shows low values in all the shadowed areas. Table 6 shows that the estimated area of bare ground is 11038 pixels relative to only 30 in the Landsat case. These pixels are probably mostly found inside the shadows. The number of pixels with 100 % snow is relatively high compared with the other dates, but still lower than the Landsat estimates. In areas turning towards north there will be detected no pixels with 100 % snow, but for the pixels in flat areas and areas facing towards south, the estimates are probably satisfactory.

2003.04.18

MODIS SCA is 80.3 % of Landsat SCA. From the Landsat image the main area seems to be completely covered with snow. Comparing the two results in Figure 11, 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 (38.4 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 16^{th} 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 open areas, 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 Jotunhimen. 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 is smaller, but still present. MODIS SCA is 86.9 % of Landsat SCA. Another 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 11 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. 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 is 89.4 % of the Landsat SCA. This is the highest value achieved for the test images. 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 88.3 % of Landsat SCA, which is about the same as the week before. There are still some small areas of ice on the lakes. As for the other May images, it seems as if the calculated SCA is generally somewhat lower for MODIS than for Landsat.

The image taken at 11:45 gives only 76.4 % of Landsat SCA.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 65.9 % 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).

5.2.3 Terrain types

In Table 7 the estimated SCA from MODIS is given as percentage of the corresponding SCA from Landsat for areas of different degree of steepness. The date 2003.08.09 is very special, as has been explained earlier. Because of the lack of snow from the last winter, the MODIS SCA is low, and almost equally low for all degrees of steepness. The result for plain areas is based on very few pixels and should not be considered valuable.

For the other dates, the best results are found in the flat areas (slope of max 10 degrees) areas, as expected. The MODIS SCA lies between 85.6 and 92.9 %. For moderate and steep slopes the results gets better with increasing sun elevation. For the plain areas, which actually are lakes, 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**	**Flat**	**Moderate**	**Steep**
2003.03.01	97.0	86.8	63.6	55.1
2003.04.18	88.9	85.6	76.9	66.3
2000.05.04	81.3	90.9	85.3	76.9
2004.05.23	78.3	92.9	88.0	84.4
2004.05.30	77.4	90.1	87.3	86.4
2003.08.09	675.8	77.9	73.7	75.2

Table 7 SCA MODIS relative to SCA Landsat in %, according to area steepness

Date	**Time UTC**	**Sun azimuth**	**Area aspect**			
			North	**East**	**South**	**West**
2003.03.01	1100	10.17	35.1	79.0	101.1	77.9
2003.04.18	1100	8.06	65.6	79.3	93.2	82.5
2000.05.04	1110	4.29	74.4	86.5	97.5	91.2
2004.05.23	1005	27.16	77.6	92.1	100.9	89.1
2004.05.30	1010	26.15	73.4	88.5	103.2	90.9
2003.08.09	1140	-2.84	47.0	64.2	157.5	107.5

Table 8 SCA MODIS relative to SCA Landsat in %, according to area aspect

In Table 8 the relation between SCA from MODIS and Landsat is shown for areas of different aspect directions. If we disregard the image from 2003.08.09, the results are mainly as expected. The results 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.

In Table 9 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	**Steepness**	**North**	**East**	**South**	**West**
2003.03.01	**Flat**	69.1	91.0	98.3	90.0
	Moderate	13.2	73.0	101.6	71.2
	Steep	0.4	48.3	116.1	56.2
2003.04.18	**Flat**	79.0	84.4	91.5	88.0
	Moderate	58.2	77.5	93.8	79.8
	Steep	33.6	63.1	100.8	69.8
2000.05.04	**Flat**	85.7	90.4	94.6	93.3
	Moderate	68.6	85.7	98.7	90.1
	Steep	43.3	70.5	106.9	86.7
2004.05.23	**Flat**	87.0	94.3	97.9	92.7
	Moderate	73.4	91.7	101.8	87.1
	Steep	60.3	84.6	108.7	84.2
2004.05.30	**Flat**	83.2	91.3	96.0	90.4
	Moderate	69.4	88.0	106.3	89.3
	Steep	54.4	79.7	122.2	103.1
2003.08.09	**Flat**	62.3	67.8	119.4	100.3
	Moderate	40.6	61.9	177.1	107.5
	Steep	26.7	62.9	309.8	161.8

Table 9 MODIS SCA in % of Landsat SCA for combinations of aspect and steepness

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 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 for the melting season from March till August in the Jotunheimen region. 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 the study are limited to the time period March – May. This means that the effect of snow impurities late in the melting season has not been studied.

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

- The algorithm underestimates the amount of snow under most conditions.
- The relative amount of estimated snow increases throughout the season, mostly due to increasing sun elevation. For the total snow area, the relative amount increases from 74.1 % in the beginning of March to 89.4 % in the end of May.
- The estimated amount of snow varies throughout the day due to variation in satellite positions and calibration values.
- The topography has large impact on the estimates. For flat areas (not more than 10 degrees slope), the relative amount varies from 85.6 % to 92.9 %, while for steep areas the variation is between 55.1 % and 86.4 %. The aspect of an area is equally important. For areas facing north there is a large underestimate, from 35.1 % to 77.6 %, while for areas facing south there even are some overestimates. The relative amount varies between 93.2 % and 103.2 %, with an overestimate even for the image from 1 March (101.1 %).
- The combination of steepness and aspect can be expressed as follows: Steep areas facing north have the largest underestimation and larger the earlier in the year. Steep areas facing south have overestimation and this occurs for all the sampled dates. For east and west, the results lie somewhere between the results for north and south. There is no significant difference between the results for east and west. There are, however, a couple of cases with unexplainable differences.

The overall conclusion is that the algorithm might be greatly improved by taking the topography into account. By calculating the steepness and aspect angle for each pixel and finding the angle between the surface normal and the direction of the incident sunlight, it should possible to get a better estimate the amount of reflected light, and thus improve the estimate of snow amount.

7 References

Barnsley, M. J. Analysis of Digital Elevation Models. Modelling Gradient and Aspect. University of Wales, Swansea, 2003.
http://stress.swan.ac.uk/~mbarnsle/teaching/envmod05/lectures/dems2d.pdf

Cadell, William. Report on the generation and analysis of DEMs for spatial modelling. March 2002.

http://www.macaulay.ac.uk/LADSS/documents/DEMs-for-spatial-modelling.pdfN

Rainis, Ruslan. Estimating sediment yield using Agricultural Non-Point Sources (AGNPS) model: The effect of slope information from different GIS software. Journal of Spatial Hydrology Vol 4, No 2, Fall 2004.

Romstad, Bård. Automatisk landformkartlegging med en kontekstuell relieffklassifikasjon. Hovedoppgave i geografi (geometrikk). Geografisk Institutt, Universitetet i Oslo, 2001. http://www.cicero.uio.no/media/1525.pdf

Solberg, Rune; Koren, Hans; and Amlien, Jostein. A review of optical snow cover algorithms, Norwegian Computing Center, Note SAMBA/26/04, October 2004.