

AN IMPROVED METHODOLOGY TO MAP SNOW COVER BY MEANS OF LANDSAT AND MODIS IMAGERY

C. Cea, J. Cristóbal and X. Pons

Dept. of geography
Autonomous University of Barcelona
Cerdanyola del Vallès, Spain
cristina.cea@uab.cat
jordi.cristobal@uab.cat
xavier.pons@uab.cat

Abstract— In this article we propose a methodology to determine snow cover by means of Landsat-7 ETM+ and Landsat-5 TM images, as well as an improvement in daily Snow Cover TERRA-MODIS product (MOD10A1), between 2002 and 2005. Both methodologies are based on a NDSI threshold > 0.4 . In the Landsat case, and although this threshold also selects water bodies, we have obtained optimal results using a mask of water bodies and generating a pre-boundary snow mask around the snow cover. Moreover, an important improvement in snow cover mapping in shadow cast areas by means of a hybrid classification has been obtained. Using these results as ground truth we have verified MODIS Snow Cover product using coincident dates. In the MODIS product, we have noted important commission errors in water bodies, forest covers and orographic shades because of the NDVI-NDSI filter applied to this product. In order to improve MODIS snow cover determination using MODIS images, we propose a hybrid methodology based on experience with Landsat images, which provide greater spatial resolution.

Keywords- Snow cover, Remote Sensing, Landsat, MODIS, Catalan Pyrenees.

I. INTRODUCTION

Accurate snow cover determination is essential to compute the volume of water that flows towards river basins when snow melts. Moreover, it is also important to determine the emissivity of this cover, an extremely useful data because it is used as an input parameter in thermal band atmospheric correction, and in species distribution modeling [1]. The information can be obtained by taking specific snow cover data during field campaigns, although this way usually does not provide a spatial and temporal cover of enough detail and quality. Alternatively, Remote Sensing could provide better snow cover estimation due to its spatial and temporal resolution. In this article we propose a methodology based on the NDSI index (obtained from radiometrically corrected images) with a threshold > 0.4 ([2] and [3]) to determine snow cover over a large and heterogeneous area by means of Landsat-7 ETM+ and Landsat-5 TM images, as well as an improvement in daily Snow Cover TERRA-MODIS product (MOD10A1), between 2002 and 2005.

II. STUDY AREA AND MATERIAL

The geographical boundary of the study area corresponds to Catalonia (north-east of the Iberian Peninsula) and it is defined by the following UTM-31 N coordinates: 260000 (minimum X coordinate), 528000 (maximum X coordinate), 4489000 (minimum Y coordinate) and 4749000 (maximum Y coordinate) with a total area of about 32000 km².

A set of 7 Landsat images (5 Landsat-5 TM and 2 Landsat-7 ETM+) of path 197 and 198 and rows 31 and 32; and 7 TERRA-MODIS calibrated radiances (MOD02HKM) and daily snow cover products (MOD10A1) of the following dates 14-01-2003, 19-03-2006, 10-02-2004, 08-11-2004, 11-01-2005, 16-03-2005, 17-04-2005 have been chosen to perform this study. We have selected cloud-free images trying to cover all months of the year to take into account different daily situations.

III. METHODOLOGY

A. Image processing: Landsat

The computation of the Landsat-5 TM and Landsat-7 ETM+ data used in snow cover mapping has been carried out by means of the following methodologies:

1) *Geometric correction*: Images have been corrected by means of conventional techniques based on first order polynomials taking into account the effect of the relief of the land surface using a Digital Elevation Model [4] obtaining a RMSE less than 30 m.

2) *Radiometric correction (non-thermal bands)*: Radiometric correction has been done following the methodology proposed by [5] which allows us to reduce the number of undesired artefacts that are due to the effects of the atmosphere or to the differential illumination which is, in turn, due to the time of the day, the location on the Earth and the relief (some zones being more illuminated than others, shadows, etc). All image pixels that fulfill the condition of having incident angles superior to 90 degrees or a lambertian angle $> 73^\circ$ in pixels that are shadowed by other pixels or, rarely, where they present anomalous reflectances are then

flagged as NODATA value. Conversion from digital numbers (DN) to radiances has been done by means of image header parameters taking into account the considerations exposed by [6].

It is worth noting that winter and autumn months usually present the maximum extent of snow cover but also the higher rate of NODATA values, especially in mountainous regions where Catalonia is partially located, because of the shadows caused by the differential illumination and the relief [5] and the local solar time that Landsat overpasses Catalonia that is approximately at 10:30.

3) *Apparent brightness temperature (ABT)*: This has been computed using the methodology proposed by [7] and [8] for Landsat-5 TM and Landsat-7 ETM+, respectively, and using the conversion parameters included in the image metadata.

4) *Cloud removal*: this has been carried out by means of the methodology proposed by [9].

B. Image processing: TERRA-MODIS

1) *Data import*: Daily snow cover products has been imported to MiraMon [10] file format reading all the necessary metadata to document and interpret the images. This product have already been corrected by USGS in a sinusoidal projection and before using we have change its projection to UTM-31 N.

2) *Geometrical correction of Level 1B MODIS calibrated radiances*: Geometrical correction has been carried out by means of ENVI software, that takes into account MODIS images bow tie effect, and following the methodology proposed by [11]. Lastly, we have added the original image metadata to apply the conversion from DN to top of the atmosphere (TOA) radiances.

C. Snow cover mapping.

One of the most widely methodologies used to map snow cover by means of remote sensing data is the methodology proposed by [2] and [14] which selects as snow cover pixels with a NDSI greater than 0.4. This methodology proposes a normalized index using green band (G) and medium infrared band (MIR), because snow reflectance is higher in the visible bands than in the medium infrared band, this characteristic allows to distinguish snow from other covers.

$$\text{NDSI} = (G - \text{MIR}) / (G + \text{MIR}) \quad (1)$$

This index has been developed to be used in radiometrically corrected images, although exist other methodologies that use this index in non-radiometrically corrected images because is supposed that a partially attenuation of atmospheric effect is corrected using a normalized index [12].

However, this threshold selects as snow cover other covers: water bodies (like dams, rivers, high mountain lakes, etc), selection of snow cover in topographic shadows, and some clouds that have a high reflectance in the medium infrared wavelength.

In order to map snow cover using Landsat data we propose two steps, the first one based on the NDSI and the second one based on an ISODATA classification in NODATA areas:

1) STEP 1: NDSI

a) *Pre-boundary snow mask*: To avoid snow pixel confusion with other covers we have been digitalized a pre-boundary mask around snow covered areas within a distance between 2 and 3 km using ABT to distinguish snow cover from other covers, especially in topographic shadows. This mask that selects a larger area than the area covered by snow is used as a starting point to map snow cover reducing commission errors from other covers without producing omission errors in snow cover.

b) *Water bodies mask*: One of the main problems of the NDSI threshold is the selection of pixels corresponding to water (streams, dams, lakes, sea water, etc) as snow. In order to improve snow cover discrimination, we have been applied a water bodies mask corresponding to a selection of the water bodies of the topographical map (at 1: 50000 scale), of the Cartographic Institute of Catalonia. High mountain lakes have been added to this mask depending if they are covered by snow or they are frozen at a certain altitude.

2) STEP 2: NODATA CLASSIFICATION

a) *NODATA snow cover*: As we have been explained in the image processing section (III.A.2), during the radiometric correction several zones have been flagged as NODATA. Depending on the date and the hour of the image acquisition and the relief of the study area, NODATA areas can represent an important loss of information. As a result, in these cases, we cannot apply the NDSI methodology in a significant part of the image and, therefore, we cannot map snow cover. In order to solve this problem, we use the non-radiometric corrected images applying a specific methodology only for NODATA areas.

This process follows three steps:

- The first step consists in obtaining the NODATA areas from the radiometrically corrected images, generating a NODATA mask which is then overlaid to the non-radiometrically corrected images. As a result, the new images only have values in the NODATA zones and the rest of the image values are equal to NODATA.
- The second step consists in applying the pre-boundary snow mask and the water bodies mask in the first step images.
- The last step consists in a hybrid classification based on an ISODATA algorithm of the areas obtained in the second step using two groups of input variables. The first group corresponds to topographical GIS variables which include altitude obtained from a Digital Elevation Model (DEM) and instantaneous radiation based on the methodology proposed by Pons [13]. The second group corresponds to the remote sensing data which include the seven non-radiometrically corrected Landsat bands and the NDSI computed with these bands. The ISODATA computation has been carried

out using two tries. The first try combines the topographical GIS variables with the remote sensing data, and the second try only combines remote sensing variables. Lastly, we have reclassified the snow clusters to obtain a binary map.

Finally, the snow cover map is obtained adding the snow cover map obtained in step 1 and the one obtained in step 2.

In order to map snow with MODIS images we have followed the methodology of [12 and 14] applied to the generation of the MODIS snow product. It is observed that the first group of criteria suggested by these same authors does a selection of correct snow in areas of scarce or null vegetation. The main problem arises with the second group of criteria, destined to discern the presence of snow in areas of dense vegetation. More precisely, the main filter of the second group of criteria is the generation of a dispersion diagram between the indexes NDSI and NDVI. The suggested thresholds generate important errors of commission in covers of dense vegetation.

Moreover, we propose to generate NDSI with calibrated radiances and a $NDSI > 0.3$ and $NDSI > 0.4$ thresholds.

At this point, the snow cover maps obtained with MODIS daily product and calibrated radiances are then tested with the one obtained with Landsat.

IV. RESULTS

A. Landsat TM and ETM+ data results.

We have obtained good results using the methodology described in the previous section (step 1).

Obtained results with winter and spring images show that the use of pre-boundary mask resolves commission of isolate pixels which belong to other covers, as well as, using the water bodies mask diminish the error of selecting water as snow. Furthermore, it has to take into account that using the NDSI threshold > 0.4 gives good results in both seasons.

Obtained results applying the NODATA classification methodology (step 2) show better results using ISODATA algorithm. In the first try, we have obtained good results in the axial zone. The results in basal zone are not optimal because commission errors are generated due to the altitudinal effect. In the second try, we have only used remote sensing data as an input for the ISODATA classification, generating about 6-12 spectral clusters, including pure snow clusters and mixed forest-snow clusters.

Table 1 shows the comparison between the different methodologies of snow cover mapping. The obtained areas without taking into account the NODATA areas are considerably smaller than those that consider the areas NODATA (columns 3 and 2, respectively). This difference is greater in winter images. Moreover, it is interesting to note that not taking into account NODATA areas between 25% and 45% of surface covered of snow is missed. However, in spring this percentage ranges between 5% and 10%.

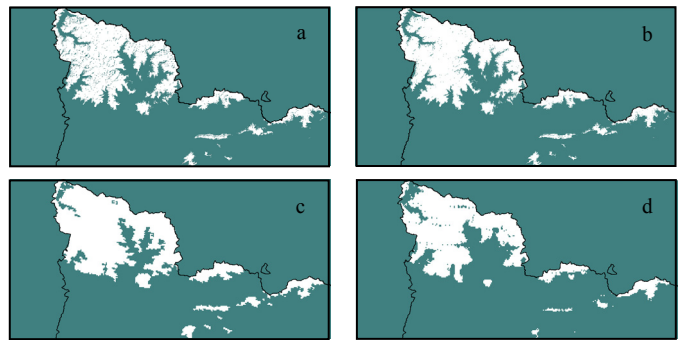


Figure 1. Snow cover maps obtained with all methodologies, date 17/04/2005. (1.a). Using Landsat images only taking in to account radiometrically corrected images (1.b) Using Landsat images taking in to account radiometrically corrected images and NODATA area. (1.c) Using MODIS daily snow product after applying the masks. (1.d) Using MODIS $NDSI > 0.3$.

B. TERRA-MODIS results

Comparing Landsat and MODIS snow cover, we can observed pixels classified as snow in areas where there is no snow, as in the area of *Cap de Creus* or in the *Serra de Collserola* adjacent to the city of Barcelona. Furthermore, in these images important errors of commission take place in areas of dense vegetation, as well as, in some areas with presence of continental water and in areas with hard orographic shadows. Even so, these effects vary according to the season of the year, observing better results in spring, summer and fall, and worse in winter.

To solve the commission errors in daily snow products we propose to use the same preboundary mask generated to obtain the snow cover with the Landsat images. The result can be observed in the figure 1c.

Generating the NDSI index with calibrated radiances and selecting values > 0.4 , snow cover is discriminated without any problem in areas without vegetation, especially highest zones of the Pyrenees range. However, in lowest zones of the alpine range with an important presence of woodland the spectral answer of snow decreases, because the confusion with the dense forest cover is important. This issue can be solved, decreasing the threshold of the NDSI up to 0.3, and incorporating the preboundary mask like in the case of Landsat images. The result can be observed in the figure 1d.

If we compare MODIS snow covered areas (see table 1) it is observed that using the snow product with the preboundary mask greater areas are obtained than in the case of the calculation of the NDSI (columns 4 and 5 respectively). This is due to last method omission errors take place in the lowest parts of the alpine range.

C. Comparison of Landsat and MODIS

Although the obtained areas are not completely comparable due to their different spatial resolution, in the case of the MODIS snow product the snow cover is higher than the obtained in the case of Landsat, not only due to the difference of size of the pixel but also because errors of commission of dense forest surface are committed.

TABLE I. SNOW COVERED AREAS OBTAINED BY DIFFERENT METHODOLOGIES

Date	LANDSAT without NODATA (ha)	LANDSAT with NODATA (ha)	MODIS snow product (ha)	NDSI MODIS (ha)
14/01/2003	181683.5	243227.7	330925.0	229020.7
19/03/2003	153641.0	170441.8	186225.0	134705.6
10/02/2003	94978.6	136837.8	192025.0	110062.6
08/11/2004	35290.9	63800.0	81725.0	62742.0
11/01/2005	62262.1	104253.2	150300.0	122200.0
19/03/2005	141894.6	182494.6	110350.0	116325.0
17/04/2005	182495.6	188435.2	215025.0	174526.6

V. CONCLUSION

The present study shows optimal results using Landsat images to obtain an accurate snow maps at a semi detail scale of Catalonia. The developed methodology minimizes commission errors of other covers and the confusion with the water bodies, using a cloud mask, a water bodies mask and preboundary mask. However, the good results obtained depend on the correct elaboration of these masks. Likewise, good results are also obtained with the method used for the discrimination of snow in the NODATA areas.

Using the daily snow product of TERRA-MODIS without any improvement can involve important errors in snow cover determination. Nevertheless, using the boundary mask allows approaching the results to those obtained with Landsat. It should be noted, however, that this alternative is not valid if there are not simultaneously Landsat images.

We have obtained similar snow cover areas in Landsat and MODIS case in the axial Pyrenees, where the biggest snow thickness is found and the snow surface is more continuous. However, the main difference between Landsat and MODIS snow cover retrieval occurs in the low altitudes where there is less snow and is mixed with the forest cover.

Although best results are obtained using Landsat images, we have to note that MODIS products can be adapted at a local scale, through a series of filters, and can be used when Landsat images are not available, and, therefore, this fact makes the use of both sensors for snow cover mapping at a regional scale complementary.

ACKNOWLEDGMENTS

It would not have been possible to carry out this study without the financial assistance of the Ministry of Science and Technology and the FEDER funds through the research project: "Compression and interactive transmission of high resolution images. Remote Sensing and Geographical Information Systems applications" (TSI2006-14005-C02-02). We would like to express our gratitude to the Catalan Water

Agency and to the Department of the Environment and Housing of the Generalitat (Autonomous Government) of Catalonia for their investment policy and the availability of Remote Sensing data, which has made it possible to conduct this study under optimal conditions. We would also like to thank our colleagues of the Department of Geography, CREAM and the CCD of the UAB who have collaborated in any way in the treatment of the images, and INTA for its efficient image subscription service.

REFERENCES

- [1] P. S. A. Beck, E. Kalmbach, D. Joly, A. Stien, L. Nilsen, "Modelling local distribution of an Arctic dwarf shrub indicates an important role for remote sensing of snow cover," *Remote Sensing of Environment*, vol 98, 1, pp. 110-121, 2005.
- [2] J. Dozier, "Spectral Signature of Alpine Snow Cover from the Landsat Thematic Mapper," *Remote Sensing of Environment*, vol 28, pp. 9-22, 1989.
- [3] J. Dozier, "Remote sensing of alpine snow cover invisible and near-infrared wavelengths," <http://www.avalanche.org/~moonstone/1991%20cssa%20symposium/R-EMOTE%20SENSING%20OF%20ALPINE%20SNOW%20COVER.htm>, 1991 [visited 28-11-2002].
- [4] V. Palà and X. Pons, "Incorporation of relief into geometric corrections based on polynomials," *Photogramm. Eng. Remote Sens.*, vol 61, pp. 935-944, 1995.
- [5] X. Pons and L. Solé-Sugrañes, "A Simple Radiometric Correction Model to Improve Automatic Mapping of Vegetation from Multispectral Satellite Data," *Remote Sensing of Environment*, vol. 47, pp. 1-14. 1994
- [6] J. Cristóbal, X. Pons and P. Serra, "Sobre el uso operativo de Landsat-7 ETM+ en Europa. X Congreso de Teledetección," *Revista de Teledetección*, vol. 21, pp. 55-59, 2004.
- [7] B. L. Markham, and J.L. Baker, "Thematic Mapper bandpass solar exoatmospheric irradiance," *Int. J. Remote Sensing*, vol. 8, pp.517-523. 1987.
- [8] R. Irish, "Landsat 7 Science Data Users Handbook," NASA. http://ftpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html. 2007 [visited 25-04-2007].
- [9] C. Cea, J. Cristóbal, P. Serra. and X. Pons, "Mejoras en la detección semiautomática de nubes y sombras en imágenes Landsat," in XI Congreso Nacional de Teledetección, Puerto de la Cruz. Tenerife. 2005
- [10] X. Pons. "MiraMon. Sistema d'Informació Geogràfica i software de Teledetecció," Centre de Recerca Ecològica i Aplicacions Forestals, CREAM. Bellaterra. ISBN: 84-931323-4-9. 2004.
- [11] W. Yang and L. Di, "An accurate and automated approach to georectification of HDF-EOS swath data," *Photogramm. Eng. Remote Sens.*, 70, pp 397-404. 2004
- [12] G.A. Riggs, D.K Hall and V.V.Salomon, "MODIS Snow Products User Guide for Collection 4 Data Product," 2003
- [13] X. Pons, "Estimación de la Radiación Solar a partir de modelos digitales de elevaciones. Propuesta metodológica," In J., Juaristi and I. Moro (Eds.), VII Coloquio de Geografía Cuantitativa, Sistemas de Información Geográfica y Teledetección. Vitoria-Gasteiz. 1996
- [14] Klein, A.G.; Hall, D.K; Riggs, G.A., "Improving snow-cover mapping in forests through the use of a canopy reflectance model," http://geog.tamu.edu/klein/publications/papers/agk_p9.pdf, 2005.