A snow cover climatology for the Pyrenees from MODIS snow products

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Abstract. The seasonal snow in the Pyrenees is critical for hydropower production, crop irrigation and tourism in France, Spain and Andorra. Complementary to in situ observations, satellite remote sensing is useful to monitor the effect of climate on the snow dynamics. The MODIS daily snow products (Terra/MOD10A1 and Aqua/MYD10A1) are widely used to generate snow cover climatologies, yet it is preferable to assess their accuracies prior to their use. Here, we use both in situ snow observations and remote sensing data to evaluate the MODIS snow products in the Pyrenees. First, we compare the MODIS products to in situ snow depth (SD) and snow water equivalent (SWE) measurements. We estimate the values of the SWE and SD best detection thresholds to 40 mm water equivalent (w.e.) and 150 mm, respectively, for both MOD10A1 and MYD10A1. κ coefficients are within 0.74 and 0.92 depending on the product and the variable for these thresholds. However, we also find a seasonal trend in the optimal SWE and SD thresholds, reflecting the hysteresis in the relationship between the depth of the snowpack (or SWE) and its extent within a MODIS pixel. Then, a set of Landsat images is used to validate MOD10A1 and MYD10A1 for 157 dates between 2002 and 2010. The resulting accuracies are 97% (κ = 0.85) for MOD10A1 and 96% (κ = 0.81) for MYD10A1, which indicates a good agreement between both data sets. The effect of vegetation on the results is analyzed by filtering the forested areas using a land cover map. As expected, the accuracies decrease over the forests but the agreement remains acceptable (MOD10A1: 96%, κ = 0.77; MYD10A1: 95%, κ = 0.67). We conclude that MODIS snow products have a sufficient accuracy for hydroclimate studies at the scale of the Pyrenees range. Using a gap-filling algorithm we generate a consistent snow cover climatology, which allows us to compute the mean monthly snow cover duration per elevation band and aspect classes. There is snow on the ground at least 50% of the time above 1600 m between December and April. We finally analyze the snow patterns for the atypical winter 2011–2012. Snow cover duration anomalies reveal a deficient snowpack on the Spanish side of the Pyrenees, which seems to have caused a drop in the national hydropower production.

1 Introduction

The Pyrenees mountain range is located in southwest Europe at the northern edge of the Iberian peninsula (43° N, maximum elevation 3404 m a.s.l.; Fig. 1). Because of the large amount of precipitation it receives, the Pyrenees range is the water tower for a region covering northern Spain, Andorra and south France. The headwaters of three major rivers in southwest Europe, namely the Ebro, the Garonne and the Adour rivers are located in the Pyrenees mountains. These rivers and their tributaries provide critical water resources for various economic activities, including hydropower generation and crop production in the irrigated lowlands.

As most of the winter precipitation falls as snow in the Pyrenees, the snowmelt is an important contributor to the river flow and shapes the hydrographs of the Pyrenean rivers (Lopez-Moreno and Garcia-Ruiz, 2004; Bejarano et al., 2010). Spring snowmelt is extensively used in downstream areas for crop irrigation during the growing season. Snowmelt is also stored in the many reservoirs located on
the Pyrenean foothills. The main functions of these reservoirs are to supply runoff for irrigation in summer and to produce hydropower. For example, in the Ebro Basin there are 299 operating dams, according to the governmental inventory (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2011). The unofficial inventory from the Spanish association of dams and reservoirs (Sociedad Española de Presas y Embalses, 2008) indicates that at least one-fourth of the dams in the Ebro Basin are used for irrigation and two-thirds for hydropower generation (other uses include river regulation, aquafarming, water supply to urban and industrial areas, etc.). In addition, many hydroelectric plants in the Pyrenees also work without the use of a dam (run-of-the-river hydroelectricity). As a result, 33% of the hydroelectricity power plants in Spain are located in the Ebro Basin, most of them being connected to the Pyrenean rivers (Fig. 2). The potential hydropower of the Ebro Basin represents 19.5% of the total potential hydropower in Spain (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2011). In France, the Pyrenean rivers are also highly exploited for irrigation and hydroelectricity (Fig. 2). The Garonne River is known as the only large watershed in France where a structural imbalance between water resources, the needs of different users and aquatic environments is officially recognized (Dupeyrat et al., 2008). The rising pressure on the water resources in the Ebro Basin is also an important concern (Milano et al., 2013).

Apart from these hydrological services, the snow cover is also critical for the tourism sector in the Pyrenees. In particular, ski resorts are an important source of income and local employment (Rived et al., 2013).

Given the importance of the snow cover in the Pyrenees, it is necessary to monitor its evolution. The snow depth is recorded daily at 19 stations at least across the whole Pyrenees mountain range. Some stations were already installed in the 1980s but most of the data are available since the 2000s. Yet, these ground measurements are essential but insufficient to describe the snow cover dynamics in the various topographic and climatic contexts of the Pyrenees mountain range. On the other hand, remote sensing data are spatially consistent and therefore can be very useful to complement in situ measurements.

Since the early 1980s, it has been shown that space-borne sensors operating in the visible and near-infrared region of the electromagnetic spectrum are very effective to map snow cover (Bowley et al., 1981; Dozier and Marks, 1987; Baumgartner et al., 1987). As of today, only low- to mid-resolution sensors such as AVHRR, PROBA-V or MODIS allow for global observations of the snow cover at a daily time step (without cloud obscuration) with a spatial resolution of 1 km to 250 m. Higher-resolution snow cover maps (30 m) are typically extracted from the Landsat program images, but they provide data at a lower frequency (16 days), which is generally inappropriate to monitor the snow cover as large snow area variations can occur within a few days during the melt season (Rango, 1993; Gómez-Landesa and Rango, 2002).

A suite of snow products were derived from Aqua and Terra MODIS data and released in 2000 (Hall et al., 2002). The MODIS snow products are now widely used for hydroclimate applications in snow dominated regions. These products were generated using the SNOMAP algorithm, which primarily relies on the normalized difference snow index (NDSI). The normalized difference vegetation index (NDVI) is also used to improve snow detection in forested areas (Klein et al., 1998). There are differences between Aqua
Table 1. Description of the in situ snow data used in this study. Stations 1–11 are telenivometers from the ERHIN program for which daily data of snow depth and snow water equivalent were available. Stations 12–19 are Météo-France stations for which daily data of snow depth only were available. Longitude and latitude are given in decimal degrees (WGS84) and elevation in meters a.s.l.

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Elevation</th>
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<tr>
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<td>42.82</td>
<td>827</td>
<td>Jan 2000–Dec 2010</td>
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freely accessible, which enables one to generate many snow maps over a large area for various periods of the year. This allows assessing MODIS snow products for varying snow conditions (e.g., fresh snow in winter, ripe snow in spring). Recently, Rittger et al. (2013) have taken advantage of this exceptional archive to validate the MODIS snow products. They found large errors during the snowmelt period and in forest areas and conclude that MODIS snow products still require to be used with caution.

The main objectives of this study are twofold.

- First, we aim to evaluate the value of the MOD10A1 snow product to generate a daily snow cover climatology in the Pyrenees for the period 2000–2013.

- Second, we use this new data set to characterize the variability of the snow cover in the Pyrenees.

The first objective is a necessary step even though many studies have already assessed the MODIS snow products accuracy in other mountainous regions. Indeed, continuing validation is important to make the information reliable, since the combination of topography, land cover and climate varies from one region to another (Rittger et al., 2013). In our case, the Pyrenees present a large physiographic variability in a rather small area and is under the influences of both Mediterranean and North Atlantic climates. Moreover, this assessment is important because the MODIS snow products are getting more and more attention from the regional agencies in charge of the water and tourism management in the Pyrenees (Parra et al., 2006). In particular, an important question for the water practitioners is the effective snow detection threshold, i.e., the value of the snow water equivalent or snow depth for which a pixel is statistically marked as snow-covered in a MODIS product.

We used both in situ and remote sensing data to assess both Aqua and Terra MODIS daily snow cover binary products (snow/no snow) in the Pyrenees. For the first time, we assembled a French–Spanish data set of continuous snow measurements from the Ebro Basin agency in Spain and Météo-France. This data set was used to validate the MODIS snow products and to determine the optimal snow detection threshold. Then, Landsat scenes over the Pyrenees corresponding to 157 dates between 2002 and 2010 were processed to generate an independent snow cover product. We did not focus on the discrepancies between the MODIS products and the Landsat or station data on specific dates or regions. We rather aimed at characterizing the range of uncertainties at the scale of the Pyrenees mountain range and across the snow season.

For the second objective, we implemented a gap-filling algorithm based on previous studies to generate a gap-free snow cover climatology from February 2000 to July 2013. This allows us to characterize the variability of the snow cover duration at the scale of the whole Pyrenees and its relationship with the topography. We show an application of this climatology to characterize the anomalous snow cover patterns during the 2011–2012 winter, which was particularly dry in the southern Pyrenees (San Ambrosio et al., 2013).

2 Data and methods

2.1 Data

2.1.1 In situ data

We assembled two important data sets of in situ snowpack monitoring in the Pyrenees (Table 1). Météo-France provided the snow depth observations at eight stations in the French Pyrenees from January 2000 to December 2010. The snow depth was recorded daily at 06:00 UTC with a 1 cm resolution. The Ebro Basin agency (Confederación Hidrográfica del Ebro) provided the snow depth and snow water equivalent data from 11 telenivometers in the Spanish Pyrenees managed as part of the ERHIN program (Evaluación de los Recursos Hídricos procedentes de la Inivación; study of winter water resources) (Parra et al., 2006). Each telenivometer is equipped with an acoustic snow gauge and a cosmic ray detector for snow water equivalent sensing (Paquet and Laval, 2006). The snow season is generally shorter at Météo-France stations (e.g., Aulus-Les-Bains, Bagneres-de-Luchon, St-Lary-Soul) because they are located at lower elevations than the telenivometers (Table 1).

2.1.2 Landsat

We used the data acquired by Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+). The data were collected from the United States Geological Survey (USGS) and the European Space Agency (ESA). The Landsat scenes spanning the Pyrenees are numbered 200-030 to 197-030 in the Worldwide Reference System 2 (eastward). There are 157 dates in our data set distributed between January 2002 and December 2010 for which at least one of these Landsat scenes is available.

2.1.3 MODIS snow products

MOD10A1 (Terra) and MYD10A1 (Aqua) snow products version 5 were downloaded from the National Snow and Ice Data Center (Hall et al., 2006, 2007) for the period 1 September 2000–2 July 2013. This corresponds to 4688 dates among which 4625 dates are available for MOD10A1 (98.7 %) and 3996 dates for MYD10A1 (85.4 %) since Aqua was launched in May 2002 and operational in July 2002. From this archive, 157 MOD10A1 were available on the same day as the Landsat data set for MOD10A1 and 139 dates for MYD10A1.

We also downloaded the MOD10A2 product, which provides the maximum snow extent from MOD10A1 over a compositing period of 8 days on the same grid.
2.1.4 Land cover

We used the Corine land cover 2000 raster data version 15 that covers both France and Spain. It is considered as reference data for land cover mapping at the Europe scale (Bossard et al., 2000). The Corine land cover was used to produce a map of forested areas by aggregation of the broad-leaved forest, coniferous forest, and mixed forest classes (63 % of the study area).

2.2 Methods

2.2.1 In situ data processing

Some snow depth or snow water equivalent values from the telemeter data set were negative in summer, probably because of a drift in the sensors’ calibration factors. These negative values were set to zero. Otherwise the data were not filtered or corrected.

2.2.2 Landsat processing

The processing of a large number of Landsat images is only feasible with an automatic cloud detection algorithm because the cloud mask is not provided with the Landsat data. Here we applied a cloud detection algorithm developed for high-resolution multispectral images from Landsat, Venµs and Sentinel-2 (Hagolle et al., 2010).

The Landsat data were processed as follows.

- Orthorectification: Landsat data available from USGS are already orthorectified. Hence, ESA data were orthorectified using USGS data as a reference following the orthorectification methodology of the Centre National d’Études Spatiales (Baillarin et al., 2004). All images were projected to Lambert-93. The superposition errors were 0.2–0.8 pixels for USGS data and 0.3–0.9 for ESA data depending on cloud coverage.

- Radiometric calibration for both data sets was made following Chander et al. (2009). The radiometric accuracy is not critical for this application.

- The scenes were assembled and resampled to a 240 m resolution.

- The cloud mask and cloud shadows mask were retrieved based on the detection of abrupt changes in the reflectance time series for every pixel (multitemporal algorithm; Hagolle et al., 2010).

- An external mask of water bodies was applied (SRTM water body data).

- The snow cover was detected based on the NDSI and the reflectance in the green and SWIR (shortwave infrared) channels (Dozier, 1989). The NDSI was defined as

\[
\text{NDSI} = \frac{\rho_{\text{green}} - \rho_{\text{SWIR}}}{\rho_{\text{green}} + \rho_{\text{SWIR}}}
\]

where \(\rho_{\text{green}}\) (resp. \(\rho_{\text{SWIR}}\)) is the top of atmosphere reflectance in the Landsat green channel (respectively, shortwave infrared at 1.6 µm). A pixel is flagged as snow if the three following conditions are fulfilled:

a. \(\text{NDSI} > 0.4\)

b. \(\rho_{\text{red}} > 0.12\)

c. \(\rho_{\text{SWIR}} < 0.16\).

These criteria were applied on reflectance corrected for a first-order slope effect (cosine correction; Meyer et al., 1993). If a group of adjacent pixels was detected as snow but entirely surrounded by cloud-covered pixels, then these pixels were flagged as cloud, otherwise thick cold clouds may be detected as snow. The mask generated with these criteria was dilated with a circular radius of three pixels to improve the detection on the snow region boundaries, which have a smaller snow thickness and generally do not fulfill all the three previous conditions. These steps and the red and SWIR reflectance thresholds were adjusted from the original formulation (Dozier, 1989) based on a visual inspection of the full-resolution images over the study area.

2.2.3 MODIS snow products processing

We extracted the “Snow Cover Daily Tile” field from MOD10A1 and MYD10A1, which includes the snow/no-snow and cloud masks. Our zone intersects the MODIS sinusoid grid tiles h17v04 and h18v04. The grids were assembled and reprojected with the nearest-neighbor method in Lambert-93 over a region of interest covering the Pyrenees using the MODIS reprojection tool (extent given in Fig. 1).

The different classes in the original product were merged into three classes: no-snow (no snow or lake), snow (snow or lake ice), no-data (clouds, missing data, no decision, saturated detector). The MODIS snow masks corresponding to the Landsat dates were also resampled to a 240 m resolution in order to match our Landsat snow mask spatial resolution.

In a second phase of this work we implemented a gap-filling algorithm to interpolate virtually all the missing values from 1 September 2000 to 1 July 2013. The algorithm was derived from Parajka and Blöschl (2008) and Gafurov and Bárdossy (2009). It works in four sequential steps.

1. Aqua/Terra combination: for every pixel if no-data was found in MOD10A1 then the value from MYD10A1 was taken. Otherwise, the value in MOD10A1 was kept. The priority was given to MOD10A1 because we found that MYD10A1 is less accurate (see Sect. 3).

2. Adjacent spatial deduction: each no-data pixel was reclassified as snow (no-snow) if at least five of the eight adjacent pixels were classified as snow (no-snow).

3. Adjacent temporal deduction: a no-data pixel was reclassified as snow (no-snow) if the same pixel was clas-
Table 2. Confusion matrices between the MODIS snow products and in situ data. The numbers correspond to percentages with respect to the number of in situ measurements. The comparison was performed both for snow water equivalent (SWE) and snow depth (SD) measurements. The detection thresholds were set to SWE_0 = 40 mm w.e. for SWE and SD_0 = 150 mm for SD. These thresholds yielded the best \( \kappa \) coefficients.

<table>
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<th>MOD10A1</th>
<th>MYD10A1</th>
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<tbody>
<tr>
<td></td>
<td>no-snow</td>
<td>snow</td>
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<tr>
<td><strong>Telenivometers</strong></td>
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<tr>
<td>SWE &lt; SWE_0</td>
<td>97</td>
<td>2.7</td>
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<tr>
<td>SWE &gt; SWE_0</td>
<td>2.2</td>
<td>98</td>
</tr>
<tr>
<td>SD &lt; SD_0</td>
<td>96</td>
<td>4.2</td>
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<tr>
<td>SD &gt; SD_0</td>
<td>4.1</td>
<td>96</td>
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<td><strong>All stations</strong></td>
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<td>SD &lt; SD_0</td>
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<td>8.1</td>
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<tr>
<td>SD &gt; SD_0</td>
<td>13</td>
<td>87</td>
</tr>
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</table>

4. The sparse remaining no-data pixels were reclassified using a classification tree (Matlab Statistics Toolbox; Breiman et al., 1984). For each date, the snow and no-snow pixels were used to fit a classification tree on four predicting variables derived from the geographic position and the topography. The variables were pixel elevation, aspect, easting and northing (i.e., \( x \) and \( y \) coordinates in Lambert-93). The tree was used to predict the class of the no-data pixels for this date.

The gap-filled pixels were flagged in the final product to maintain a record of the original data.

2.2.4 Comparison

We computed the confusion matrices between the MODIS product snow/no-snow classification and both reference data sets (i.e., in situ data or Landsat data), which were considered as the truth. Based on these results we computed the overall accuracy, precision and the kappa coefficient (noted \( \kappa \); Cohen, 1960). The overall accuracy (AC) is the proportion of the total number of predictions that were correct (i.e., snow or no-snow). The precision (\( P \)) is the proportion of the predicted snow presences that were correct. In the analysis, we mainly used the \( \kappa \) coefficient because this statistic incorporates both information on agreement and disagreement between the MODIS products and the validation data (Klein and Barnett, 2003). For in situ data, the comparison was performed both for snow water equivalent (SWE) and snow depth (SD) measurements.

1. In situ data: the MODIS product snow presence/absence was extracted at each station. For each date, a pixel was considered to be correctly classified as snow if the snow depth value on the same day (or the SWE value) is higher than a threshold value noted SD_0 (or SWE_0).

We tested 40 logarithmically spaced values between 0 and 8 m for SD_0 and 0 and 3 m w.e. (water equivalent) for SWE_0. The same method was applied to the SWE data from the telenivometers, the SD data from the telenivometers alone and the SD data from all stations.

2. Landsat data: every pair of MODIS and Landsat snow masks obtained on the same day was compared on a pixel basis. The comparison was made only for the pixels which were not masked by the union of MODIS and Landsat cloud masks (i.e., where snow or no snow detection was possible for both data sets). For MOD10A1, a total of \( 14.7 \times 10^6 \) pixels were compared.

Figure 3. Time series of in situ data and MODIS data at Ordiceto station. The black dots are the daily snow depth (SD) and snow water equivalent (SWE) measurements. The color bars in the background indicate the snow presence (blue), absence (green) and no data (white) from MOD10A1.
Table 3. Statistical measures of the comparison between the MODIS product and in situ data, computed from the results presented in Table 2 (N: sample size, A: overall accuracy, κ: kappa coefficient).

<table>
<thead>
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<th>MOD10A1</th>
<th>MYD10A1</th>
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<td>Telenivometers</td>
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<td>SD (10^3)</td>
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<tr>
<td>A</td>
<td>0.96</td>
</tr>
<tr>
<td>κ</td>
<td>0.92</td>
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Figure 4. Comparison of MODIS products with in situ data. Each graph shows the variation of the statistical agreement between both data sets with the snow detection threshold. Left: the detection threshold is in SWE and evaluated with measurements from the telenivometers. Right: the detection threshold is in SD evaluated with all available stations (telenivometer and Météo-France). AC: overall accuracy, TP: true positive, FP: false positive, TN: true negative, FP: false positive, P: precision, κ: kappa coefficient.

with the Landsat snow masks, among which 13.4% were classified as snow in the Landsat data.

The gap-filled product was also evaluated by comparison with the in situ data. The comparison with Landsat was not performed because most of the no-data pixels are due to cloud cover, which also obstructed the Landsat image on the same day. However, we compared our gap-filled product with the 8-day composite product MOD10A2, which is often used in hydrometeorological studies.

3 Results

3.1 In situ data vs. MODIS products

A first visual inspection of the time series suggests that there is a good agreement between in situ observations and the MODIS product, as shown here in the case of Ordiceto station only (Fig. 3).

From these data an optimal SWE detection threshold is found between 20 and 60 mm w.e. (top row in Fig. 4). For SD, the range of optimal values is narrower between 100 and 120 mm (middle and bottom rows in Fig. 4). The optimum is nearly identical for MYD10A1 but the agreement is a bit lower than for MOD10A1 as indicated by the κ curve. In what follows, we have set SWE₀ = 40 mm w.e. and SD₀ = 150 mm (Table 2). The resulting confusion matrices (Table 2) and statistical measures (Table 3) further indicate that an excellent agreement is found between the SWE data and MOD10A1 (κ = 0.95), but the agreement decreases if MYD10A1 is considered. Another result is that the classification accuracy is higher with the SWE variable than with the SD variable for the same stations (Table 2). The agreement between MODIS and in situ data significantly decreases when considering SD for all available stations (Table 3). In any case, however, the agreement remains acceptable since the lowest κ is 0.74.

The seasonal differences in the detection threshold were further analyzed based on the SD data from the telenivometers and MOD10A1 (Fig. 5). The results show that there is a trend in the optimal SD value (Pearson’s correlation R = 0.90, p = 0.002). The maximum κ are found for smaller snow depth in the early snow season than in the late season. Similar results were obtained with the SWE, but the relationship was slightly less significant (R = 0.86, p = 0.007).

3.2 Landsat vs. MODIS products

The results show that 81.5% of the Landsat snow-covered pixels are correctly classified in MOD10A1 (Table 4). For
data sets (MOD10A1 coefficients indicate a good agreement for both MODIS
and Landsat). Yet, the false negative rate is close to 18 % (Table 4). Yet, the
snow detection is not significantly deteriorated by the snow proper-
ties (e.g., lower reflectance of ripe snow cover in late spring). For both MOD10A1 and MYD10A1, there is a lower agreement with Landsat when the comparison is made only over the forested areas (Table 5). However, the loss of accuracy is higher for MYD10A1. This is consistent with the previous studies (Sect. 1). In particular, the proportion of correctly classified snow pixels drops by 9.5 % (from 81.6 to 72.1 %) in forested areas, whereas it drops by 4.1 % for MOD10A1 (from 81.5 to 77.4 %).

3.3 Gap filling

A virtually gap-free snow cover product with a daily time step from 1 September 2000 to 1 July 2013 was generated from MOD10A1 and MYD10A1. The gap-filling reduced the fraction of no-data pixels from 49 to 0.38 % (Fig. 7). The fraction of no-data decreased by a factor of about 10–20 % at every iteration from the previous stage, except for the spatial deduction step, which had a low effect, and the classification tree, which reduced drastically the no-data fraction by 90 %. The classification tree allowed for a complete removal of the no-data values for all the dates in which some no-data pixels remained after the previous steps. The 0.38 % missing values correspond to the 17-day gap in June 2001 for which the classification tree was not applicable.

We found a substantial agreement between this gap-filled product and all in situ snow depth data. The $\kappa$ coefficient ($\kappa = 0.75$, $N = 27 684$) is a bit lower than the one obtained with MOD10A1 ($\kappa = 0.79$, Table 3) but nearly equal to the one obtained with MYD10A1 ($\kappa = 0.74$).

The total snow cover area from the gap-filled product was also controlled using MOD10A2 (Fig. 8). As an example, we show the hydrological year 2005–2006 to illustrate how the gap-filling made substantial changes to the initial data and
Figure 6. Snow coverage calculated from Landsat and MODIS snow products (Terra MOD10A1, Aqua MYD10A1) for 157 dates (139 dates for MYD10A1) distributed between 2002 and 2010 over the Pyrenees. The color indicates the month of the year. The snow coverage is defined as the fraction of the cloud-free area which is covered by snow in the study area (Fig. 1). For each date, the cloud-free area is defined as the intersection of the cloud-free areas in Landsat and MODIS products.

Figure 7. Evolution of the number of pixels classified as no-data (e.g., clouds) during the gap-filling procedure.

how it revealed the shape of a typical snow depletion curve during the melt season. Similar results were obtained for the other years.

4 Discussion

4.1 In situ data vs. MODIS products

For the validation with in situ data, it was useful to merge the Ebro Basin and Météo-France databases because it enabled expanding the range in station elevation and thus to obtain a more robust conclusion. $\kappa$ coefficients are within 0.74 and 0.92 depending on the product and the variable, but the highest accuracy was obtained between MOD10A1 (Terra) and the SWE measurements. As expected, the agreement was a bit lower when considering MYD10A1 (Aqua). The inclusion of Météo-France measurements resulted in a significant decrease of the agreement (Table 3). These stations have a lower mean elevation (Table 1) than the Ebro Basin telenivometers; hence, the snow cover is more discontinuous or “patchy” in their vicinity. For example, three stations from the Météo-France data set are located in valley bottoms (near hydroelectricity plants); hence, their spatial representativeness at the scale of the MODIS product pixel (about 500 m) is limited.
Figure 9. Comparison between MOD10A1 and Landsat for two dates. Left column: MOD10A1 vs. Landsat classification (TP: true positive, FP: false positive, TN: true negative, FN: false negative). MOD10A1 false negative areas are mainly located along the snow cover edges. Middle column: Landsat and MOD10A1 classifications used for the comparison. Right column: location of the input swath granules (MOD10_L2 product) used to generate the MOD10A1 tiles (sinusoidal map projection). The MOD10A1 snow mask is distorted on 19 March 2009 because it was constructed from the border areas of two input granules where the bow-tie effect is most pronounced.

In spite of these variations we could identify consistent detection thresholds in SD and SWE (Table 4, Fig. 4). However, a clear seasonal trend was detected in the optimal SD and SWE detection threshold (see Fig. 5 for the case of the SD). This result is interesting because it reflects the hysteresis in the relationship between the amount of snow on the ground and its extent, which was often observed in alpine catchments (e.g., Magand et al., 2014). Small snow depths can cover large areas during the accumulation period. However, the spatial variability of the snow depth increases over the snow season due to ablation and redistribution processes. As a consequence, the minimum snow depth value to cover a MODIS pixel increases over the snow season.

4.2 Landsat vs. MODIS products

Regarding the comparison with Landsat, we also obtained a good agreement, but a manual screening of the comparison maps revealed that a large fraction of the misdetections was located along the snow cover edges, in agreement with previous studies in alpine and arctic regions (Déry et al., 2005; Rittger et al., 2013). An example is shown in Fig. 9. The snow commission in MODIS products can be due to the effect of forest obscuration (Parajka et al., 2012) because the lower boundary of the snow cover is often situated in forested areas in the Pyrenees. In this study we could detect a deleterious effect of the forests by comparing MODIS products with Landsat over forested areas. This method assumes that the Landsat snow detection was accurate enough to be considered as a ground truth. This assumption may not be always be valid, although the snow classification method for Landsat is well established. Indeed we could also observe snow commission errors in our Landsat snow maps data set along the snow cover edges. This may artificially increase the agreement with MODIS products. However, we consider that Landsat misclassifications are less frequent than MODIS.

Another possible cause for this error, which was not specifically investigated here, is the effect of the MODIS sensor view angle. This is illustrated by the image of 19 March 2009 in Fig. 9. On this day, the Pyrenees are on the edges of both input granules from the MOD10_L2 swath product (i.e., the input data used to generate the MOD10A1), where the MODIS instrument “bow-tie” effect is the most pronounced (Gómez-Landesa et al., 2004). This configuration causes a distortion of the gridded snow product MOD01A1 over the Pyrenees. The consequence is an increase of the false negative along the edges of the snow cover.

Lastly, another likely explanation is that the surface temperature screening in the snow mapping algorithm (Hall et al., 2001) is too strict so it eliminates true snow pixels in low elevation areas. The thermal threshold was discarded for the reprocessing of the collection 6 of MODIS snow products (Hall and Rigg, 2013); thus, we can expect some improve-
of both Mediterranean and oceanic climates (Fig. 10, bottom panel). The cloud cover probability decreases in summer but remains substantial throughout the year. The highest cloud probability is found in April. Unfortunately this one of the months when the snow cover monitoring is the most useful because it corresponds to the beginning or the middle of the snowmelt season. This is an issue especially if the MODIS products are to be used under real-time conditions for river flow forecasting.

5 Application of the snow cover data set

5.1 Spatiotemporal influences on the mean snow cover duration

The new gap-free snow cover data set was used to compute the mean monthly snow cover duration (SCD), i.e., the number of snow days in the Pyrenees. We represented here the mean SCD per elevation band to characterize the climatological influence of the elevation on the snow cover dynamics (Fig. 11). It shows that the number of snow days increases strongly from the 800–1600 m a.s.l. band to the 1600–2400 m a.s.l. band between November and April. This is consistent with López- Moreno and Vicente Serrano (2007), who report a 0 °C isotherm around 1600–1700 m a.s.l. in the Spanish Pyrenees for the same months. Over 2400 m a.s.l. the data indicate that the snowpack covers the surface virtually all the time between December and April. The melt

Figure 11. Mean snow cover duration in the Pyrenees over 2000–2013 for different elevation bands. The snow cover duration is the number of days with snow in our gap-filled product. It was computed with the same elevation bands as in Fig. 1, except for 3200–3400 m a.s.l. (only four pixels at the MODIS resolution). Otherwise the fractional areas of each elevation band in the study domain are 53 % (10–800), 31 % (800–1600), 13 % (1600–2400), and 2.5 % (2400–3200).

4.3 Gap filling

The cloud obscuration is an important drawback of snow products generated from remote sensing instruments operating in the visible–infrared wavelengths. Here we had to interpolate an important fraction of the pixels to produce a consistent snow cover data set (about 50 %; Fig. 7). Similar cloud cover was reported other studies. After combining Aqua and Terra snow products only 5.3 % of the cloud pixels were converted to snow pixels. However, this represents about the half of the total snow pixels in the final product. The largest reduction in cloud obscuration is obtained through the temporal filter for up to 5 days (Fig. 7), in agreement with previous studies (Parajka and Blöschl, 2008; Hall et al., 2010; Gao et al., 2011). Beyond 5 days a higher uncertainty in the snow maps is expected but it is a necessary tradeoff to further reduce the cloud obscuration in the Pyrenees. We examined the cloud cover in the original product to evaluate the spatial uncertainty due to the gap filling. We used MOD10A1 to map the probability of cloud occurrence in the study area over 2000–2013 (Fig. 10, top panel). The cloud probability in the Pyrenees is more important in the northwest because the prevailing westerlies bring moist air from the North Atlantic into the continent, whereas the southeastern Pyrenees are more influenced by the Mediterranean climate, with a lower nebulosity. The cloud cover map also reflects the rain-shadow effect due to the orographic lifting of the air masses coming from the Atlantic by the Cantabrian Mountains and the Pyrenees in the west coast of the Iberian Peninsula. The seasonal variability of the cloud cover also reflects the influence

Figure 10. (a) Fraction of cloud-covered pixels in MOD10A1 over 2000–2013. (b) Mean monthly cloud coverage from MOD10A1 in the study area.
Figure 12. Mean snow cover duration in the Pyrenees over 2000–2013 for the four main aspect classes (W: west-facing slopes, N: north-facing slopes, E: east-facing slopes, S: south-facing slopes). The snow cover duration was computed only for the area above 800 m a.s.l.

Figure 13. Illustration of the anomalous snow patterns in the Pyrenees during the 2012 winter. Top panel: mean snow cover duration (days) in January and February. Middle panel: snow cover duration in January and February 2012. Bottom panel: snow cover duration anomaly.
duction dropped in early 2012 in comparison with the mean value over 1995–2012 (Fig. 14). The annual production was also lower in spite of a recovery in April–May. At the national scale the total production was higher than the 1995–2012 average (all sources of energy included), which means that the energy demand was high. Hence, it is likely that the 2012 drop in hydropower production was caused by the 2012 winter drought in the Spanish Pyrenees, which we also observed in the snow cover data (Fig. 13). Further analysis is necessary to establish if and how the snow deficit contributed to this drop. The gross of the snowmelt generally occurs between April and July, but snow melting can be important throughout the winter in the lower elevation areas. It is also possible that hydroelectric dam managers reduced their hydropower production in anticipation to the coming deficit of snowmelt in winter.

6 Conclusions

We found an overall very good agreement between the MODIS Aqua/Terra products and two independent snow cover data sets generated from in situ (stations) and remote sensing observations (Landsat). Landsat data confirmed that the snow cover edges are prone to commission (snow not detected), particularly when the sensor view angle is large. Also, the uncertainties in the final snow product increases due to the interpolation of the cloud-covered pixels, particularly in the northwestern Pyrenees and during the winter and spring months.

In spite of these limitations the results of this study support the conclusion that the MODIS snow products provide valuable information on snow cover at the scale of the Pyrenees range.

Using all in situ data we could determine a statistically optimal detection threshold, i.e., the snow depth or snow water equivalent value from which it is very likely that a pixel is classified as snow-covered in MODIS products. We found that an acceptable SWE detection threshold is between 20 and 60 mm w.e. and a SD threshold between 100 and 120 mm for both MOD10A1 and MYD10A1. We recommend to consider these ranges of values to convert the snow depth simulated by a snowpack model into snow cover area at the MODIS resolution in the Pyrenees, e.g., for model validation or data assimilation.

The MODIS snow products should be used more carefully for hydrology because it is less accurate in the transition areas where the snowmelt is fast. However, they can provide meaningful insights for climatological studies provided that the missing values are interpolated. This is particularly revealing for a transboundary mountain range like the Pyrenees where hydroclimatic observations are collected by various agencies without a joint framework or a common data depository. We used this gap-filled snow cover product to compute the climatological snow cover duration in the Pyrenees for the first time, to our knowledge. This information can now be used to study the spatiotemporal dynamics of the Pyrenean snow cover since 2000. Here, we were able to reveal the asymmetrical snow patterns during the 2012 winter (Fig. 13). A strong snow cover duration anomaly is evident in the Spanish Pyrenees, reflecting a precipitation deficit which may have caused a temporary drop in the hydropower production at the national scale. In order to further use MODIS data to improve hydropower prediction, the best solution may be the assimilation of MODIS data into a hydrological model. However, an issue is the cloud cover which can reduce significantly useful data in real-time conditions.

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References


Ault, T., Czajkowski, K., Benko, T., Coss, J., Struble, J., Spongberg, A., Templin, M., and Gross, C.: Validation of the MODIS
snow product and cloud masking using student and NWS cooperative
Baillarin, S., Gleyzes, J., Latry, C., Bouillon, A., Breton, E., Cunin, L., Vesco, C., and Delvit, J.: Validation of an automatic
runoff forecast based on multisensor remote-sensing information,
Bejarano, M. D., Marchamalo, M., de Jalón, D. G., and del Tánago, M. G.: Flow regime patterns and their controlling
factors in the Ebro basin (Spain), J. Hydrol., 385, 323–335,
Bossard, M., Feranec, J., and Otahel, J.: CORINE land cover technical
Bowley, C. J., Barnes, J. C., and Rango, A.: Satellite snow mapping
and runoff prediction handbook, Tech. rep., NASA Technical
Paper 1829, National Aeronautics and Space Administration,
Breiman, L., Friedman, J., Stone, C. J., and Olshen, R. A.: Classifi-
cation and regression trees, CRC Press, Boca Raton, Florida,
USA, 1984.
Chander, G., Markham, B. L., and Helder, D. L.: Summary of cur-
rent radiometric calibration coefficients for Landsat MSS, TM,
ETM+, and EO-1 ALI sensors, Remote Sens. Environ., 113,
Cohen, J.: A coefficient of agreement for nominal scales, Educ. Psy-
Déry, S., Salomonson, V., Steiglitz, M., Hall, D., and Appel, I.: An approach to using snow areal depletion curves inferred from
MODIS and its application to land surface modelling in Alaska,
Dozier, J.: Spectral signature of alpine snow cover from the Landsat
Dozier, J. and Marks, D.: Snow mapping and classification from
Dupeyrat, A., Agosta, C., Saquet, E., and Hendrickx, F.: Sensibilité
aux variations climatiques d’un bassin à forts enjeux: le cas de
la Garonne, in: Proceedings 13th IWRA World Water Congress,
vol. 15, Montpellier, France, 2008.
Gafurov, A. and Bárdossy, A.: Cloud removal methodology from
MODIS snow cover product, Hydrol. Earth Syst. Sci., 13, 1361–
Gao, Y., Lu, N., and Yao, T.: Evaluation of a cloud-gap-filled
MODIS daily snow cover product over the Pacific Northwest
Gómez-Landesa, E. and Rango, A.: Operational snowmelt runoff
forecasting in the Spanish Pyrenees using the snowmelt runoff
to address the MODIS bowtie effect, Can. J. Remote Sens., 30,
Hagolle, O., Huc, M., Pascual, D., and Dedieu, G.: A multi-
temporal method for cloud detection, applied to FORMOSAT-
2, VENµS, LANDSAT and SENTINEL-2 images, Remote Sens.

S. Gascoin et al.: Snow cover climatology for the Pyrenees

Hall, D. and Riggs, G.: Accuracy assessment of the MODIS snow
Hall, D. and Riggs, G.: MODIS snow cover products, in: Global
Cryosphere Watch (GCW) Snow-Watch Workshop, Toronto, Canada, 2013.
Hall, D., Riggs, G., and Salomonson, V.: Development of methods
for mapping global snow cover using moderate resolution imaging
spectroradiometer data, Remote Sens. Environ., 54, 127–140,
1995.
Hall, D., Riggs, G., and Salomonson, V.: Algorithm Theoretical Ba-
sis Document (ATBD) for the MODIS snow and sea ice-mapping
algorithms, Tech. rep., Goddard Space Flight Center, Greenbelt,
194, 2002.
Hall, D., Riggs, G., and Salomonson, V.: MODIS/Terra Snow Cover
Daily L3 Global 500 m Grid V005, National Snow and Ice Data
Center, Boulder, Colorado, USA, 2006.
Hall, D., Riggs, G., and Salomonson, V.: MODIS/Aqua Snow Cover
Daily L3 Global 500 m Grid V005, National Snow and Ice Data
Hall, D., Riggs, G., Foster, J., and Kumar, S.: Development and
evaluation of a cloud-gap-filled MODIS daily snow-cover product,
www.ine.es (last access: 10 June 2014), 2013.
Klein, A. and Barnett, A.: Validation of daily MODIS snow cover
maps of the Upper Rio Grande River Basin for the 2000–2001
Klein, A., Hall, D., and Riggs, G.: Improving snow cover mapping
in forests through the use of a canopy reflectance model, Hydrol.
of regional snowline elevation (RSLE) from MODIS images for seasonally snow covered mountain basins, J. Hydrol., 519B,
Lopez-Moreno, J. and Garcia-Ruiz, J.: Influence of snow accumulation and snowmelt on streamflow in the cen-
tral Spanish Pyrenees, Hydrolog. Sci. J., 49, 787–802,
López-Moreno, J. I. and Vicente Serrano, S. M.: Atmospheric cir-
culation influence on the interannual variability of snow pack in the Spanish Pyrenees during the second half of the 20th century,
Magand, C., Ducharne, A., Le Moine, N., and Gascoin, S.: Intro-
ducing hysteresis in snow depletion curves to improve the water
budget of a land surface model in an Alpine catchment, J. Hy-
of the snow-covered area data product from MODIS, Hydrol.
Meyer, P., Itten, K., Kellenberger, T., Sandmeier, S., and Sand-
meier, R.: Radiometric corrections of topographically induced
effects on Landsat TM data in an alpine environment, ISPRS J.
Milano, M., Ruelland, D., Dezetter, A., Fabre, J., Ardoin-Bardin, S.,
and Servat, E.: Modeling the current and future capacity of water

resources to meet water demands in the Ebro basin, J. Hydrol., 500, 114–126, 2013.