



**Snow cover
climatology for the
Pyrenees**

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This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

A snow cover climatology for the Pyrenees from MODIS snow products

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Received: 26 September 2014 – Accepted: 27 October 2014 – Published: 12 November 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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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 (we) and 105 mm respectively, for both MOD10A1 and MYD10A1. Kappa coefficients are within 0.74 and 0.92 depending on the product and the variable. 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 % ($\kappa = 0.85$) for MOD10A1 and 96 % ($\kappa = 0.81$) for MYD10A1, which indicates a good agreement between both datasets. The effect of vegetation on the results is analyzed by filtering the forested areas using a land cover map. As expected, the accuracies decreases over the forests but the agreement remains acceptable (MOD10A1: 96 %, $\kappa = 0.77$; MYD10A1: 95 %, $\kappa = 0.67$). We conclude that MODIS snow products have a sufficient accuracy for hydroclimate studies at the scale of the Pyrenees range. Using a gapfilling algorithm we generate a consistent snow cover climatology, which allows us to compute the mean monthly snow cover duration per elevation band. 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.

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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 snow melt 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

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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).

5 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 1980's but most of the data are available since the 2000's. 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.

15 Since the early 1980's, 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 global observations of the snow cover at daily time step (without cloud obstruction) 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).

25 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

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The comparison with ground data is a robust and precise method to validate satellite snow maps. However, a limitation is that the spatial representativeness of each measurement is generally unknown. It can be assumed that a ground observation is valid for the whole pixel above a certain snow depth threshold (Maurer et al., 2003). The other type of validation is performed using Landsat-derived snow maps as a reference, since Landsat high-resolution data allow an accurate detection of snow even in mountains (Hall and Riggs, 2007). The advantage of this method is that there is no issue on the spatial representativeness of the reference data. Moreover, it allows an evaluation of MODIS snow maps in regions where the in situ station network for snow monitoring is insufficient. This technique was initially used to assess the SNOMAP algorithm (Hall et al., 1995, 2002; Klein et al., 1998). The comparison was limited to one or a few Landsat scenes with low or null cloud coverage. The small numbers of scenes allowed a manual removal of clouds. Since 2009, the Landsat archive is freely accessible, which enables to generate many snow maps over a large area for various periods of the year. This allows the assessment of 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 high misdetection rate during snowmelt period and in forest areas, showing that MODIS snow products still require to be used with caution.

Here, our objective is to investigate the value of the MOD10A1 snow product to generate a daily snow cover climatology in the Pyrenees for the period 2000–2013. As we recalled above, many studies have already assessed the MODIS snow products accuracy in other mountainous regions, but 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 dataset of continuous snow measurements from the Ebro basin agency in Spain and Météo-France. This dataset 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.

In order to further make the data useful for hydroclimate studies (e.g. to estimate a mean snow cover duration) it is necessary to interpolate the missing values. Thus we implemented a gap-filling algorithm based on previous studies to generate a snow cover climatology from February 2000 to July 2013. In the last section of this article 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 datasets of in situ snowpack monitoring in the Pyrenees (Table 1). Météo-France provided the snow depth observations at 8 stations in

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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 Innivación, 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).

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 World-wide Reference System 2 (eastward). There are 157 dates in our dataset 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 to 2 July 2013. This corresponds to 4688 days among which 4625 days 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 dataset 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.

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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 a 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 telenivometer dataset 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 multi-spectral images from Landsat, Ven μ s 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'Etudes Spatiales (Baillarin et al., 2004). All images were projected to Lambert-93. The superposition errors were 0.2 to 0.8 pixels for USGS data and 0.3 to 0.9 for ESA data depending on cloud coverage.

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- Radiometric calibration for both datasets 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 (multi-temporal 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 channels (Dozier, 1989). The NDSI was defined as:

$$\text{NDSI} = \frac{\rho_{\text{green}} - \rho_{\text{SWIR}}}{\rho_{\text{green}} + \rho_{\text{SWIR}}} \quad (1)$$

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

- NDSI > 0.4,
- $\rho_{\text{red}} > 0.12$
- $\rho_{\text{SWIR}} < 0.16$.

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

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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

5 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
10 the original product were merged in 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.

15 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 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
20 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)
25 if the same pixel was classified as snow (no-snow) in both the preceding and the antecedent grid. The preceding and antecedent grids were searched within

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a sliding temporal window, whose size was incremented if there was still a no-data value. This means that if a pixel was marked as no-data in grid $n + 1$ and/or in grid $n - 1$ (sliding window of 2 days), then the algorithm started again with a sliding window of 3 days (i.e. the test was done with grids $n + 1$ and $n - 2$, or grids $n + 2$ and grid $n - 1$). For this study we allowed the window size to be incremented up to 9 days in order to fill a long gap from 20 March 2002 to 28 March 2002 included. The longest data gap lasted 17 days in summer 2001 due to a power supply failure of the MODIS instrument on board Terra (15 June 2001 to 2 July 2001). This gap was not filled because this period is not critical for snow cover monitoring.

4. The sparse remaining no-data pixels were reclassified using a classification tree (Breiman et al., 1984, Matlab Statistics Toolbox). 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 gapfilled pixels were flagged in the final product to maintain 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 datasets (i.e. in situ data or Landsat data), which were considered as the truth. Based on these results we computed the accuracy, precision and the kappa coefficient (Cohen, 1960, noted κ). The 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. For in situ data, the comparison was performed both for snow water equivalent (SWE) and snow depth (SD) measurements.

lower elevation than the telenivometers (Table 1). Only the comparison with MOD10A1 is shown here but at this stage the result is visually similar for MYD10A1.

From these data an optimal SWE detection threshold is found between 20 and 60 mm w.e. (top row in Fig. 5). For SD, the range of optimal values is narrower between 100 and 120 mm (middle and bottom rows in Fig. 5). The optimum is nearly identical for MYD10A1 but the agreement is a bit lower than for MOD10A1 as indicated by the kappa curve. In what follows, we have set $SWE_0 = 40$ mm w.e. and $SD_0 = 105$ 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 ($\kappa = 0.95$), but the agreement decreases if MYD10A1 is considered. Another result is that the classification accuracy is higher with the SWE variable than with 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 kappa is 0.74.

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 MYD10A1 the result is similar (81.6%), but the number of pixels that were compared is lower and the fraction of snow-covered pixels in this sample was also lower (Sect. 2.2). As a consequence, the performances are slightly better for MOD10A1 (Table 5). Figure 6 illustrates the higher dispersion of MYD10A1 with respect to Landsat snow cover area. It also shows that the snow coverage tended to be underestimated by MOD10A1. The confusion matrices also indicate that MODIS has a lower snow detection than Landsat since the false negative rate is close to 18% (Table 4). Yet, the kappa coefficients indicate a good agreement for both MODIS datasets (MOD10A1 $\kappa = 0.85$, MYD10A1 $\kappa = 0.81$, both statistically significant at the 1% level). There is no evident dependency between the comparison results and the observation season (Fig. 6), which suggests that the MODIS snow detection is not significantly deteriorated by the snow properties (e.g. lower reflectance of ripe snow cover

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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, which is consistent with previous remarks (Sect. 1). In particular, the proportion of correctly classified snow pixels drops by 9.5 % (from 81.6 to 72.1 %), against 4.1 % for MOD10A1 (from 81.5 to 77.4 %).

3.3 Gap-filling

A virtually gap-free snow cover product with a daily timestep from 1 September 2000 to 1 July 2013 was generated from MOD10A1 and MYD10A1. The gapfilling 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 to 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 a complete removal of the no-data values for all the dates for which it remained some no-data pixels after the previous steps. The 0.38 % missing values correspond to the 17 days gap in June 2001 for which the classification tree was not applicable.

We found a substantial agreement between this gapfilled 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 gapfilled product was also controlled using MOD10A2 (Fig. 8). As an example we show the hydrological year 2005–2006 to illustrate how the gapfilling made substantial changes to the initial data, and how it revealed the shape of a typical snow depletion curve during the melt season. Similar results were obtained for the other years.

The gapfilled product was used to compute the mean monthly snow cover duration (i.e. the number of snow days) in the Pyrenees. We represented here the mean snow cover duration per elevation band to characterize the climatological influence of the elevation on the snow cover dynamics (Fig. 9). It shows that the number of snow days

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increases strongly from band 800–1600 m.a.s.l. to band 1600–2400 m.a.s.l. 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 season occurs between March and June, in agreement with e.g. Lopez-Moreno and Garcia-Ruiz (2004).

4 Snow cover pattern in winter 2012

We used the daily snow cover product generated from MOD10A1 and MYD10A1 after gapfilling. The mean snow cover duration between the 1 January and 1 March was computed for each pixel over the period 2000–2013 excluding 2012. The snow cover duration between the 1 January 2012 and 1 March 2012 was computed separately (Fig. 10). Both maps reveal an anomalous snow cover distribution during the winter 2012. Above-normal mean snow cover duration is observed in the northern part of the Pyrenees, contrasting with a strong snow deficit across the southern part. In situ SWE measurements in the Ebro catchment corroborate this analysis, as a large deficit was also recorded in most stations (Fig. 11).

Given the importance of the Ebro basin for the hydroelectricity in Spain (Fig. 2), we extracted monthly energy production data in Spain from the Spanish Statistical Office database (Instituto Nacional de Estadística, Ministerio de Industria, Energía y Turismo, 2013). The hydropower production dropped in early 2012 in comparison with the mean value over 1995–2012 (Fig. 12). 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 winter 2012 drought in the Spanish Pyrenees, that we also observed in the snow cover data (Fig. 10). Further analysis is necessary to establish if and how the snow deficit contributed to this drop. The gross of the snowmelt generally occurs

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between April and July, but snow melting can be important throughout the winter in the lower elevation areas. It is also possible that hydroelectric dams managers reduced their hydropower productions in anticipation to the coming deficit of snowmelt in winter.

5 Conclusions

5 We found an overall very good agreement between the MODIS Aqua/Terra products and two independent snow cover datasets generated from in situ and remote sensing observations.

Regarding the validation with in situ data, it was useful to merge the Ebro basin and Météo-France databases because it enabled to expand 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 dataset 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.

15 Using all in situ data we could determine an 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.

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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 regions. An example is shown in Fig. 13. The snow commission in MODIS products can be due to the effect of forest obstruction (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 valid, although the snow classification method for Landsat is well-established. Indeed we could also observe snow commission errors in our Landsat snow maps dataset 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 the 18 March 2009 in Fig. 13. On this day, the Pyrenees are on the edges of both input granules from the MOD10_L2 swath product, where the MODIS instrument “bowtie” 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 Riggs, 2013), thus we can expect some improvements with respect to this issue at least in the next MODIS snow product release.

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

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Table 1. Description of the in situ snow data used in this study. Stations 1 to 11 are telenivometers from the ERHIN program for which daily data of snow depth and snow water equivalent were available. Stations 12 to 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 m a.s.l.

ID	Name	Longitude	Latitude	Elevation	Period
1	Quimboa	−0.76	42.87	1810	Oct 2008–Jan 2013
2	Izas	−0.43	42.75	2080	Oct 2008–Aug 2012
3	Roya	−0.45	42.79	1971	Oct 2008–Feb 2013
4	Bachimana	−0.22	42.79	2220	Oct 2008–Jan 2013
5	Lapazosa	−0.08	42.71	2140	Oct 2008–Jun 2012
6	Ordiceto	0.28	42.67	2380	Oct 2008–Feb 2013
7	Renclusa	0.65	42.67	2180	Oct 2008–Feb 2013
8	Salenques	0.70	42.61	2600	Oct 2008–Jul 2013
9	Eriste	0.45	42.63	2350	Oct 2008–Jan 2013
10	Airoto	1.03	42.71	2380	Oct 2008–Feb 2013
11	Aixeus	1.37	42.61	2400	Oct 2008–Jun 2013
12	Aulus-Les-Bains	1.33	42.80	733	Jan 2000–Dec 2010
13	Mont-Dolmes	1.75	42.85	1500	Jan 2000–Dec 2010
14	Port-Daula	1.12	42.77	2140	Jan 2000–Dec 2010
15	Maupas	0.55	42.72	2430	Oct 2000–Dec 2010
16	Bagnères-de-Luchon	0.60	42.80	620	Jan 2003–Dec 2010
17	St-Paul-Doueil	0.55	42.83	1115	Dec 2004–Dec 2010
18	Eget	0.27	42.78	1016	Jan 2000–Dec 2010
19	St-Lary-Soul	0.32	42.82	827	Jan 2000–Dec 2010

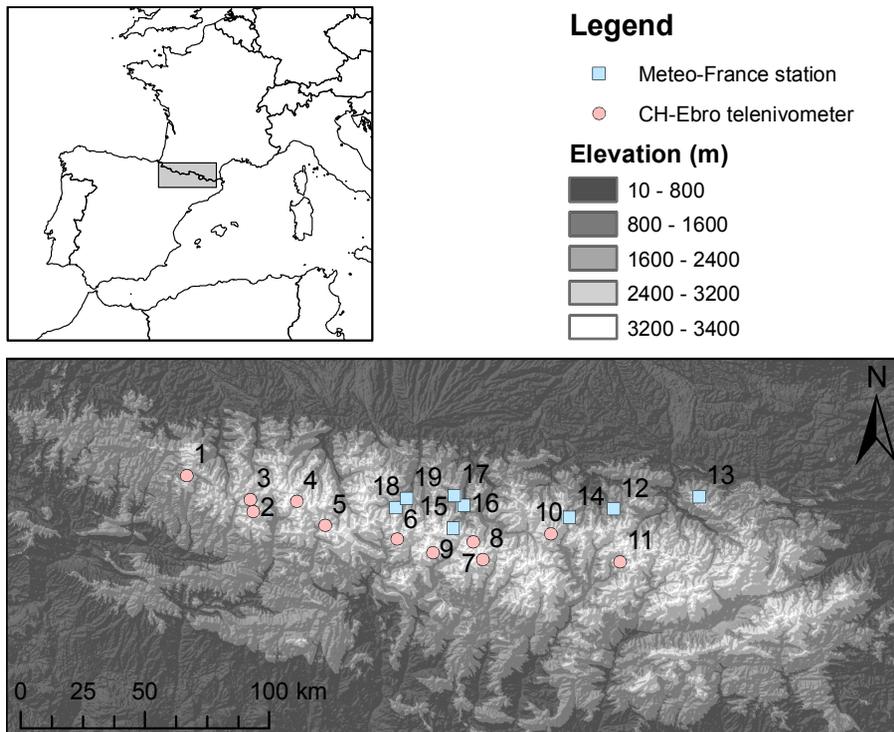


Figure 1. Shaded relief map of the study area and location of the snow monitoring stations used in this study (map projection Lambert-93). The rectangle is the area of interest used for remote sensing data (corner coordinates: upper left $x = 320$ km, $y = 6250$ km, lower right $x = 680$ km, $y = 6100$ km).

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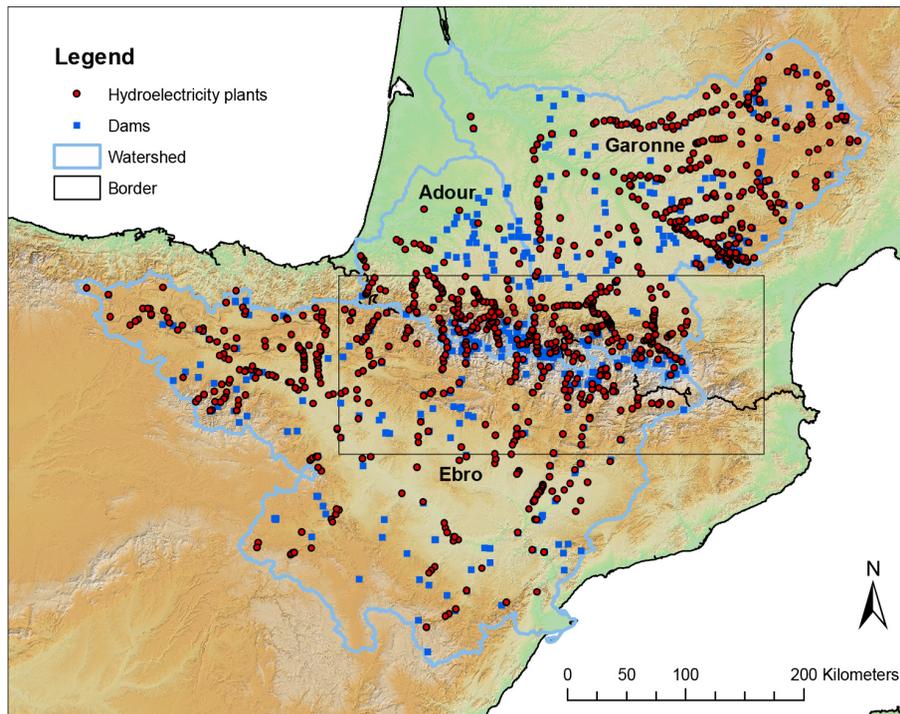


Figure 2. Hydraulic infrastructures in the Adour, Garonne and Ebro rivers basins.

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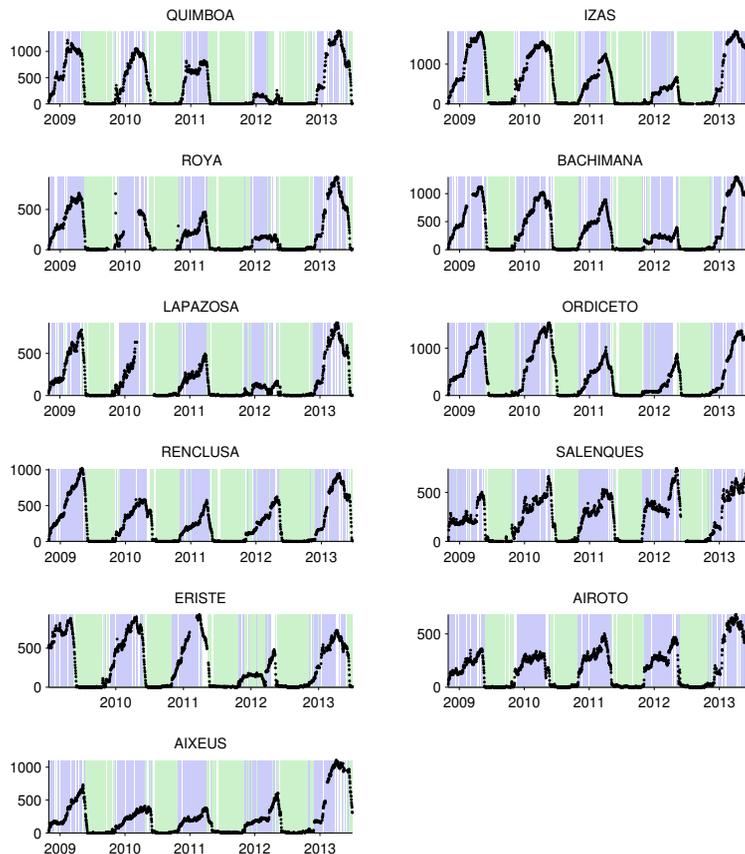


Figure 3. Timeseries of in situ SWE measurements and MOD10A1 at each telenivometer station. The black dots are the daily SWE measurements. The color bars in the background indicate the snow presence (blue), absence (green) and no data (white) from MODIS data.

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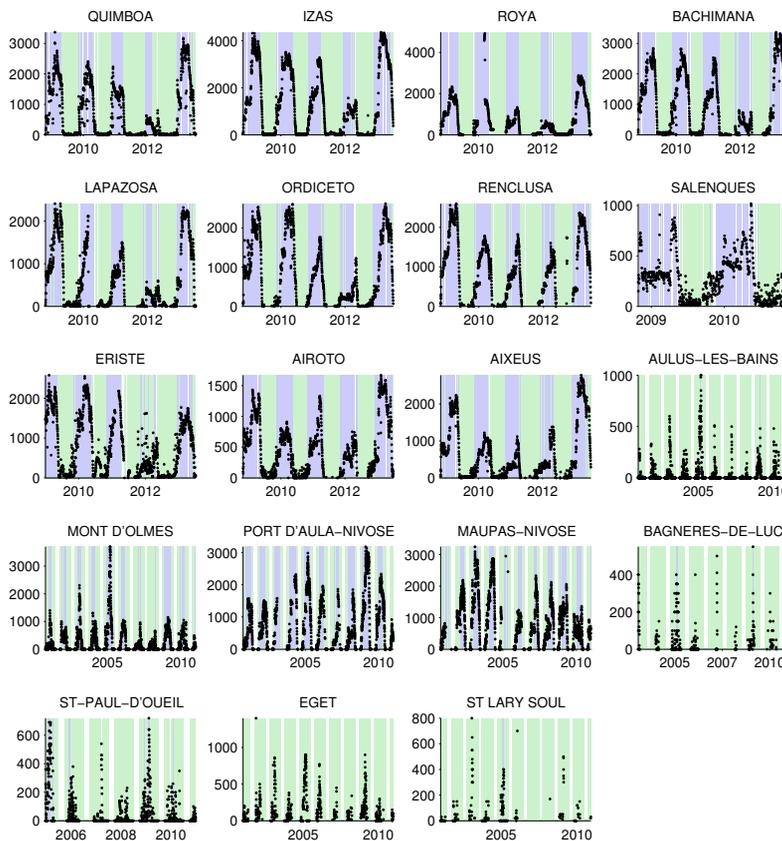


Figure 4. Timeseries of in situ SD measurements and MOD10A1 at each station. The black dots are the daily SD measurements. The color bars in the background indicate the snow presence (blue), absence (green) and no data (white) from MODIS data.

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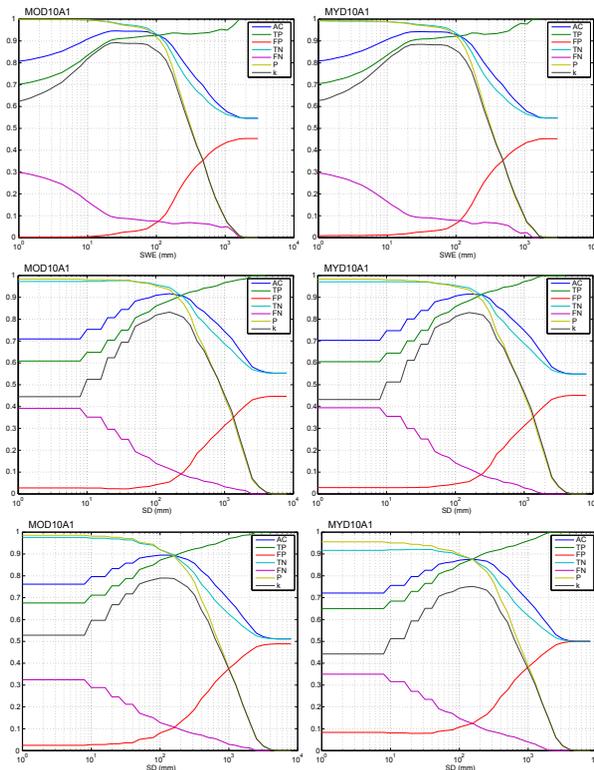


Figure 5. Comparison of MODIS products with in situ data. Top row: reference data are the SWE measurements from the telenivometers, middle row: SD measurements from the telenivometers, bottom row: SD data from all stations. Each graph shows the variation of the statistical agreement between both datasets with the snow detection threshold: AC: accuracy, TP: true positive, FP: false positive, TN: true negative, FP: false positive, P: precision, k: kappa coefficient.

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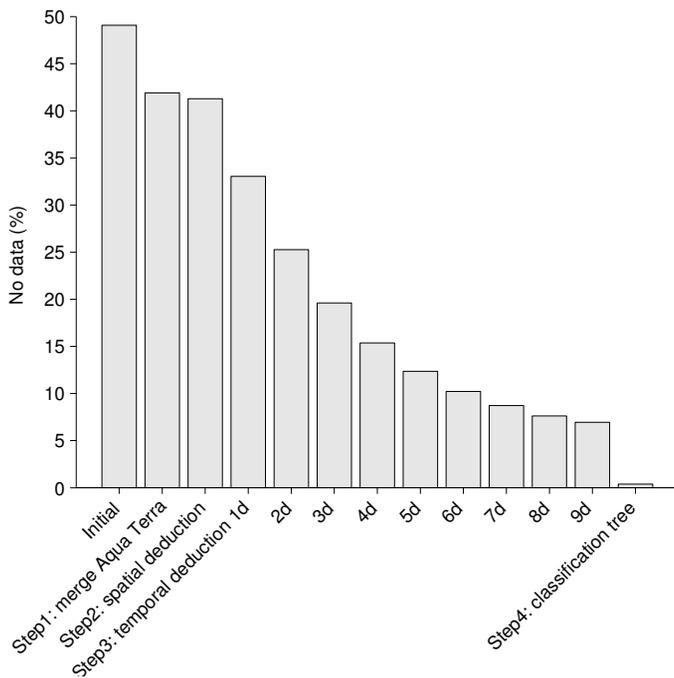



Figure 7. Evolution of the number of pixels classified as “no-data” (e.g. clouds) during the gapfilling procedure.

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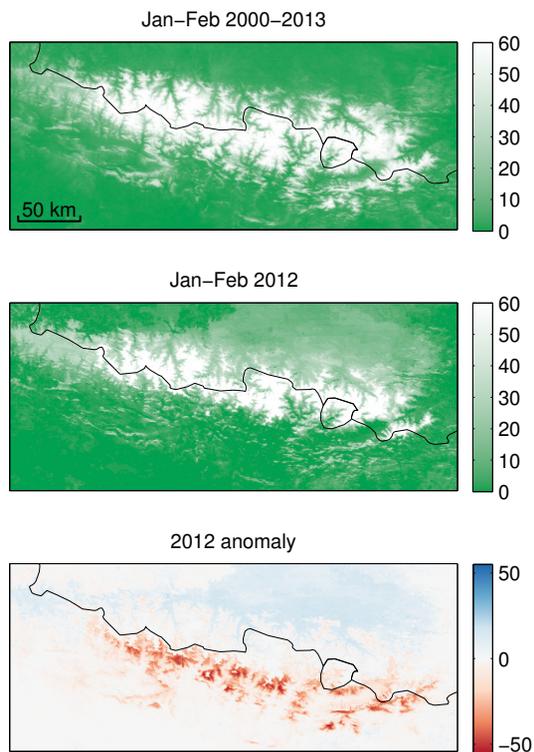


Figure 10. Illustration of the anomalous snow patterns in the Pyrenees during the winter 2012. Top panel: mean snow cover duration (days) in January and February, Middle panel: snow cover duration in January and February 2012. Bottom panel: snow cover duration anomaly.

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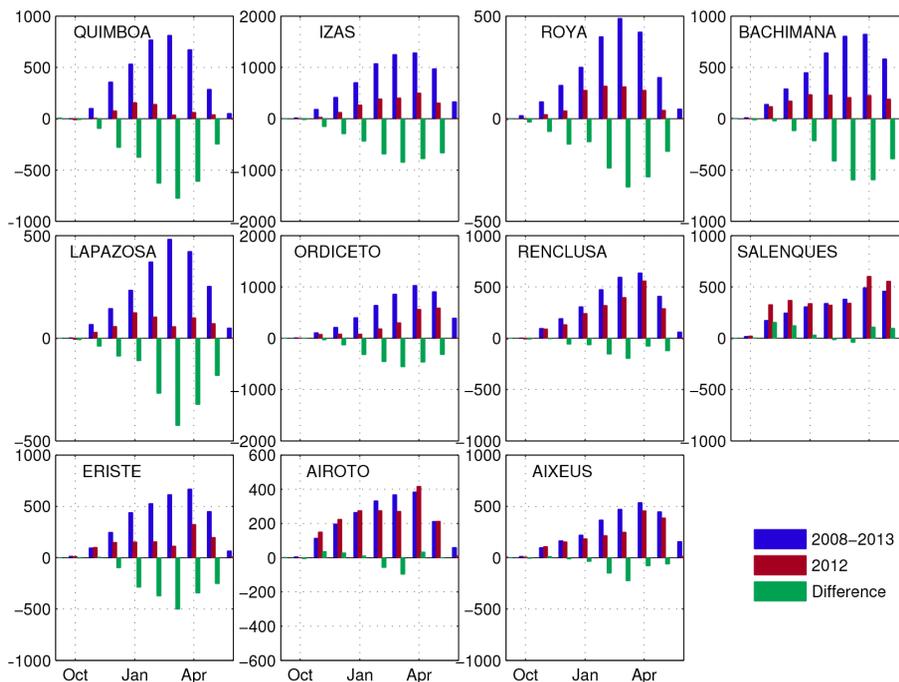


Figure 11. Snow water equivalent (mm) from in situ snow stations (Ebro basin telenivometers), blue: mean monthly monthly value over 2008–2013, red: monthly mean in 2012, green: monthly departures in 2012.

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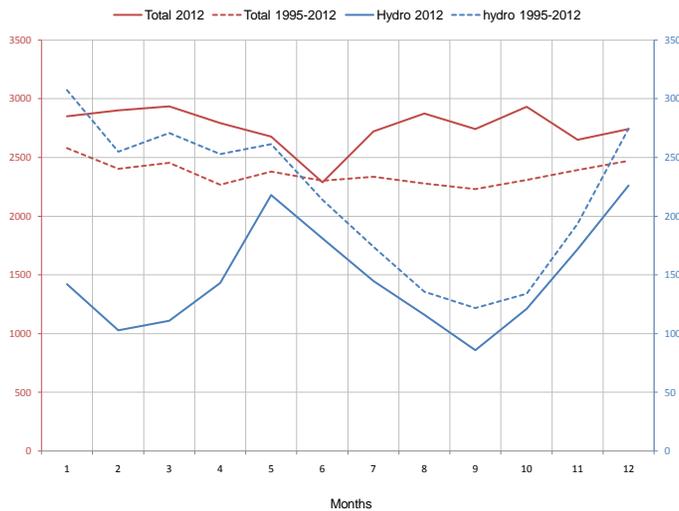


Figure 12. Monthly energy production in Spain (units: kTep). The right y axis is for hydropower, the left y axis is for the total energy production.

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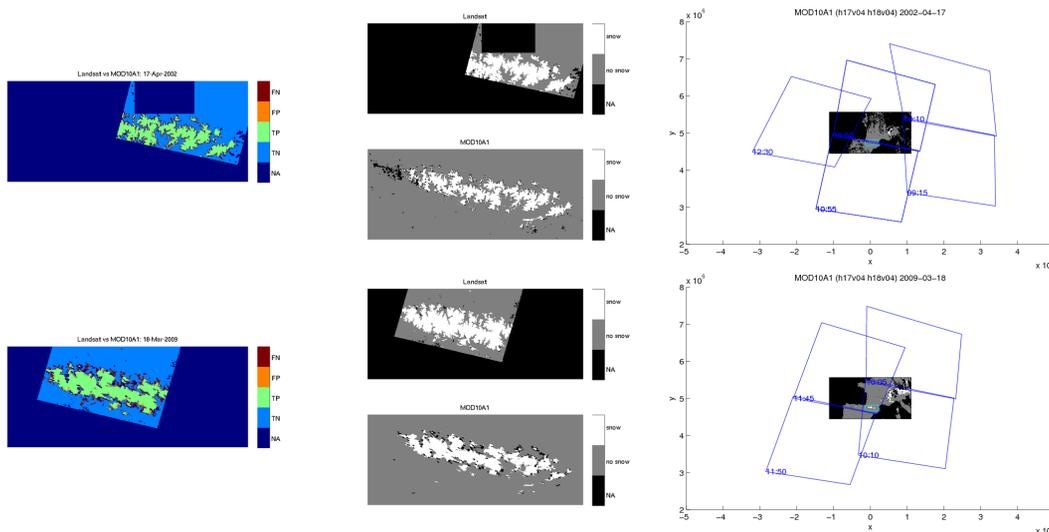


Figure 13. Comparison between MOD10A1 and Landsat for two dates. Left column: MOD10A1 vs. Landsat classification (TP: true positive, FP: false positive, TN: true negative, FP: false positive). MOD10A1 false negative are mainly located along the snow cover edges. Middle column: Landsat and MOD10A1 classifications 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 18 March 2009 because it was constructed from the border areas of two input granules where the bowtie effect is most pronounced.

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