

A snow cover climatology for the Pyrenees from MODIS snow products (hess-2014-424) **Author's Response to reviewers**

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The referees comments are marked in *italic blue* and our response in black.

1 Response to Referee 1 (J. Parajka)

First, we would like to thank J. Parajka for his careful evaluation of our work and his valuable comments. We found interesting results thanks to his suggestions. We have written a point-by-point response below. The changes were marked in bold in the manuscript.

General comments

The study evaluates the accuracy of daily MODIS snow cover products and estimates mean monthly snow cover duration in Pyrenees region. The MODIS snow cover maps are compared with in situ snow depth measurements at 19 stations and Landsat snow images in the period 2002-2010. The results show good snow cover mapping accuracy of MODIS and indicate snow cover duration anomalies which are likely responsible for decreasing hydropower production. Overall, the study is interesting and within the scope of HESS. The novel scientific contribution is, however, not clearly presented. What is the main research question here? There are many studies evaluating accuracy of MODIS snow products (as already indicated in the manuscript), but it is not clear what is going to be novel here, how this study contributes to some new scientific knowledge and/or improved understanding of spatial and temporal snow cover variability. Although authors indicate the importance of the role of topography, land cover and climate on snow cover variability (i.e. p. 12536, l.24-25), the results do not show a clear message to this question. In order to more clearly demonstrate the scientific contribution, more in depth analyses are needed in the results section as well as a comprehensive discussion section need to be added to the manuscript (i.e. in a separate section). This will allow to compare the results with other studies and more clearly demonstrate the added value of the findings. The climate setting in the Pyrenees is likely quite different as compared e.g. to the Alps, so this aspect could be highlighted more as well.

We understand that our paper is a bit atypical because it deals with several aspects related to the MODIS snow products (comparison with station data, comparison with Landsat data, gapfilling, spatio-temporal analysis), which are typically treated separately and more thoroughly. However, few papers describe the overall process from the MODIS data evaluation to its application for actual

water resource issues. Here our objectives were (i) to evaluate MODIS products to generate the first snow cover climatology in the Pyrenees (ii) to apply this climatology to characterize the snow cover variability in the Pyrenees. We have reworked the introduction to clarify (p.6-7)).

We have also reshaped the manuscript to include a comprehensive discussion on the validation results and the uncertainties linked to the gapfilling. The new discussion section is now followed by a separate section on the application of the new snow cover climatology to describe the main features of the snow patterns in the Pyrenees and to present the case of the 2012 drought. The paper is now organized as follows:

1	Introduction	3
2	Data and methods	7
2.1	Data	7
2.1.1	In situ data	7
2.1.2	Landsat	8
2.1.3	MODIS snow products	8
2.1.4	Land cover	9
2.2	Methods	9
2.2.1	In situ data processing	9
2.2.2	Landsat processing	9
2.2.3	MODIS snow products processing	11
2.2.4	Comparison	12
3	Results	13
3.1	In situ data vs. MODIS products	13
3.2	Landsat vs. MODIS products	14
3.3	Gap-filling	15
4	Discussion	15
4.1	In situ data vs. MODIS products	15
4.2	Landsat vs. MODIS products	16
4.3	Gap-filling	17
5	Application of the snow cover dataset	18
5.1	Spatio-temporal influences on the mean snow cover duration . . .	18
5.2	Snow cover pattern in winter 2012	19
6	Conclusions	20

In order to enhance the analysis of the spatio-temporal dynamics, we included a new figure on the mean snow cover duration as a function of the slope's aspect (Fig. 12). This figure complements the figure on the mean snow cover duration per elevation band (Fig. 11). We added the following comment in Sect.5.1:

“It shows that the snow cover tends to persist longer on north-facing and east-facing slopes. This is consistent with the expected effect of the solar radiation on the snowpack energy balance. North-facing slopes receive less solar energy. West and east facing slopes are exposed to the same insolation but west-facing slopes receive solar radiation in the afternoon at the hottest time of day,

which explains why the snow melts faster than on the east-facing slopes. If we further normalize the SCD with respect to the mean monthly SCD (not shown here), we see more clearly that the difference between east and west facing slopes increases over the snow season (from November to June). This is consistent with the previous explanation, because the effect of the solar radiation becomes more evident during the ablation season.”

I would suggest to compare not only the overall mapping accuracy, but also seasonal differences, potential spatial and temporal variability in the detection threshold,...]

The temporal variability in the MODIS accuracy was already addressed in the case of the Landsat comparison (in Fig. 6 the colors indicate the month of the year), as explained in Sect.3.2:

“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 in late spring).”

However this was not done in the case of the comparison with in situ data. As suggested, we performed an analysis of the seasonal differences in the detection threshold (Sect. 3.1). We used the snow depth and SWE data from the telenivometers to compute the best detection threshold for every month in the snow season (November-June). We included a new figure in the manuscript because we think that the results interesting (Fig. 5). Indeed we found a significant seasonal trend in the best detection threshold, which is consistent with the properties of the snow cover. The results are shown only for the snow depth but similar results were obtained with the SWE (although a bit less significant). We also added this comment in the Discussion (Sect. 4.1):

“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 (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.”

[...] as well as seasonal variability in the cloud coverage.

We have included a new figure to show the spatial and seasonal variability of the cloud cover probability in the MOD10A1 product (Fig. 10). We have written a new section based on this figure in the discussion (Sect 4.3).

[...] The comprehensive Landsat dataset can be potentially also used to evaluate the factors controlling MODIS sub-grid snow cover variability.

It is true that full resolution Landsat images could be used to validate the snow cover fraction product (SCF) and not only the binary product (SCA), but for this study we have chosen to focus on the SCA because, this product is sufficient to characterize the snow cover at the scale of the Pyrenees. In addition, a new analysis of SCF would raise some specific methodological issues. In the Pyrenees, where the forest cover is important, as stated by Rayleigh et al. (2014) errors in the MODIS subpixel snow coverage cannot really be assessed with Landsat images, because the Landsat sensor line of sight is obstructed by forest canopy (see also Kane et al., 2008). In addition, another kind of gap-filling algorithm must be implemented to interpolate the SCF (interpolation of continuous snow fraction values instead of snow classes).

Specific comments

1) I would suggest to consider using consistent terminology with the other MODIS assessment papers. For example, the overall accuracy (index) instead of Kappa, MODIS over-, under- estimation errors. See e.g. a synthesis of MODIS studies in Parajka and Blöschl (2012).

We thank the reviewer for this comment. In the previous version what we called “accuracy” is referred to as “overall accuracy” in Parajka and Blöschl (2012). We corrected this in the new version. However, we mainly used the kappa coefficient in our analyses because this test statistic incorporates both information on agreement and disagreement between the classification and the validation data (as recommended by Klein and Barnett 2003 for MODIS snow products). This was added in Sect. 2.2.4.

2) Landsat processing. It is not clear why and how are the maps resampled to 240m spatial resolution? Why not to look at MODIS subgrid variability?

The Landsat were resampled to 240 m because the multi-temporal cloud detection algorithm requires much computer time and also performs better at lower resolution. This trade-off allowed us to process 160 Landsat dates, which is rarely done, and thus to increase the potential range of snow cover properties. As commented above, we agree that the full resolution Landsat images could potentially be used to validate the SCF product, which is provided in addition to the SCA in the daily MODIS products. In our opinion, the SCA product is already very useful at the scale of the mountain range to determine the snow cover duration for a given pixel, as illustrated in the section devoted to the 2012 drought.

3) SD detection threshold: How it is estimated to 105mm, when the resolution of snow depth reading is 1 cm?

We thank the reviewer for this comment, because it was an unfortunate mistake now corrected. It is 150 mm.

4) There are 13 Figures, however, text in the results section is rather short. Please consider to present more in depth analyses to balance the overall structure and story of the paper.

5) Figures: When looking on Figures, it is difficult to see some clear story and take home message of the paper. Please consider to show the main results more clearly (e.g. instead of all stations, present in more detail some typical or interesting, those which will support the message of the paper).

We added a new discussion section and we expanded the analysis of the spatio-temporal dynamics of the snow cover as explained above, also in line with the suggestions of Referee 2. We merged the Figures 3 and 4 into one single figure showing only Ordiceto station SWE and SD time series. We also removed the figure 11 in the previous version (anomalies in the 2012 snow water equivalent data from the telenivometers).

2 Response to Referee 2

We would like to thank Referee 2 for his/her attentive reading and the encouraging comments. We agreed with most of the suggestions and modified the manuscript accordingly. We have written a point-by-point response below. The changes were marked in bold in the manuscript.

The authors assess the accuracy of the standard MODIS snow gridded products, MOD10A1 and MYD10A1, on the seasonal snow cover mapping in the Pyrenees. They compare results from the snow maps with in-situ measurements. They also use Landsat images to validate the MODIS snow maps. They find high accuracies for the satellite-derived snow cover maps, with a slightly higher accuracy found for the MOD10A1 (Terra) snow maps. Using the snow maps they compute a mean monthly snow cover duration in the Pyrenees, and analyze snow patterns in the 2011-12 winter and relate that to a drop in hydropower. While I like the paper a lot, I feel that there are several important topics described, and that the topics are not all equally well-developed. For example, very little is said about the snow cover duration in different elevation bands, in the Results section and in the Abstract, though there is a nice figure (Fig. 9). I would like to see a larger discussion of this interesting result. Also, how exactly can the snow maps be used to improve or predict hydropower production? That is discussed but a more detailed discussion of that would also be useful.

We thank the Referee for these interesting comments. As explained above we have reorganized the manuscript to enhance the sections devoted to the discussion of the results. We have now put the analysis of the snow cover patterns in a separate section (Sect. 5). We have expanded the discussion on the snow cover duration (SCD) in Sect 5.1. We incorporated an additional figure showing the effect of the slope aspect on the SCD for the areas above 800 m asl. The figure is commented in Sect. 5.1 but we copy here the paragraph:

“It shows that the snow cover tends to persist longer on north-facing and east-facing slopes. This is consistent with the expected effect of the solar radiation on the snowpack energy balance. North-facing slopes receive less solar energy. West and east facing slopes are exposed to the same insolation but west-facing slopes receive solar radiation in the afternoon at the hottest time of day, which explains why the snow melts faster than on the east-facing slopes. If we further normalize the SCD with respect to the mean monthly SCD (not shown here), we see more clearly that the difference between east and west facing slopes increases over the snow season (from November to June). This is consistent with the previous explanation, because the effect of the solar radiation becomes more evident during the ablation season.”

Regarding the question on how snow maps can be used to improve or predict hydropower production, we can answer that the best solution is probably the assimilation of MODIS data in a hydrological model. However, an issue is the cloud cover which can reduce significantly the useful data in real time conditions. For example, in response to the first Referee, we have showed that the cloud cover is significant all year long, but especially in April when the snow melt contribution to streamflow is important. This comment was added to the Conclusion.

Finally and very importantly, it seems that there is new information provided in the Conclusions. Some wording (which is good wording) should be described in the Results section first and then mentioned again in the Conclusions.

We have removed some parts of the conclusion so that no new information is given. All the new information is given in the section devoted to the Results of the validation (Sect. 3) or in the Application section (Sect. 5). We hope that this new structure will satisfy the referees.

Figures: I cannot read the labels on the figures easily; the font is quite small on a lot of them. Please go through the figures to determine if they are all

needed. There are quite a few and many are not explained very well in the text.

We merged the Figures 3 and 4 into one single figure showing only Ordiceto station SWE and SD time series so it is easier to read. We also removed the figure 11 in the previous version (anomalies in the 2012 snow water equivalent data from the telenivometers).

So my suggestion is to try to develop all of the major findings or topics a bit better, or take one out and use it for a companion paper.

We have expanded the discussion on the spatio-temporal dynamics of the snow cover that can be extracted from this snow cover climatology, also based on the comments by Referee 1. We agree that this paper contains a lot of information (more than we expected at the beginning) and we could have split this study in two papers. However, we would like to insist on keeping all the elements in a single manuscript, because we want to provide to the reader the full process: i.e. the accuracy assessment of the original data, the method to fill the cloud-covered pixels, and the application to develop knowledge on the hydroclimate in the Pyrenees. We believe it is important to keep all the pieces together to illustrate how MODIS snow products data can be used, and what level uncertainties is expected.

Abstract Please provide some results of snow cover duration per elevation band in the Abstract.

We have included this result in the abstract: *There is snow on the ground at least 50% of the time above 1600 m between December and April.*

Introduction – there are numerous acronyms that need to be spelled out with the first usage.

We double-checked to make sure that all the acronyms are defined (except for three satellite acronyms AVHRR, PROBA-V and MODIS).

Page/Line 12533/15 change to functions

done

12535/2 should reference Klein et al., 1998 here

done

12535/4 & 5 this should read NDSI instead of NDVI and NDSI should be spelled out

It is not a mistake, the vegetation index is actually used in the algorithm to lower the NDSI detection threshold in forested areas. *12536/7 should also reference Salomonson and Appel, 2004 and 2006*

done

12536/14 should read “. . .which enables us to generate. . .”

done

12536/18&19 should re-phrase this sentence for clarity

12545 end of Section 3.2 - the last couple of sentences are a bit confusing and should be re-written for clarity

We rephrased these sentences to clarify.

12546/8 product should be products

corrected

12547/20 an should be a

corrected

12548/20 please describe MOD01A1 - it just comes out of the blue, though it's possible that I missed a description of it earlier in the paper

We assume that the Referee refers to MOD10_L2. We added that it is the input swath data used to generate MOD10A1.

12548/25 also reference Riggs et al., 2006 online User Guide to snow products

Actually we did not use this guide. As suggested by the data provider we cited: 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.

References I don't understand the 5-digit numbers at the end of each reference?

I presume that the 5-digit numbers are the line numbers where the reference is given (this was automatically generated by the Copernicus LaTeX style).

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 (we) and 150 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 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 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 is known as the only large watershed in France where a structural imbalance between wa-

ter resources, the needs of different users and aquatic environments is officially recognized
55 (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).

60 Given the importance of the snow cover in the Pyrenees, it is necessary to monitor its evo-
lution. 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
65 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 1980's, it has been shown that space-borne sensors operating in the visi-
ble 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,
70 only low to mid-resolution sensors such as AVHRR, PROBA-V or MODIS allow global ob-
servations of the snow cover at daily time step (without cloud obstruction) with a spatial res-
olution 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
75 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 hydro-
climate applications in snow dominated regions. These products were generated using
80 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 and

Terra products as Aqua MODIS band 6 detectors are not functioning, while band 6 is used for the Terra product to compute the NDVI (Hall and Riggs, 2007). As a consequence the NDVI test for forested areas is not activated for Aqua products. The successive versions of the MODIS snow products were compared with snow maps obtained from other sources at similar or lower resolution (i.e. relative validation, Hall et al., 2002; Klein and Barnett, 2003; Maurer et al., 2003; Simic et al., 2004; Rittger et al., 2013) and validated using ground snow measurements (i.e. absolute validation) (Klein and Barnett, 2003; Maurer et al., 2003; Simic et al., 2004; Ault et al., 2006; Parajka and Blöschl, 2006; Arsenault et al., 2014). Most of these studies were done using the Terra MODIS daily snow product (MOD10A1). More comprehensive reviews can be found in Hall and Riggs (2007) and Parajka et al. (2012). Despite the variety of methods used among these studies, the results led to the same conclusion that Terra MODIS snow cover products have a higher overall accuracy than snow maps derived from VEGETATION or AVHRR. The typical absolute accuracy of MOD10A1 is 93 % but depends on the land cover (Hall and Riggs, 2007; Arsenault et al., 2014). The accuracy is lower in forested areas (Simic et al., 2004; Parajka et al., 2012). Other important sources of misdetection are cloud/snow confusion (Rittger et al., 2013), the variation of the sensor viewing angle and the reprojection from the original swath data to the sinusoid grid (Arsenault et al., 2014). The accuracy of Aqua snow product is similar although less documented. A comparison with Terra snow maps indicated a lower accuracy at least in forested areas as expected (Hall and Riggs, 2007).

Alternative snow cover detection algorithms were developed for MODIS reflectance data, which showed better accuracies (Sirguey et al., 2008; Rittger et al., 2013). However these codes are not operational globally and imply the processing of large amount of data to get a snow map, which restrict the number of potential users. In contrast, MODIS snow products are available at the global scale through Internet usually with a short delay of eight days.

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 (**Salomonson and Appel, 2004; 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 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 dataset 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 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.

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 datasets of in situ snowpack monitoring in the Pyrenees (Table 1). Météo-France provided the snow depth observations at 8 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 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). **The snow season is generally shorter at Météo-France stations (e.g. Aulus-Les-Bains, Bagnères-de-Luchon, St-Lary-Soul) because they are located at lower elevation 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 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.

190 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

195 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

200 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

205 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, 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.

- 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 μm). A pixel is flagged as snow if the three following conditions are fulfilled:

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

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 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.

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 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 classified as snow (no-snow) in both the preceding and the antecedent grid. The preceding and antecedent grids were searched within 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 **overall accuracy**, precision and the kappa coefficient (Cohen, 1960, noted κ). 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. 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 datasets). For MOD10A1, a total of
 14.7×10^6 pixels were compared with the Landsat snow masks, among which 13.4 %
were classified as snow in the Landsat data.

The gapfilled product was also evaluated by comparison with the in situ data. The com-
parison 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 com-
pared our gapfilled 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 kappa curve. In what fol-
lows, we have set $SWE_0 = 40$ mm w.e. and $SD_0 = 150$ mm (Table 2). The resulting confu-
sion 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.

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 kappa 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 a 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 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 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 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.

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 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.

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

395 located along the snow cover edges, in agreement with previous studies in alpine regions.
An example is shown in Fig. 9. 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
400 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 dataset along the snow cover edges.
This may artificially increase the agreement with MODIS products. However, we consider
405 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. 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
410 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 Pyre-
nees. 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
415 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.

4.3 Gap-filling

420 **The cloud obstruction is an important drawback of snow products generated from re-
mote 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**

dataset (about 50%, Fig. 7). 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. Hence, we further 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 north-west because the prevailing westerlies bring moist air from the North-Atlantic into the continent, whereas the south-eastern 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 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 snow melt season. This is an issue especially if the MODIS products is to be used under real time conditions for river flow forecasting.

5 Application of the snow cover dataset

5.1 Spatio-temporal influences on the mean snow cover duration

The new gap-free snow cover dataset 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 band 800–1600 m a.s.l. to band 1600–2400 m a.s.l. between Novem-

ber 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). **There is snow on the ground at least 50% of the time above 1600 m between December and April.**

We further analyzed the snow cover duration variability as a function of the slope's aspect for the area above 800 m a.s.l. (Fig. 12). It shows that the snow cover tends to persist longer on north-facing and east-facing slopes. This is consistent with the expected effect of the solar radiation on the snowpack energy balance. North-facing slopes receive less solar energy. West and east facing slopes are exposed to the same insolation but west-facing slopes receive solar radiation in the afternoon at the hottest time of day, which explains why the snow melts faster than on the east-facing slopes. If we further normalize the SCD with respect to the mean monthly SCD (not shown here), we see more clearly that the difference between east and west facing slopes increases over the snow season (from November to June). This is consistent with the previous explanation, because the effect of the solar radiation becomes more evident during the ablation season. This process is contributing to the hysteresis in the relationship between the SWE and the SCA, which was identified above (Sect. 4.1).

For this analysis we used the same elevation and aspect grid as for the gap-filling (Sect. 2.2.3). Hence, a fraction of the snow cover climatology was constructed based on the same elevation and aspect data. However, this fraction is too small to significantly modify the results of this analysis (Fig.7).

5.2 Snow cover pattern in winter 2012

As above, we used the new gap-free snow cover dataset to compute the mean snow cover duration between the 1 January and 1 March 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. 13). 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 (**not shown here, but visible in the case of Ordiceto station Fig 3**).

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. 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 winter 2012 drought in the Spanish Pyrenees, that 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 dams managers reduced their hydropower productions 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 datasets 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), in particular 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, in particular in the north-west 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 a 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. But 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 gapfilled 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 spatio-temporal dynamics of the Pyrenean snow cover since 2000. Here, we were able to reveal the asymmetrical snow patterns during the winter 2012 (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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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

Table 2. Confusion matrices between the MODIS snow products and in situ data. The numbers correspond to percentage 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.

	MOD10A1		MYD10A1	
	no snow	snow	no snow	snow
Telenivometers				
$SWE < SWE_0$	97	2.7	97	2.8
$SWE > SWE_0$	2.2	98	2.6	97
$SD < SD_0$	96	4.2	95	4.6
$SD > SD_0$	4.1	96	4.2	96
All stations				
$SD < SD_0$	92	8.1	89	11
$SD > SD_0$	13	87	15	85

Table 3. Statistical measures of the comparison between MODIS product and in situ data, computed from the results presented in Table 2 (N : sample size, A : overall accuracy, κ : kappa coefficient).

	MOD10A1			MYD10A1		
	Telenivometers		All stations	Telenivometers		All stations
	SD	SWE	SD	SD	SWE	SD
$N (10^3)$	7.4	7.9	11.4	6.7	6.7	9.1
A	0.96	0.98	0.89	0.97	0.96	0.87
κ	0.92	0.95	0.79	0.94	0.91	0.74

Table 4. Confusion matrix obtained from the comparison of Landsat snow maps with Aqua/Terra MODIS snow maps. The numbers correspond to percentage with respect to Landsat data. The results are given for all the study area (“all”), and the area covered by forests only (“forest”).

		MOD10A1			
		No snow		Snow	
		all	forest	all	forest
Landsat	No snow	99.0	98.1	1.00	1.93
	Snow	18.5	22.6	81.5	77.4
		MYD10A1			
		No snow		Snow	
		all	forest	all	forest
Landsat	No snow	98.2	96.9	1.85	3.12
	Snow	18.4	27.9	81.6	72.1

Table 5. Statistical measures of the comparison between MODIS products and Landsat, computed from the results presented in Table 4 (N : sample size, A : overall accuracy, κ : kappa coefficient). The results for the forested areas are indicated in parentheses.

	MOD10A1	MYD10A1
N (10^6)	14.7 (5.41)	11.2 (4.05)
A	0.97 (0.96)	0.96 (0.95)
κ	0.85 (0.77)	0.81 (0.67)

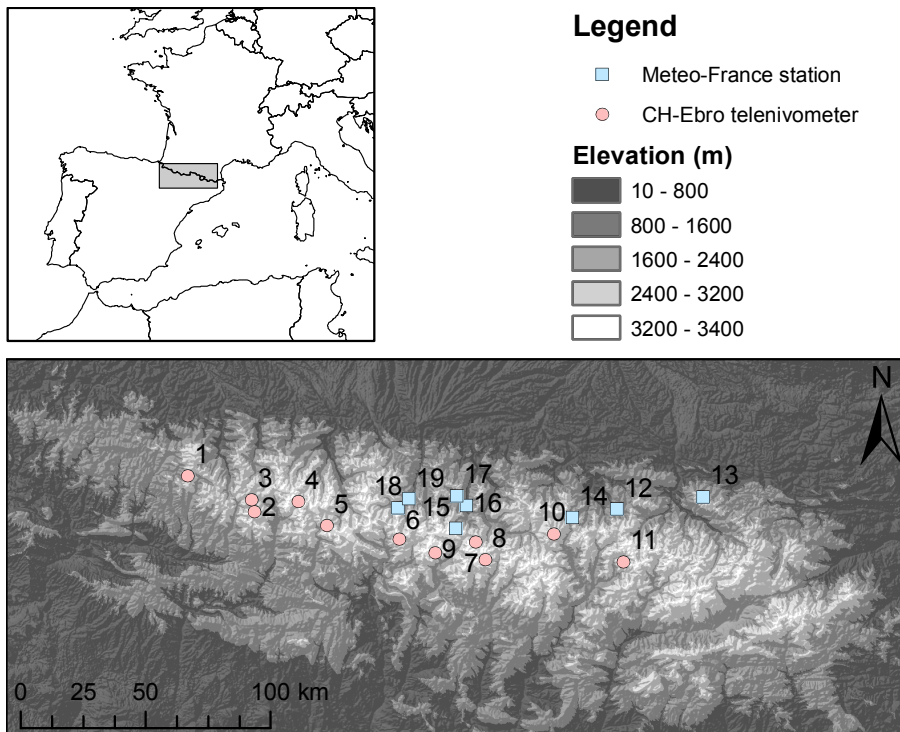


Figure 1. Shaded relief map of the study area and location of the snow monitoring stations used in this study (map projection Lambert-93). The rectangle is the area of interest used for remote sensing data (corner coordinates: upper left $x = 320$ km, $y = 6250$ km, lower right $x = 680$ km, $y = 6100$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

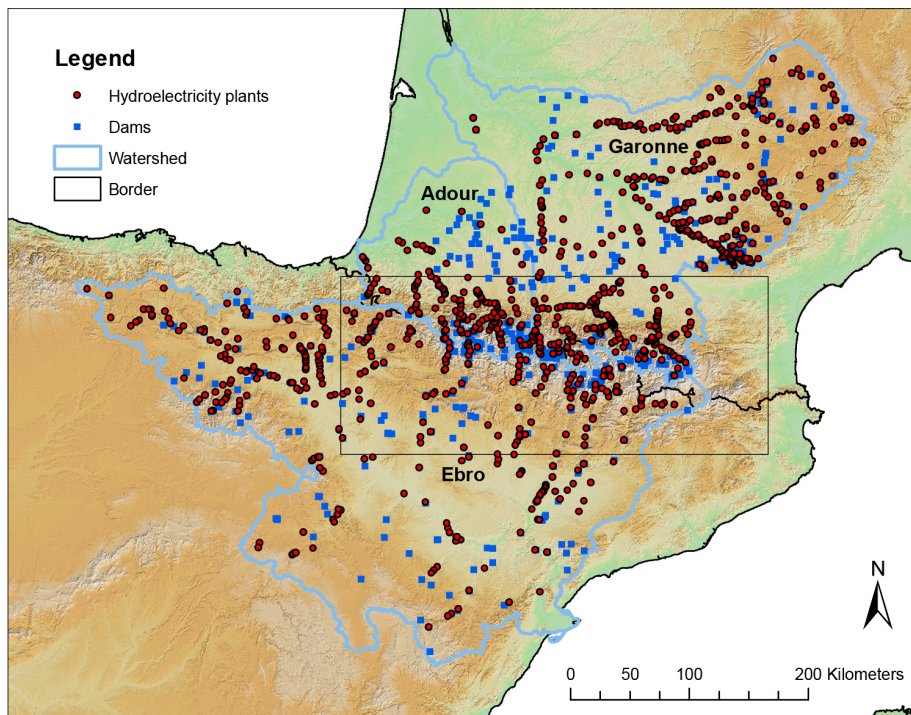


Figure 2. Hydraulic infrastructures in the Adour, Garonne and Ebro rivers basins.

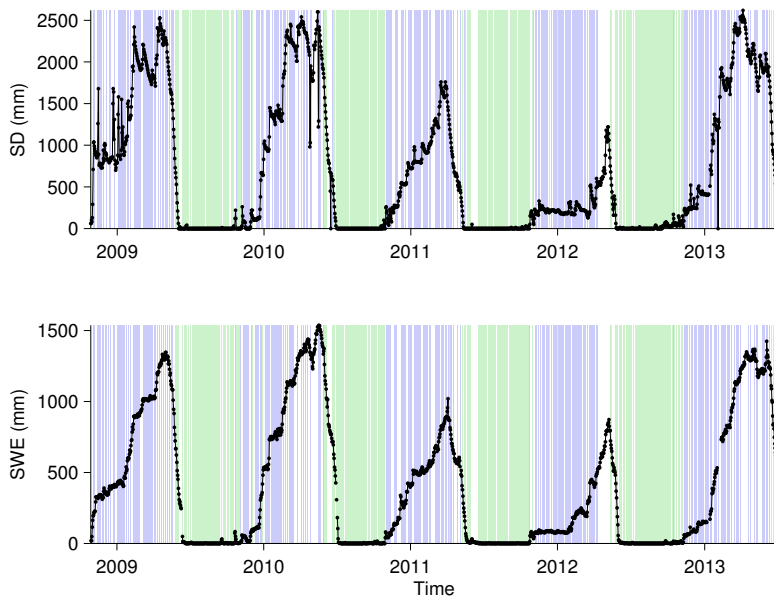


Figure 3. Timeseries of in situ data and MODIS data at Ordiceto station. The black dots are the daily snow depth (SD) and snow water equivalent (SWE) measurements. The color bars in the background indicate the snow presence (blue), absence (green) and no data (white) from MOD10A1.

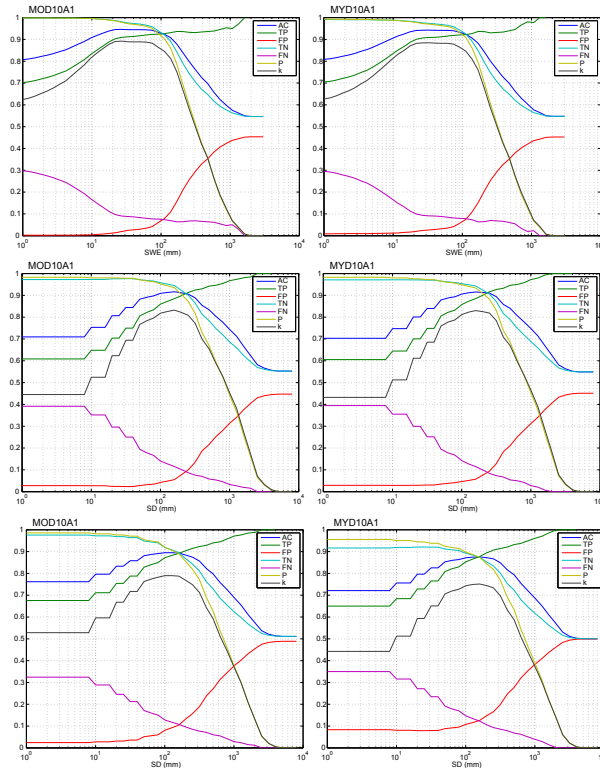


Figure 4. Comparison of MODIS products with in situ data. Top row: reference data are the SWE measurements from the telenivometers, middle row: SD measurements from the telenivometers, bottom row: SD data from all stations. Each graph shows the variation of the statistical agreement between both datasets with the snow detection threshold: AC: overall accuracy, TP: true positive, FP: false positive, TN: true negative, FP: false positive, P: precision, k: kappa coefficient.

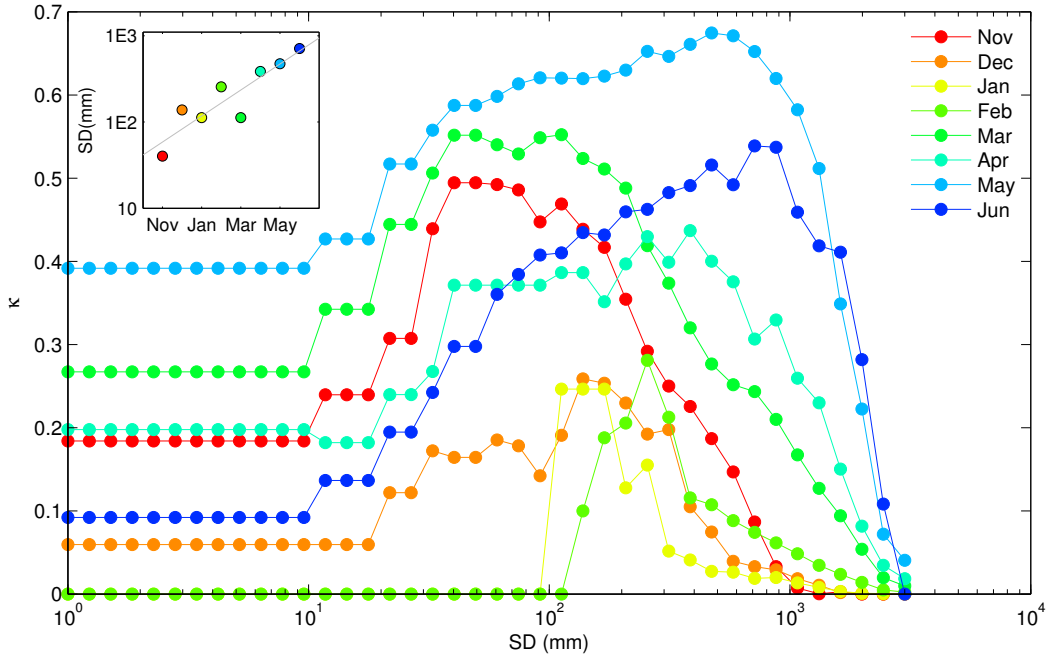


Figure 5. Evolution of the kappa coefficient with the value of the snow depth detection threshold for each month of the snow season. Here only the telenivometers data and the MOD10A1 product were considered. The snow depth value giving the maximum kappa was extracted for each month and plotted against the month (inset). The linear fit was calculated with log-transformed values of the SD (Pearson's correlation $R = 0.90$, $p = 0.002$)

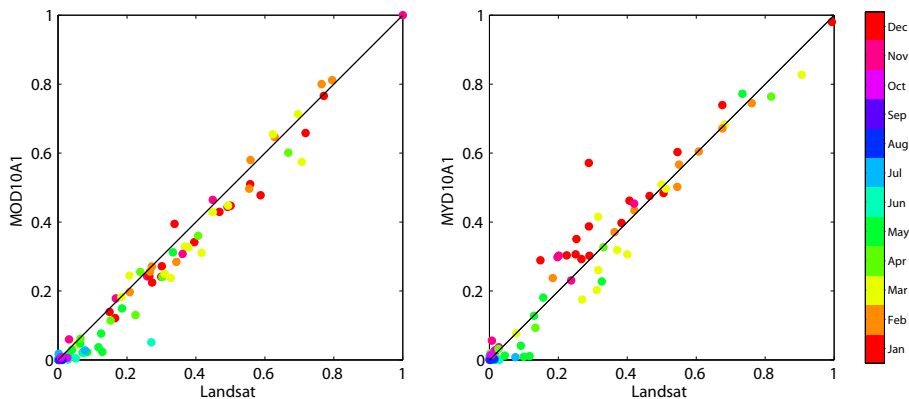


Figure 6. Snow coverage calculated from Landsat and MODIS snow products (Terra MOD10A1, Aqua MYD10A1) for 157 dates (139 dates for MYD10A1) distributed between 2002 and 2010 over the Pyrenees. The color indicates the month of the year. The snow coverage is defined as the fraction of the cloud-free area 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.

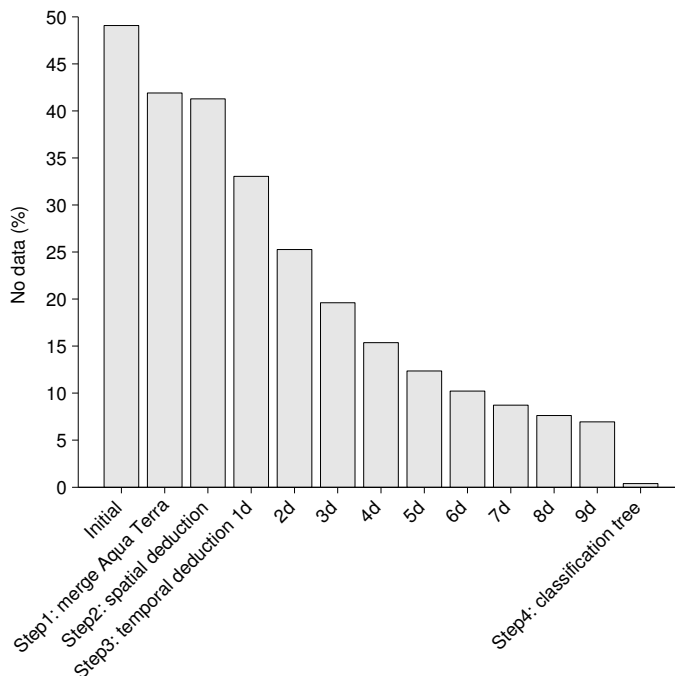


Figure 7. Evolution of the number of pixels classified as “no-data” (e.g. clouds) during the gapfilling procedure.

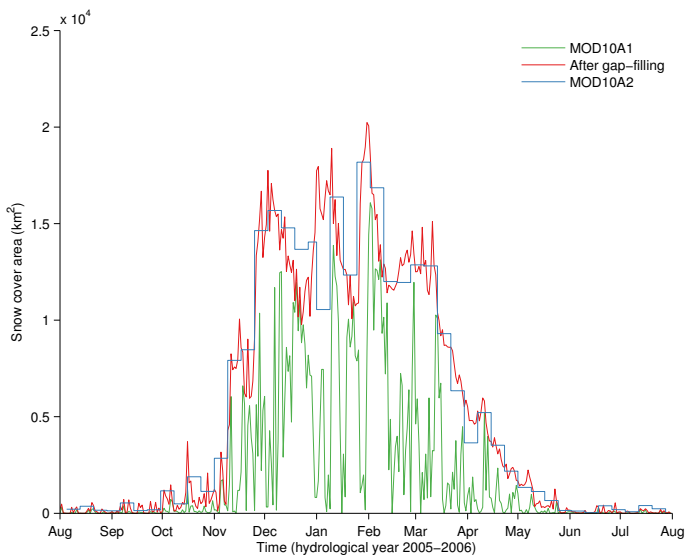


Figure 8. Snow cover area evolution in the Pyrenees over the hydrological year 2005–2006 for three products: MOD10A1, the gap-filled product from MOD10A1 and MYD10A1 (this study) and MOD10A2 (8 day maximum snow extent).

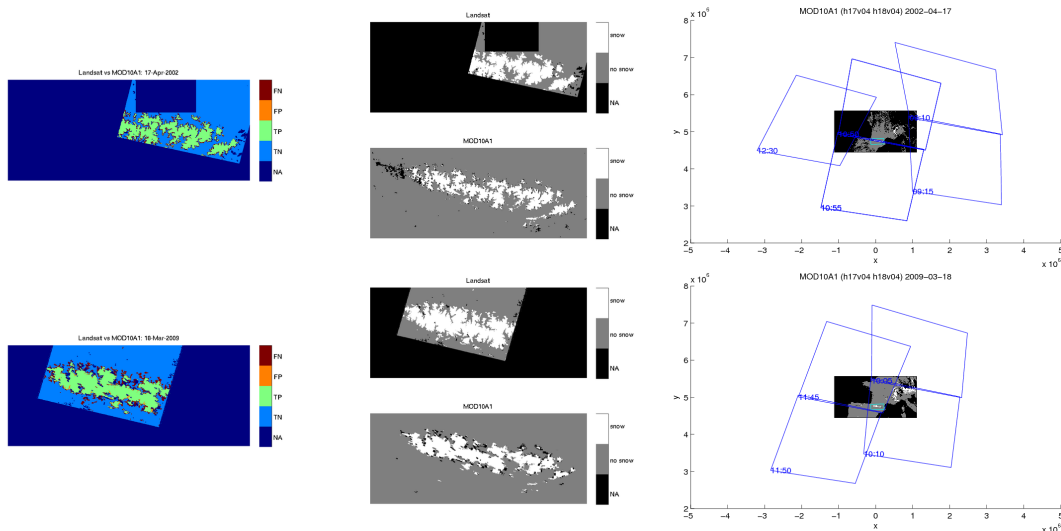


Figure 9. Comparison between MOD10A1 and Landsat for two dates. Left column: MOD10A1 vs. Landsat classification (TP: true positive, FP: false positive, TN: true negative, FP: false positive). MOD10A1 false negative are mainly located along the snow cover edges. Middle column: Landsat and MOD10A1 classifications 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.

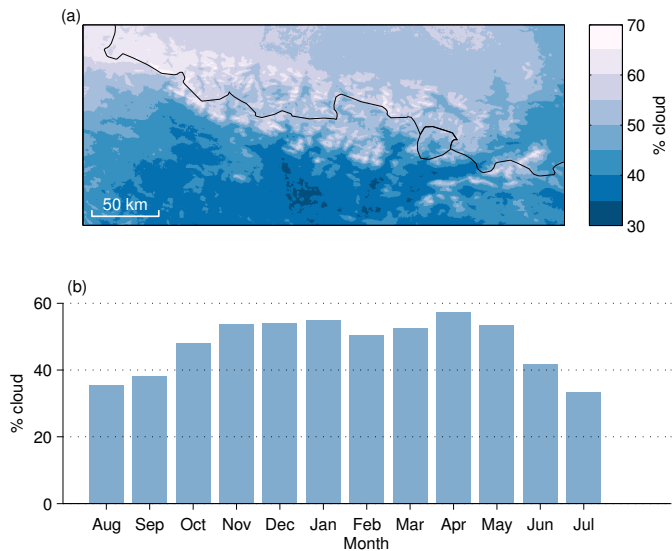


Figure 10. (a) Fraction of cloud covered pixels in MOD10A1 over 2000–2013 (b) Mean monthly cloud coverage from MOD10A1 in the study area.

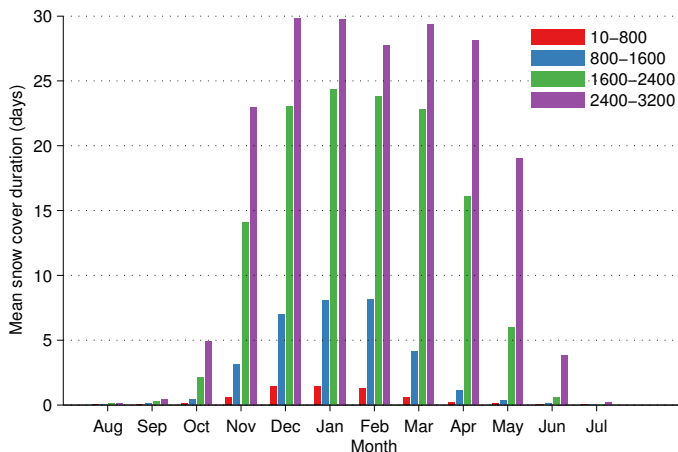


Figure 11. Mean snow cover duration in the Pyrenees over 2000–2013 for different elevation bands. The snow cover duration is the number of days with snow in our gapfilled product. It was computed with the same elevation bands as Fig. 1, except for 3200–3400 m a.s.l. (only 4 pixels at the MODIS resolution). Otherwise the fractional areas of each elevation band in the study domain are: 53 % (10–800), 31 % (800–1600), 13 % (1600–2400), 2.5 % (2400–3200).

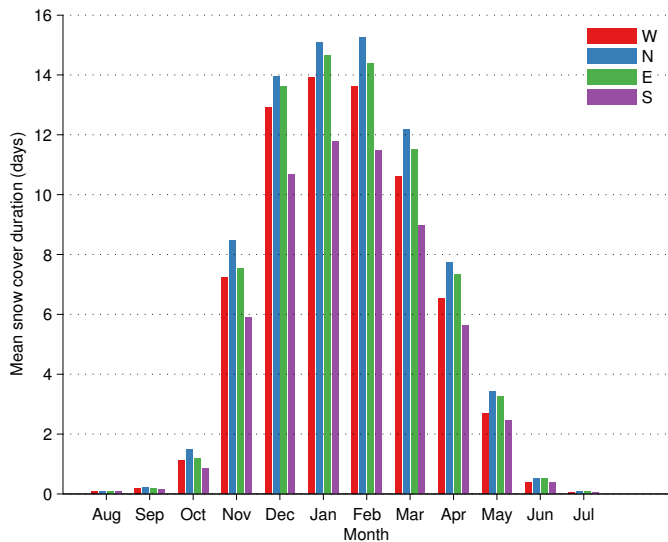


Figure 12. Mean snow cover duration in the Pyrenees over 2000–2013 for the four main aspect classes (W:west-facing slopes, N:north-facing slopes, E:east-facing slopes, S:south-facing slopes). The snow cover duration was computed only for the area above 800 m a.s.l..

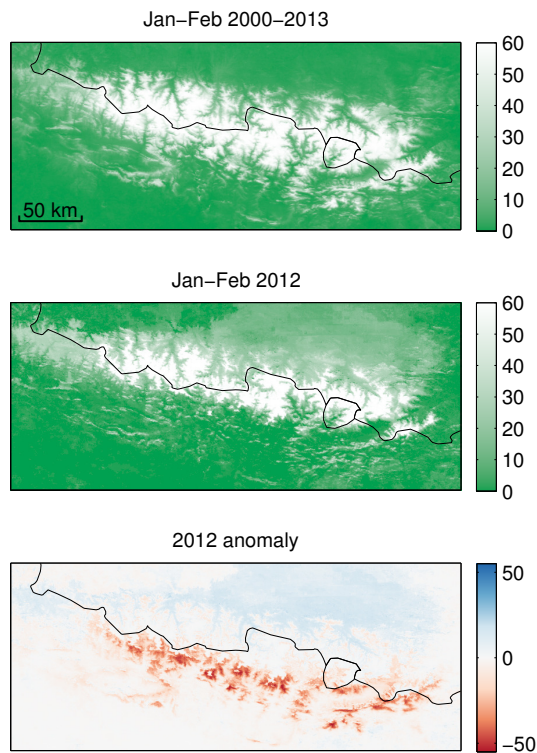


Figure 13. Illustration of the anomalous snow patterns in the Pyrenees during the winter 2012. Top panel: mean snow cover duration (days) in January and February, Middle panel: snow cover duration in January and February 2012. Bottom panel: snow cover duration anomaly.

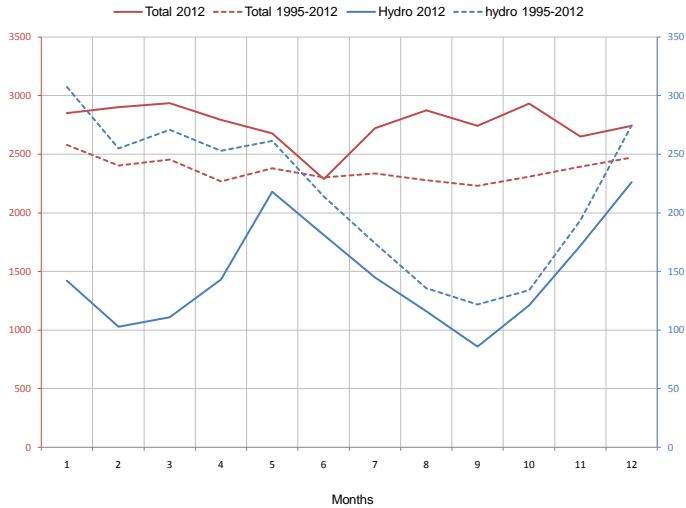


Figure 14. Monthly energy production in Spain (units: kTep). The right y axis is for hydropower, the left y axis is for the total energy production.