MODELED SNOW COVER IN PYRENEES MOUNTAINS AND CROSS-COMPARISONS BETWEEN REMOTE-SENSED AND LAND-BASED OBSERVATION DATA.

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ABSTRACT: Only few studies have already attempted to assess the distribution and magnitude of seasonal snowpack under the varying climate of the Pyrenees. In using modeling tools (SCM chain), Météo-France/CEN has generated a distributed climatology of the main meteorological and snow parameters at the spatial scale of the massif for the Pyrenees over the period 1958-2008. This work aims at validating it for different research uses. In particular, in the framework of the FluxPyr Project, a new study was conducted using MODIS snow satellite data over Pyrenees which gave the opportunity to perform a lot of cross comparisons during the last ten years and thus to complement the other classical validations. The MODIS information of snow cover coverage was compared to a corresponding modeled value obtained by a downscaling procedure. All results are then shown globally over the whole period in order to filter the downscaling noise and the small-scale effects over the computation grid which is also used for the comparisons with the data from the manual snow-weather observation network. The results show a close agreement between all involved information sources (> 80% between MODIS and SCM). The main discrepancies occur in the vicinity of the low elevations of the continuous snow cover (~60%), especially in the most eastward massifs. In addition the forest areas do not exhibit more differences that the forest free ones. The human observations are always close of the MODIS data (92% for snow occurence) and of SCM (89% for snow occurrence and 71% for depth).

KEYWORDS: Snow depth comparisons, MODIS remote-sensed data, climatology, SCM chain.

1. INTRODUCTION

An accurate estimation of the main characteristics of the snow cover over the Pyrenean chain is an important information for several geosciences applications in including avalanche hazard estimation and snow climatic studies which are two of our main goals. Few studies have attempted to assess the distribution and magnitude of the Pyrenean snowpack with modeling tools except in the framework of climate changes works as Lopez-Moreno (2009) for getting reference fields. With the previous experience of the Alps (Durand et al., 2009a & b), and always in using the SAFRAN/Crocus (SCM) model chain (Durand et al, 1999), Météo-France/CEN has generated a distributed climatology of the meteorological surface parameters and of various snow cover parameters for the Pyrenees (23 mountain massifs of about 500 km^2 across France, Spain and Andorra) (Maris et al, 2009) which covers the period 1958-2010. Concerning these different fields, an intensive work of validation has been done, mainly based on human or automatic field measurements during all the computation period. In addition, the FluxPyr European Project gave the opportunity to perform a new and independent validation of the snow surface distribution at fine scale in comparing the MODIS satellite outputs (Hall et al., 2001 & 2006) and our modeled results. This short paper will thus show briefly the main features of the obtained meteorological and snow climatologically fields over the Pyrenees and will focus on the different performed validation tests.

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2. DATA AND MODELS USED

2.1 MODIS.

We used the snow products MOD10A1 and MYD10A1 (Hall et al., 2001 & 2002) issued from the MODIS platform aboard respectively of the Terra and Aqua satellites and downloaded for the project from the National Snow and Ice Data Center (NSIDC, web site : http://nsidc.org/). We only used the snow coverage information on cloud-free pixels at 500m resolution for the 2000 to 2010 (Dec. to May) period in order to determine the fraction of the pixel area which is covered by snow. These data are produced by NSIDC using the SNOMAP algorithm and have been post-processed by CESBIO laboratory who also performed an extensive validation of MODIS daily snow cover product (Gascoin et al., 2012) by using the Landsat cloud classification method. This previous study increases thus our confidence in the reliability of this satellite product.

2.2 Land-based Observations.

The observations made in the French and Andorran Pyrenees are performed within the framework of the snow-weather observation network of Météo France. It is about a specific network, dedicated to the forecast of the avalanche risk. These observation sites, which are a little more than 50 in number, are mainly located in the Pyrenean ski resorts, and are in general close to the bottom of the ski tracks in a place representative of the environment, rather flat, not much windy and quite far from buildings. Their elevations are between 1000 and 2400 m, most of them being in the more limited range 1500-2100 m. Patrollers of the ski resorts, specially trained by Météo France, carry out the observations. The observations are done twice a day, near 08:00 and 13:00 local time from December 15 to April 30 of each winter. The observation sites of the Spanish Pyrenees can be, as in France, located in ski resort areas, but some of them are in mountain refuges. However, their global elevations are in a more reduced altitude range than in France between 1500 and 2200m. The observed parameters, the twice-daily frequency and the duration of the winter observation season are the same as in France.

2.3 Numerical models and produced fields.

Since the mid 1990's, Météo-France has operationally used an automatic system in order to simulate weather parameters, snow cover stratigraphy and avalanche risk at various altitudes, aspects and slopes for a number of mountainous regions (massifs) in Pyrenees. This chain which includes three numerical models, SAFRAN, Crocus and MEPRA (SCM chain) is usually applied for operational avalanche forecasting (Durand et al, 1999) and for retrospective snow research works. One of these works is a climatologically re-analyze project (1958-2010). Pyrenean chain is thus divided into 23 massifs (figure 1) of about 500 km2 where modeled snow and weather parameters are available in a geographical distributed way, at different elevations (by 300m step), 7 aspects and 2 slopes (20 and 40°).

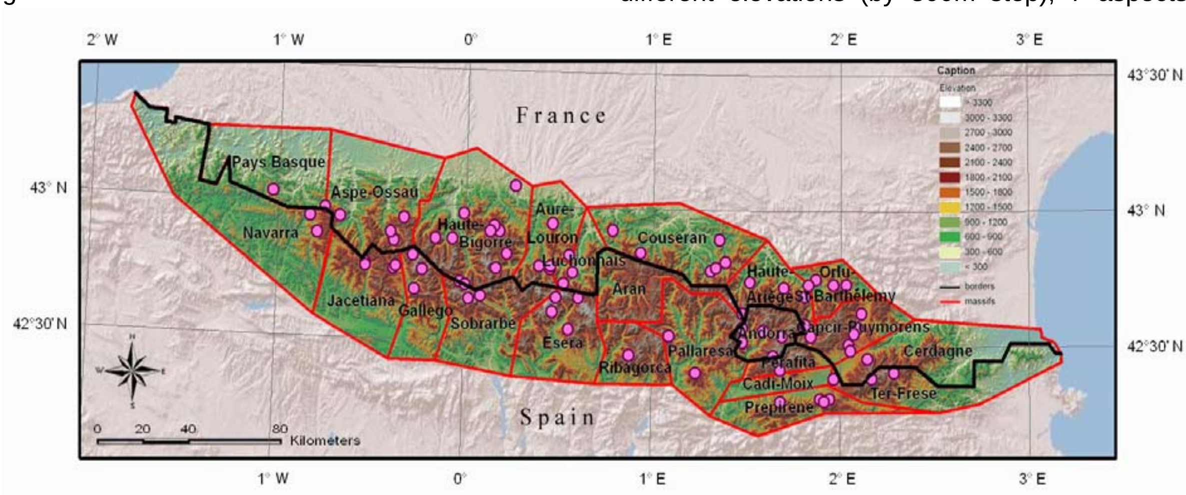

Figure 1 : The division of the Pyrenean chain into 23 climatologically homogeneous massifs (red lines) located in France (10 massifs), Spain (12 massifs) and Andorra (borders in black lines). Pink dots indicate field observation sites.

The suite is organized around the Crocus snow model which calculates the energy and mass evolution of the snow cover with a vertical discretization up to 50 layers of variable thickness in including snow metamorphisms and a representation of each snow crystals types. Crocus is thus forced by the SAFRAN objective analysis which provides hourly values of temperature, wind, cloudiness, humidity, precipitation conditions and incoming radiations. The way of running of SAFRAN consists in melting a « a priori » information coming from a meteorological "NWP" models with the observed information from land-based networks described above. No MODIS data nor snow information is used into the chain and snow fields in output are only derived from the meteorological fields in input. This assessment is at the root of our further comparisons. It is also worth noticing that the full system is never re-initialized along the year.

3. MASSIF-SCALE CLIMATOLOGY

At the root all the variables are hourly available at every elevation/aspect/massif and for three slopes (flat-20-40°). A brief averaged overview of this sample is given in figure 2 which exhibits the mean number of days with an occurrence of snow on the ground (snowdepth > 5cm) at 1800m on the entire period (Maris, 2009). On this figure the impact of prevailing northwest meteorological conditions accompanied by Atlantic low pressures is clearly visible with a marked west-east gradient both in France and in Spain. Rainy and snowy active systems are generally weakened in the eastern Mediterranean part. The north-south gradient is mainly due to foehn effects by northern fluxes. For all these reasons the minimum is located in the east-southern Spanish massifs.

4. VALIDATION PROCESSES

This paper focuses on three kinds of validations based on the MODIS products covering thus only the 2000-2010 periods. We shall show here the different operators used for the comparisons.

4.1 MODIS/SCM cross validation.

In order to compare the SCM outputs with other sources of snow data which are geographically referenced, we have projected the distributed SCM values on a regular topographic grid covering the study areas. We thus used a DEM coming from the mission “Shuttle Radar Topography Mission” (SRTM) (Farr T. G. et al. ,2007) with a step of 90m allowing to compute with accuracy enough an estimation of the local slopes and aspects at each point. As our goal was mainly to determine an estimation of the snow coverage variability at the location of the satellite pixel (about 500m large), this 90m horizontal mesh size was estimated consistent with the initial SCM spatial discretization presented previously in § 2.3 even if it is intrinsically finer. The main limitations occurred when the grid point elevation was outside of the SCM global vertical range, which is variable according to the massif, or when the grid point elevation was vertically situated between a non-snowy and a snowy SCM level. A simple interpolation scheme, treating at best at possible the previous limitations, was then used for the local interpolation. Even if some local inaccuracies due to fine local effects (topography, wind action, vegetation effects …) could occur, the final result was thus a full and consistent map of modeled snow depths covering the satellite path and allowing to determine over each satellite pixels a modeled snow coverage ratio computed over about 25 grid points. This computed ratio is thus directly comparable to the own satellite output of snow coverage at the same location with a spatial resolution of about 500m.

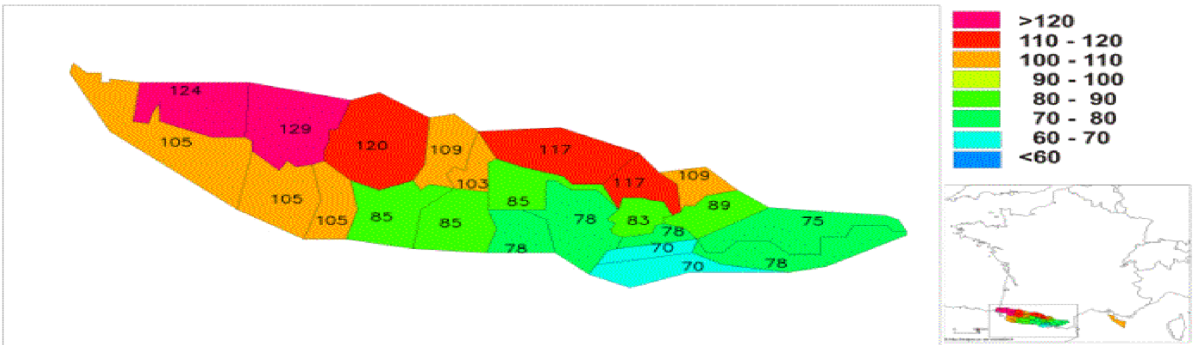

Figure 2 : Mean yearly number of days with snow on the ground (snowdepth > 5cm) at 1800m a.s.l for every massifs during the 1958-2008 period.

4.2 Fields Observations/SCM.

Each observation site of the snow-weather observation network is linked to a particular grid point of the 90 m grid. However, a direct comparison between the SCM outputs and the observation data is not fully judicious because of the difference of spatial representativity between the SCM chain (massif scale) and a local measurement. The same treatment used for MODIS comparisons was applied on the SCM outputs. A spatial area of about 500m by 500m (identical to the previous satellite pixel) centered on the point of observation was again defined in order to compute a limited set of 4 parameters describing the modeled snow cover conditions in the neighboring of the observation site (min, max, mean, central) and suited for a an easy comparison with the observed values during all the observation period in limiting the impact of the local variability. This raw way of processing was estimated relevant for limiting in average as much as possible the spatial scale effects between the observations (large variability and important small scale effects) and the chain (no small scale signal, smoothed larger scale values, artificial accuracy in the grid representation) which can induce some spurious bias and RMS in the comparisons.

4.3 MODIS/ Fields Observations.

In this case, only the occurrence or the lack of snow can be used to compare the data observed by satellite and those measured manually on the ground. Thus, for each observation site and each day common in the two sets, the binary respective values « snow » or « no-snow » are compared. For the satellite, a fraction 0% of snow will be regarded as an absence of snow while a positive fraction will be regarded as a presence of snow. In the same way, a manually measured snow depth deeper than 0 cm will be representative of a presence of snow, while a 0 cm value means an absence of snow. This calculation was also extended to the whole available data in order to carry out total statistics on the whole Pyrenean chain.

5. RESULTS AND DISCUSSIONS

5.1 MODIS/SCM.

Every day, at each satellite occurrence a comparison is done based on the difference of the two ratios. Over the full 10 years period, the averaged difference makes it possible to classify the pixels in one of the four following quality grades: very weak difference (difference less than 10% in snow coverage ratio), weak difference (difference between 10% and 50%), strong difference (50% and 75%), very strong difference (difference more than 75%). In addition, the use of the database Corine Land Cover (Bossard et al., 2000), relating to the occupation of the soil cover, makes possible to determine precisely the pixels located in a forest area in order to highlighting the possible effects of these wooded areas, effects not taken into account by the SCM chain. The forest fraction for each satellite pixel was thus computed in following the same process as for the snow-covered fraction.

The figure 3 exhibits the results of these four quality grades according five elevation classes for the entire period (« winter » months from November to may) and all the massifs. We can see low differences between the two data sets on the entire Pyrenees, except for elevations between 1500 and 2000 m where there are more significant differences. Around these altitudes the snow cover is often discontinuous, and there are consequently more differences between the two data set. This range of elevation corresponds roughly to the winter fluctuations of the vertical limit between snow and rain implying a larger variability in the occurrence of snow on the ground. Globally, very low differences are more frequent when the fraction of snow is null (no snow) or very high (continuous snow cover). On the opposite, high differences are more frequent when the snow cover is discontinuous.

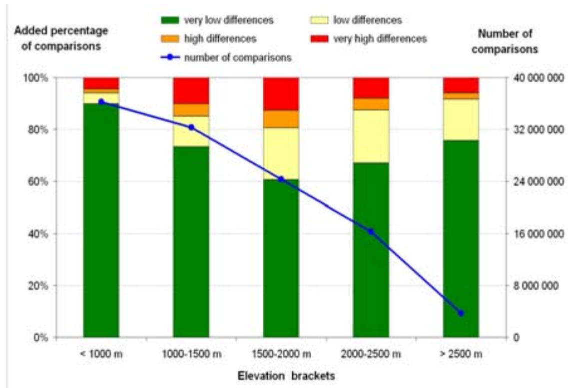

Figure 3 : Number of comparisons between modelled and observed snow occurrence divided into four quality classes according several elevation classes.

The figure 4 focuses on the "weak differences" localizations (corresponding to the green bar of the figure 3) in précising the temporal proportion of such weak differences for each spatial point. We can see that low differences are more frequent at low altitudes (valleys and plains) when the differences are the least frequent at middle altitudes and in the East part of the Pyrenees. The figure 5 allows to analyze the effects of the forest for the elevations under 2000 m a.s.l. Forest areas are not taken into account by SAFRAN-Crocus and are expected to influence MODIS satellite measurements (Gascoin et al., 2012). However, forest effects do not seem to be presently a source of difference for a climatologically study. Several other comparisons (not shown here) showing the variations of the agreement rates according the different massifs, the year or the month were also performed and confirmed the good spatial and temporal consistency of the results.

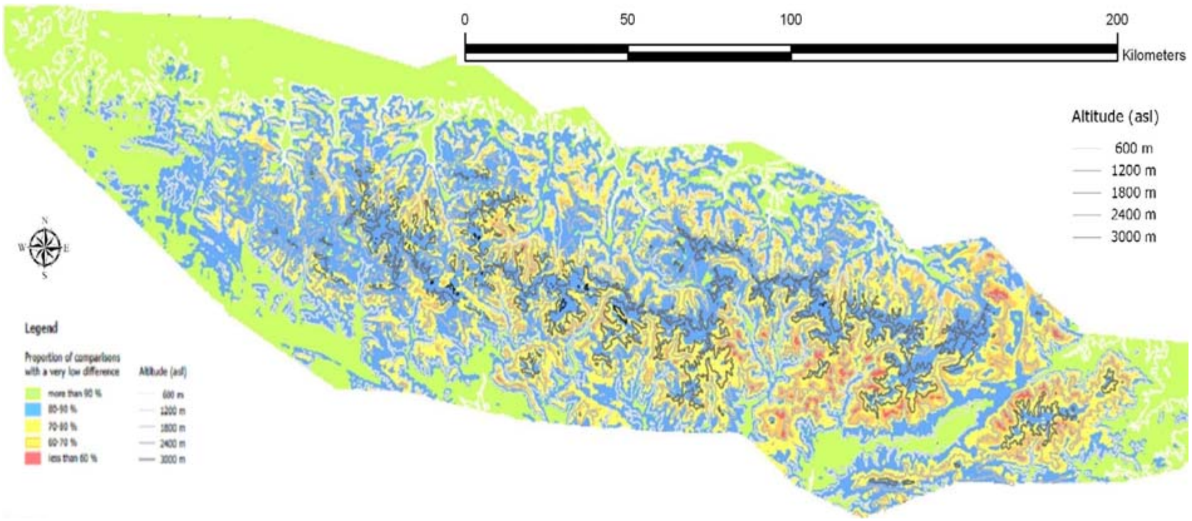

Figure 4 :Localisation of the site showing a very low difference between MODIS satellite SCM chain (green bar in figure 3, distributed as a function of massif, elevation, aspect and slope) (February 2000 to July 2010 period)

5.2 Field Observations/SCM.

In a first step, the comparison was based on the only occurrence of snow or not snow on the ground as previously for the satellite in combining the previous snow parameters in order to reduce the uncertainties. The agreement rate was found greater than 89% for all the available observations (~71) during all the 10 winter periods. Modeled snow depths were then directly compared to all the observation series according to two modeled threshold values (low, high) based on the previous snow parameters (Payen, 2011). The so induced three comparison classes (which mid class, including the mean value, has at least an amplitude of 20 cm) allow to roughly take into account the characteristics of the observation sites (flat, not windy, not too far from building, operated by non-meteorologists) and their fine scale variability. In addition, they filter also the small amplitude uncertainties of the model and its rather low spatial definition. In our comparisons, we shall consider that the result is correct when the observed value is comprised between the two thresholds (mid class).

Briefly, on the whole set of compared data, 70,9 % of the field observations have been found correct (into the middle class), when only 11% were below the low threshold and 18,2% were above the high threshold. The “low” case concerns mainly 6 observation sites which data are quite systematically low when the “high” case concerns only 2 sites.

5.3 MODIS/ Field Observations.

This last test aims at making our comparisons more complete and homogeneous. All the observation sites and the MODIS data have been used over the ten winters which gives a robust number of comparisons of about 47513 values. Among them 92% were found similar in term of snow occurrence on the ground. However, if most of the sites exhibit good results, and especially those which have the most important number of measurements, some of them show a lower agreement rate. For instance, two sites disagree on more than 30% of the compared days (“Ax Bonascre” and “St Pierre des Forçats”); their localisation (woody aspects near ski tracks) can explain a part of these discrepancies. We can also observe (not shown here) a certain homogeneity by sites in the comparisons. The sites which show “relatively” bad results are the same whatever the other source of data, SCM or MODIS.

6. CONCLUSION

Even if the SCM has been operationally used for many years by human forecasters, its climatologically applications are of prime importance and require suited validation procedures. The main limitation for these studies is the quite large spatial representation of the modelled fields and the internal assumptions of the model as the massif homogeneity and the no taking into account of the drifting snow and of the surface nature as forest. However, a large number of comparisons in the validation procedures can minimize the impact of these simplifications and give information at the modelling scale. The present study, limited to the last ten years because based on MODIS

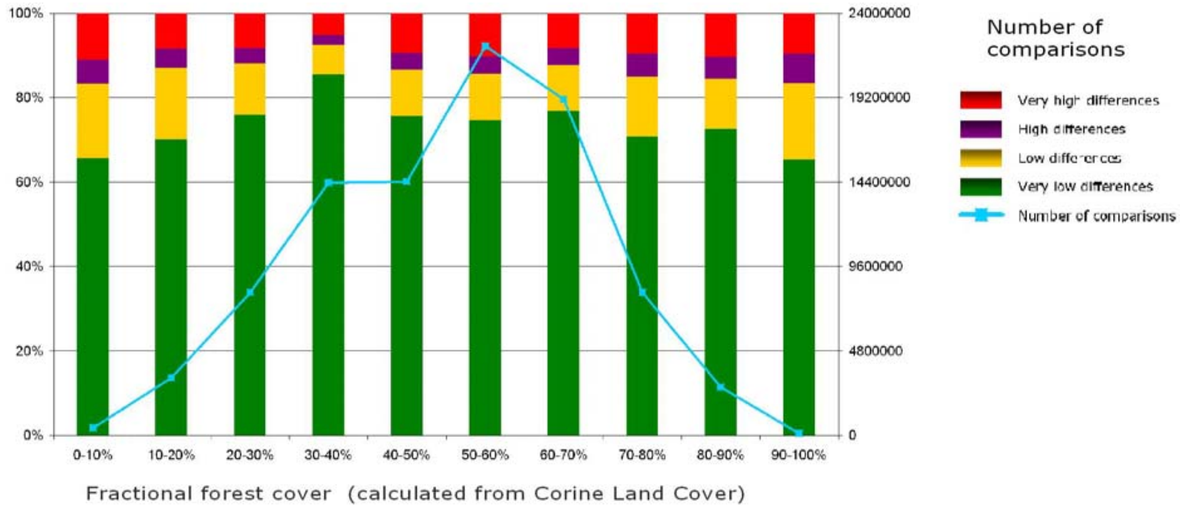

Figure 5 : Number of comparisons between modelled and observed snow occurrence divided into four quality classes according several fractional forest classes.

availability, is thus one among these different validation attempts. Its main characteristic is that it is consistent in term of crossed comparisons; the three sources of information, SCM, MODIS and field data are mutually compared between each of them.

In term of snow occurrence on the ground, we saw a very good agreement between all the involved sources. More discrepancies appear when the snow coverage is discontinuous generally at locations close of the limit between snow and rain. These areas show most of the differences between SCM and MODIS but they also are intrinsically those which concentrate most of the uncertainties in the SCM or MODIS computations. In addition, comparison results are relatively worse in the eastern part of the Pyrenean chain probably due to local and small scale phenomena as snow drift events in the framework of Mediterranean eastern meteorological circulations. Field measurements agree also well with both SCM and MODIS. However, some limited sites exhibit a systematic discrepancy with the two other series which seems due to local topographic effects.

Globally, this work has shown a good accuracy of both MODIS and SCM products during the past ten years, but other studies will follow for the older periods.

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ACKNOWLEDGEMENT: This work has been performed in the framework of the FLUXPYR (POCTEFA Programme EFA 34/08 -Interreg IV-A),) and took a great benefit of numerous student dissertations. We also warmly thank NSIDC for providing MODIS data and S. Gascoin (CESBIO) for his advices and post-processing tasks.