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On the use of MODIS Snow Cover Product for assessing snow extension and duration over the Po river basin

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SUMMARY Changes in climatic forcings on the Mediterranean area are foreseen by many global and regional models. Long-term temperature variations are expected to affect snow dynamics, thus impacting on the timing of the hydrologic response in Alpine catchments. Several authors agree in predicting a shift of the hydrologic regime in the major European rivers, due to a changed behavior of mountain valleys. In this context, digital snow maps are a powerful tool for reproducing large-scale snow distribution and extension. The use of such information for hydrological purposes is now considered an outlet of great practical interest. Here, we consider the Snow Covered Area (SCA) Product and develop a procedure for snow detection from MODIS data (MODerate resolution Imaging Spectroradiometeron on board Terra and Aqua satellites). MODIS snow maps have proven to be very reliable, despite the presence of cloudiness can mask the ground, thus preventing any snow detection. An application to Po river basin, in northern Italy, is here proposed. Daily maps of few years (2003-2007) have been analyzed and compared with the Digital Elevation Model (DEM) of the study area. By some clear-sky days we got complete maps of snow areas throughout the seasons, reproducing large-scale snow cover duration and its dependence on altitude. Focusing on the issue of cloudiness, we highlighted its increase at higher elevation. From our point of view, after this first attempt, MODIS Snow Products seem to have great applicative potentiality. However, many applications are conditioned to the possibility of providing a reliable estimation of ground conditions beneath the clouds.

Keywords: MODIS, Snow Maps, Po River, Climate change, Cloud Removal, Hydrologic Regime

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We would thank Renata Vezzoli for making available some digital maps of the Po river basin.

1. INTRODUCTION

In the context of climate change [53, 29, 11], the impact of snow dynamics on the hydrologic response is of interest for many environmental and socio-economic reasons [6, 3]. On the one hand, the water volume stored in the snowpack over the annual cycle from snow accumulation to snowmelt holds a rate of precipitation that reaches the ground only after the end of the winter season. On the other hand, snow cover depths, distribution and duration are strongly affected by climate change, making the hydrology of mountain areas more susceptible to temperature and precipitation changes [17, 55, 4, 51, 23, 50]. As results, climate change is expected to have a significant impact on water availability of snow-dominated regions [6, 3]. The discharges generated by mountain areas largely contribute to the streamflow of many rivers that cross the most populated and economically developed regions in Europe. The issue is thus of interest for water resource management and may have several socio-economic consequences on the European continent.

Since its regime depends both on temperature and precipitation, snow can be considered a reliable indicator of climate change [12, 6]. As a proxy of the energy net balance, temperature determines the switch between rain and snow as well as the occurrence of snowmelt or refreeze. Winter precipitation rules the amount of snow accumulating over the region while its spatial variability affects snow distribution (in the Alps precipitation increases with altitude [43]). Moreover, snow cover depths and distribution are not only the results of diurnal values of temperature and precipitation, but a product of the history of these two variable from the beginning of the accumulation season [5]. For these reasons long-term fluctuations of snow depths and snow covered areas provide a signal of changed climatic forcings. For example, interannual variations in the mean values of such indicators are considered a powerful tool for investigating climate change impact on snow-dominated regions and its implication on water resources [5].

Focusing on Po river system, Alpine areas cover 35% of the basin and contribute on average for the 53% of the total discharge [50]. Understanding the long-term variability of snow duration, distribution and snow water equivalent at the basin scale may be an important element in modeling climatic change impacts on the regime of the major Italian river. Furthermore, studies on this topic for such river basin seem absent or uncompleted. In this prospective, remote sensing of northern Italy can be useful for reconstructing recent long-term snow variability. In particular, MODIS Snow Cover Products seem very attractive because of their high spatial and temporal resolution and their accuracy and consistency [20, 45, 54, 1, 31]. This work provides a first attempt to apply MODIS snow cover maps over the Po valley. Benefits and drawbacks will be presented, with a focus on the issue of cloudiness [10, 30, 32, 33].

2. PREDICTION OF CLIMATE CHANGE IMPACTS ON THE HYDROLOGIC REGIME OF THE MAJOR EUROPEAN RIVERS

The European Alps are the most studied mountain area of the world in terms of weather and climate and related environmental characteristics. The prediction of a changing behavior of the snow-dominated Alpine valleys could be a key element for water resource management of the major rivers in the Middle-South Europe [6, 50]. The Alps operate as a water reservoir for four of Europe's largest river basins: the

Danube, Rhine, Rhone and Po flow across the most strategic areas of the continent from an economic point of view. A large part of the European population and thousands of industries located in the lowlands rely on water precipitated and stored in Alpine regions [50]. The occurrence of precipitation under solid form (snow) rather than liquid (rain) associated with low temperatures affecting mountain areas during the winter, determines a delay in the hydrological response due to the temporary accumulation of the forcing on the ground [3, 50, 40]. The expected increase in mean temperatures will result in shorter duration of snow covers and earlier snowmelt runoff that will induce a temporal shift in the Alpine river regimes. The discharges from highly snow-dominated catchments will be anticipated, thereby influencing the steamflows across the lowlands. Changes are expected for the Rhine [44, 25, 18, 19], for the Rhone [9, 7] and for the Danube [13]. The authors agree in forecasting a response of these rivers to a global warming characterized by increased winter and spring streamflows accompanied by a decrease in the average summer discharges. Together with a different distribution of the precipitation over the seasons, early snowmelt due to higher average temperatures is predicted to be the major cause of regime changes.

Figure 1:
A view from Passo dello Stelvio (2758 m a.s.l. - Sondrio, Italy), on May 21th 2012. Snow is still over areas facing north and gentle slopes.

3. SNOW COVER DURATION AND SNOW PRECIPITATION TRENDS ON THE ITALIAN ALPS

Recent snow cover changes were detected in the Swiss Alps, and confirmed by several studies [5, 24, 42, 28]. The reduction of snow cover duration at low elevations was generally associated with the increased mean winter temperature [42, 41, 28]. Only few works analyzed the trend of snow cover duration and snow precipitation in the Italian Alps during the last century, due to absence or shortage of historical records of monthly and seasonal snow cover extension. Through the historical time series of snow cover duration and cumulated snowfalls from 18 stations, located between 714 m and 2529 m altitude, [49] showed a reduction of the cumulative seasonal snowfall and snow duration for the last 40 years, with an increased rate since 1990s. The trend was observed both for the western and eastern regions, and was marked especially in springtime at low altitude (below 1500 m). Even some studies on the shrinkage of Italian glaciers have been carried out, typically showing a declining trend [8, 27, 2]. However, a complete study over the region covering all the range of elevations and longitudes has not been performed. Snow cover maps are a useful tool for the assessment of recent snow cover variability at large spatial scales, since they provide grid information on snow extent for the whole study area.

4. MODIS DAILY SNOW-COVERED AREA (SCA) PRODUCTS

The use of snow cover maps for hydrological purposes is considered an effective tool even if they provide information only on the spatial distribution of the snowy areas. When combined with local assessments or measurements of the snow water equivalent (SWE), it may allow to estimate the snow resource over the basin. In the context of remote sensing for snow detection, the high spatial (500 m) and temporal (daily) resolution of MODerate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites makes MODIS snow products very attractive for hydrological modeling, stated that many authors demonstrated their accuracy and consistency with ground-based observations [20, 31, 45, 54, 1]. The Spectroradiometers employed by Terra and Aqua satellites provide a snow covered area product (SCA) free available in the National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center. The maps belong to the last collection (Collection 5, [34]) of the MODIS Snow Products, released after the last reprocessing which began in September 2006. Collection 5 replaced the products of the previous reprocessing (Collection 4, [35]), showing improvements in the cloud-mask product and improved screening for erroneous snow. MOD10A1 is a set of daily MODIS snow products available from February 2000 that contains daily snow maps from the Terra satellite, while MYD10A1 are similar products derived from the MODIS on board the Aqua satellite, launched in May 2002. The MOD10A1 and MYD10A1 products provide the daily snow albedo [22], the fractional snow cover (FSC) [39, 38] and the snow cover daily tile. The last product is the one of most interest for our purposes since it contains the binary information snow/no snow in each pixel.

MOD10A1 and MYD10A1 are generated through a mapping of pixels derived from the swath products MOD10L2 and MYD10L2 to their geographic locations in a MODIS-specific global sinusoidal projection. The name "swath" is due to the fact that it represents the snow cover acquired in approximately 5 minutes of MODIS scans. The selection of one daily observation is performed by a scoring algorithm which identifies the observation nearest local noon and closest to nadir.

4.1 NORMALIZED DIFFERENCE SNOW INDEX

The detailed description of the MODIS snow algorithm can be found in the Algorithm Theoretical Basis Document [16]. We provide here an overview on some key procedures involved. The procedure for snow identification employed by MODIS Snow Products works on a pixel-by-pixel basis involving a grouped-criteria technique which uses the Normalized Difference Snow Index (NDSI) and other spectral threshold tests [15, 21]. The NDSI is defined as a measure of the relative magnitude of the characteristic reflectance difference between the visible and short-wave IR reflectance of snow [16]. The snow-mapping algorithm (Snowmap) consists of some tests and decision rules that identify snow and lake ice in each pixel of a MODIS image, and it is able to map snow cover even in dense forests. Discrimination techniques for identifying snow and cloud are based on differences between cloud and snow/ice reflectance and emittance characteristics [16]. The NDSI-based criteria can separate snow from most obscuring clouds, however it does not always discriminate optically-thin cirrus clouds from snow.

4.2 SNOW - CLOUD DISCRIMINATION

Clouds are masked using data from the MODIS Cloud Mask data product (MOD35) with daily temporal and 1 km spatial resolution. Such cloud masks represent an input for the Snowmap algorithm. If the cloud data product provides evidence of cloud, the pixel under examination is classified as cloud, otherwise it is processed by Snowmap. However, the edges of snow cover, where snow is sparse or thin, are frequently identified as cloud by the cloud mask algorithm [34]. A solution for the problem has not been formulated yet. Also the opposite case may occur, leading to very small amounts of erroneous snow mapped in some cloud conditions. The latter situations are determined firstly by a failure of the cloud mask algorithm in identifying clouds and then by a misclassification in the snow algorithm (some cloud may present spectral features more similar to snow). Anyway after the latest improvement of the cloud mask algorithm snow and cloud confusion errors have been noticeably reduced in Collection 5 [34, 36].

4.3 LIBERAL CLOUD MASK The standard, conservative, cloud mask is derived from MOD35 and overlapped to the map of the study area. Several solutions were tested in order to find a more appropriate cloud mask for snow-mapping applications. One of them was to select a subset of cloud spectral tests results from MOD35 to generate a second, more liberal, cloud mask within the snow algorithm [35]. The choice of introducing also a new experimental cloud mask for snow mapping descended from the aim of reducing cloud obscuration, by allowing for analysis of snow in pixels under translucent or very thin clouds. Moreover few studies found that in the transition zones from snow to land MODIS cloud masks inherited from MOD35 frequently mapped edges of snow-covered areas as cloudy, often in a suspicious way [20]. The main advantage of a liberal cloud mask is that it allows the snow analysis on more pixels, preventing also the misclassification of some snow pixels as cloud. On the contrary, during the summer or in regions where snow should not exist, the conservative cloud mask from unobstructed field-of-view flag of MOD35 seems more reliable, since it prevents that some types of ice clouds would be falsely identified as snow. In Collection 4, the standard cloud mask was used to produce snow maps in the "Snow Cover" and the liberal cloud mask is used to produce the snow map in the "Snow Cover Reduced Cloud". [1] found that the target of removing the false detection of snow as clouds, especially along the boundary between snow and no snow, was achieved using the Snow Cover Reduced Cloud product. However, the improvements provide by the new criteria were outweighed by the disadvantage in situations where actual clouds were not mapped and were then classified as land by the snow algorithm, although it was actually snow cover beneath the clouds [34]. Overall the conservative cloud mask from MOD35 resulted more accurate and reliable than the experimental liberal cloud mask, which was dropped in Collection 5 [34].

4.4 MAPPING SNOW COVER IN FORESTED AREAS In forested location, snow covered areas usually present a lower NDSI requiring the adoption of a different threshold. Forested pixels are identified by a normalized difference vegetation index (NDVI). The NDVI is defined similarly to the NDSI, and it has been effectively adopted for monitoring global vegetation conditions throughout the year [47, 48]. A lower NSDI threshold is then employed for identifying snow cover on forested pixels. The Snowmap algorithm thus combines the NDVI and the NDSI in order to discriminate between snow-free and snow covered forests, adapting the new criteria to forested areas without compromising the performance over other land covers [21]. MODIS Snow Product also uses a surface temperature threshold, based on MODIS product MOD11A1, to eliminate spurious snow cover in areas where the retrieved surface temperature exceeds 280 K [37].

4.5 MODIS FRACTIONAL SNOW COVER PRODUCT

The recent "fractional snow cover" (FSC) product [39, 38] is based on an empirical relationship between the fractional snow cover and the NDSI, and it was developed in the decade following the MODIS launch. It is now available from Terra since 2000 and from Aqua since 2002, providing for each pixel the percentage of surface covered by snow. Our choice of adopting the binary product SCA instead of the fractional one is due to its wider use in the last ten years which has made available several assessments of its reliability.

5. ASSESSMENTS OF MODIS SCA PRODUCT

Several studies performed assessments on MODIS product quality, comparing snow maps with in situ information for regions characterized by different environmental conditions. In this section we provide a review of the "absolute validations" completed, in which the MODIS daily snow maps are compared with ground measurements or maps from Landsat data, considered to be the "truth". The comparison between MODIS SCA maps and ground information can be done only for those pixel not obscured by clouds, thus assuming an high performance of the employed algorithm for cloud detection. Errors from snow-cloud misclassification need to be identified through other means, for example by a visual examination or by a comparison with images from other satellites.

[20] compared daily snow cover maps of the Upper Rio Grande Basin produced from MODIS on board the Terra satellite (MOD10A1) against in situ Snowpack Telemetry (SNOTEL) measurements for the 2000/2001 period. They concluded that errors in mapping extra snow and missing snow by MODIS are comparable, indicating an overall classification accuracy in the order of 88%. They also showed that the majority of the cases when MODIS fails to map snow occurs for snow depths of less than 4 cm. Even most of the discrepancies occurring early and late in the snow season were associated with thin and patchy snowpack conditions. A similar seasonal pattern to the errors was later detected by [45], with lower agreement during the early part of the snow season and during snow melt. Overall, in [45] the MOD10A1 results exhibited an average percentage agreement of 93% with the in situ data.

In the transition zones, [20] suspected the cloud mask product (MOD35) to map edges of snow-covered areas as cloud, after a comparison with data from the National Operational Hydrologic Remote Sensing Center. Even if by visual examination, the frequent lack of a clean transition from snow-covered to snow-free areas suggested further investigations on the MODIS cloud masking accuracy. The same interpretation can be found in [46], for a basin located in the upper Euphrates River, resulting from a visual comparison between the original MODIS image and the MODIS SCA maps. Although an attempt was made in order overcome the problem by introducing a more liberal mask, it was subsequently abandoned for the loss of accuracy in detecting clouds showed by the new algorithm.

[45] compared daily snow cover maps (MOD10A1) acquired over Canada with almost 2000 meteorological stations throughout a 160-days period in 2001. They outlined the dependence on land-cover types of the agreement between snow maps and ground information, with lowest accuracy affecting evergreen forests where the MOD10A1 maps tended to overestimate snow cover. The dependence on land cover type was first suggested by [16], who noted that the performance of MODIS maps were dependent on land cover, with lowest accuracy for forests and mixed agriculture and forest.

Under clear sky conditions, a low omission error (misclassifying snow as non-snow covered land) was found by [54] using four representative SNOTEL stations as constraints for the upper Rio Grande basin from February 2000 to June 2004. They reported an overall accuracy for these stations ranged from 92% to 96%.

In Europe, [31] compared daily MODIS snow maps from Collection 4 with in situ data of 754 climate stations over the whole Austria. This study seems to be of interest focusing on our targets, since the wide and heterogeneous Austrian territory presents similarities with our case study (Po river basin). The range of altitude covered by these two regions is similar, as it is the size of the study area. Moreover, given the closeness of the Po river basin to the southern part of Austria, the two regions have certainly similarities in terms of climate. [31] report on cloud-free days, a classification accuracy with an average of 95%. They also investigated the conditions which led to the loss of accuracy, thus concluding that there was not a relationship between the classification errors and dominant land cover type or local topographical variability. On the contrary, they reported the presence of clear seasonal patterns to the errors. For the same percent of snow cover pixels over the study area, the different condition of the snowpack in spring and autumn was considered the likely reason of the systematic variations in the product accuracy. Since the snowpack in spring is well developed, the errors tend to be smaller than they are in early winter. In agree with what reported by [20] for the upper Rio Grande, they found that overestimation and underestimation errors balances during most of the year.

[26] tested the accuracy of MOD10A1 with in situ observation data under cloud-free conditions during four snow seasons from November 1 to March 31 for the period 2001-2005, in northern Xinjiang pastoral area. Daily measurements of snow depth, minimum, maximum and mean temperature were observed at 20 climate stations located in areas with different slope, aspect and land cover type. The authors reported an overall accuracy of MODIS daily snow cover mapping algorithm in clear sky condition higher than 98.5%. Analyzing the sources of errors, they found that snow depths and land cover types play the major role. Similarly to what found by [20], a snow depth of 3 cm was individuated as a possible threshold for the product accuracy, with MODIS difficulties in individuating snow depths lower than this value because of the surface reflectance affected by the soil conditions.

All these studies focused on the assessment of MODIS SCA by performing tests on MOD10A1 products, provided by the MODIS on board the Terra satellite. The one employed by the Aqua satellite was conceived in order to provide an identical set of products (MYD10A1). However, the non-functional detector of band 6 on the Aqua MODIS imposed a replacement with the similar spectral signature of snow in 7 in the snow-mapping algorithm. Also the cloud mask algorithm in MYD35 adopted this replacement. Such forced change may slightly affect the accuracy of the MYD10A1 products that have not yet been assessed in detail, as stated by [14].

A comparison between Terra and Aqua snow maps was carried out by [52], from 1 September 2003 to 31 August 2004. The study area and the climatic stations involved are the same of [26]. For cloud-free pixels the agreement of land classification from MODIS Terra and Aqua daily snow cover products was close to 100% for the entire hydrologic year. They reported a good accuracy even in the snow classification, but with a seasonal pattern which reached higher values in the winter months. They also showed that major disagreements took place in the transitions zones from snow to land. Since MODIS Terra and Aqua cross the equator at different times, it was not possible to affirm if the disagreement was depended on a changed condition (snow may melt away or accumulate) or on a different output of the two snow map algorithms while analyzing the same snow/land distribution. However under clear sky condition Terra and Aqua daily snow products resulted to have similar accuracy when compared with in situ snow depth data.

We want to point that all the MODIS products tested in such works belong to Collection 4 or previous reprocessing. Given the high accuracy shown by the several assessment under clear sky condition, the most significant factor affecting snow detection seems snow/cloud discrimination. The errors may be caused either by identifying cloud as snow, or snow as cloud. Snow/cloud confusion generally occurs in cloud-shadowed land, or and thin, sparse snow cover. However, [14] and [34] reported a notable improvement in snow mapping after the last reprocessing, due to improvements in the Collection 5 cloud-mask algorithm. Moreover, since the problem exists mainly in cells where the amount of snow is scarce, it may not have a significant impact on the assessments of the SWE at the basin scale. For these reasons, the products in Collection 5 look even more attractive for our purposes.

6. CLOUD REMOVAL ALGORITHMS

The primary limitation in using MODIS Snow Products is that no information on ground conditions are available beneath cloud covered areas. During the year clouds may obscure on average most of the study area, thus restricting the efficacy of the MODIS maps for hydrological targets. For example [31] indicated that, on average, clouds obscured 63% of Austria in the period from February 2000 to December 2005. [26] found that cloud covers wider than 10% of the study area occurred on 99% of the MODIS daily snow product from November 1 to March 31 of year 2001 to 2005 in northern Xinjiang area, China. Analyzing several snow seasons recorded by the two MODIS instruments over the Trans Himalayan region, [33] reported a mean cloud percentage over the study area between 20% and 37% for Terra images and between 32% and 48% for Aqua. The advantage to benefit of a product with daily temporal resolution is therefore conditioned to the ability of estimating the presence of snow in areas obscured by clouds. Several procedure have been developed in order to reproduce daily snow distribution in overcast condition, combining temporal and spatial information obtained from neighboring areas [10, 30, 32, 33]. The algorithms usually involves few steps, which progressively remove the cloudiness. Some of them are based on physical evidence (e.g. the probability of finding snow increases at higher altitude), others relate the feature of the hidden regions with those of surrounding visible locations. Since all the algorithms combine spatial information coming from cells already classified, the proceeding of the solution in series rather than in parallel makes available at each step new classified areas, thus improving the efficacy of the next.

7. STUDY AREA

Po is the major Italian river and one of the most important fluvial system in Europe from an economic point of view. It flows more than 650 km eastward across northern Italy, from a spring seeping from a stony hillside at Pian del Re, Piemonte, through a delta projecting of 380 square kilometers into the Adriatic Sea between Venice and Ravenna.

Its drainage area covers approximately 74000 square kilometers, of which about 71000 located in Italian territory, a quarter of the national territory. The remaining afferent area is

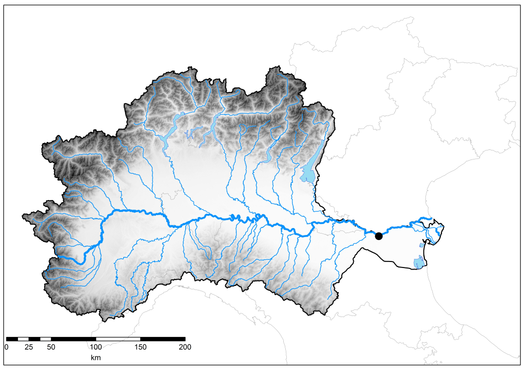

Figure 2:
Main river network of the Po valley: the closure is usually set at Pontelagoscuro (FE), a few tens of kilometers from the mouth.

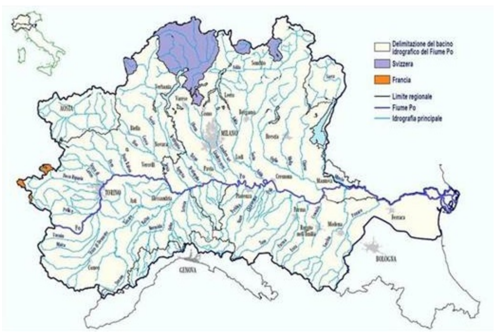

Figure 3:
The territory drained by the Po and its tributaries.

Source: ARPA Lombardia

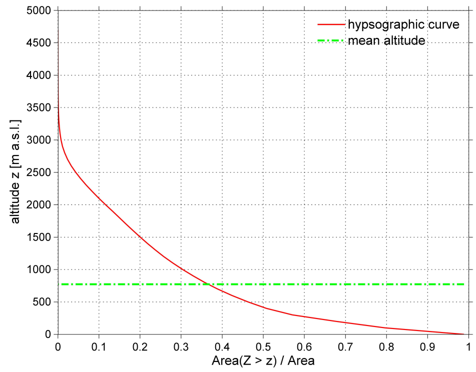

Figure 4:
Hyprographic curve of the Po river basin derived from the DEM.

located for the most part in Switzerland (Toce river basin) and for a smaller part in France. Considering the level of utilization of water resources for agricultural and industrial purposes, the Po basin is a focal point of the Italian national economy.

Through its tributaries, the river drains mountain regions that reach altitudes above 4700 m a.s.l. in the Aosta Valley.
The hypsographic curve shows the relationship of the area to the elevation for the specified terrain. The Po case is plotted on the graph (Figure 4), where the x-axis represents the surface areas (or relative surface area) which lies above and below a marked elevation while the y-axis represents the elevations above the sea level. The hypsographic curve has been obtained from the DEM with 500 m spatial resolution. The figure shows that more than 30% of the area lies above 1000 m a.s.l., where snow dynamics are expected to have an important effect on the hydrologic cycle. As we will show, this percentage is an indicative value of the snow covered area in the middle of the winter. These evidences imply that the accumulation and melting of the snowpack at the different altitudes come in regulating the streamflow. Further investigations could be addressed to the study of the impact of these processes on the lowland outflows. The spatial and temporal evolution of the snow cover over the basin is thus one of the core issue in characterizing the hydrologic regime of such river, as well as for assessing its susceptibility to changing climate conditions.

8. DATA PRE-PROCESSING

Daily Snow Products MOD10A1 and MYD10A1 are selected and downloaded from the Nasa's EOSDIS "Reverb", the next generation metadata and service discovery tool. We use Collection 5 processing of MODIS images [34]. Snow cover daily tiles are provided in hierarchical data format and in sinusoidal projection. Snow maps of Northern Italy are then projected into UTM WGS84 coordinate system, Zone 32N, and overlapped by a mask of the Po river basin, in order to identify pixels belonging to the study area and to clean up the image from unnecessary data. MODIS Snow products use a Sinusoidal grid tiling system. Tiles are 10 degrees by 10 degrees at the equator. The study area is entirely covered by the h18v04 tile with 500 m spatial resolution. After the transformation, we reclassified the MODIS snow cover maps from originally 16 pixel classes [34] to four classes: snow, land, clouds and others. "Missing data" and "No decision" fields are treated equally to cloud pixels, where the snow existence has to be estimated. Since any cloud removal algorithm would process snow maps through information from the DEM, a compatibility of these two grids is required, both in term of cell dimension and location. The DEM of the catchment was obtained from the Elevation Model of Italy with 200 m spatial resolution, overlapping the shape file of the study area. The elevation model was then resempled to 500 m spatial resolution, using the nearest neighbor assignment, to match the spatial resolution of snow cover data.

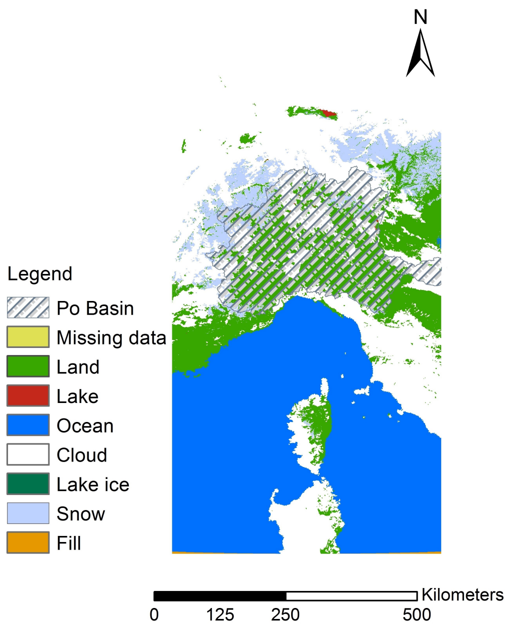

Figure 5:
MOD10A1: Snow cover daily tile February 15th, 2004.

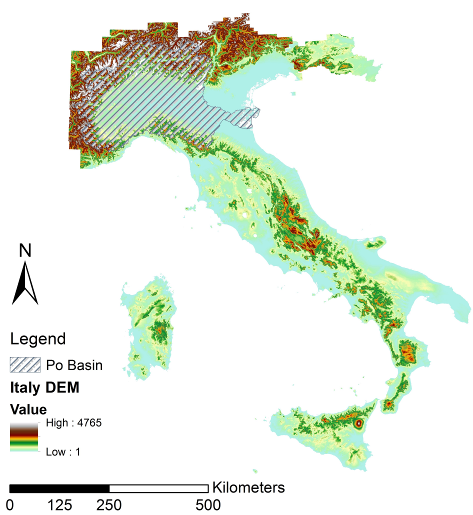

Figure 6:
DEM of Italy with cell size 200 m X 200 m.

9. APPLICATION OF THE MODIS SCA PRODUCT TO THE PO VALLEY

We downloaded and processed daily Terra and Aqua SCA maps from January 2003 to December 2007.

Figures 8, 9, 10 represent three maps extracted

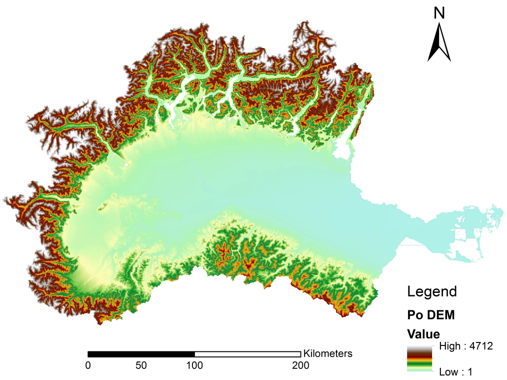

Figure 7:
Po DEM with 500 m spatial resolution.

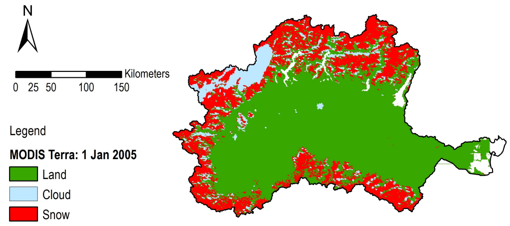

Figure 8:
Processed MODIS Terra snow map on January 1st, 2005.

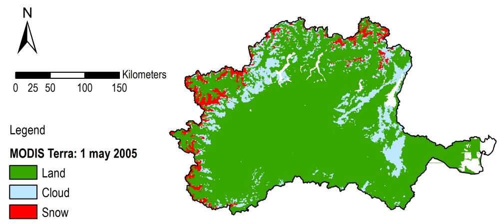

Figure 9:
Processed MODIS Terra snow map on May 1st, 2005.

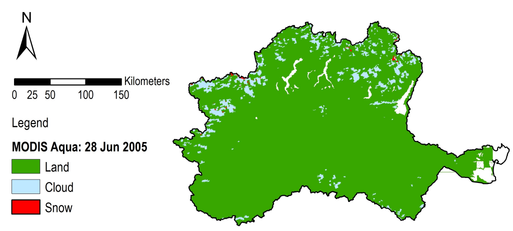

Figure 10:
Processed MODIS Aqua snow map on June 28th, 2005.

from the 2005 melting season, selected because of the low cloudiness that allows to observe the distribution of the snowy areas over the entire basin. The first image shows the MOD10A1 product on January 1st, 2005 when the snowpack is well developed and snow is widespread covering the whole Alpine region and the Tuscan-Emilian Apennines. The mean altitude of the snow covered areas is 1680 m a.s.l. Figure 9 shows snow distribution in the middle of the melting season, when snow is present only in the uplands at the highest elevations. Figure 10 is the snow map from the Aqua MODIS at the end of June, when snow existed only around the major Italian glaciers.

As indicative value of the fluctuation of the snow covered area throughout the year, in the Figure 8 snow is about the 30% of the pixel not masked by clouds, while this percentage decreases to 5% (Figure 9, average elevation of the snow-covered pixel of 2640 m a.s.l.) and 0.2% (Figure 10, where the mean altitude of the snow covered cells exceeds 3260 m a.s.l.) through the melting season.

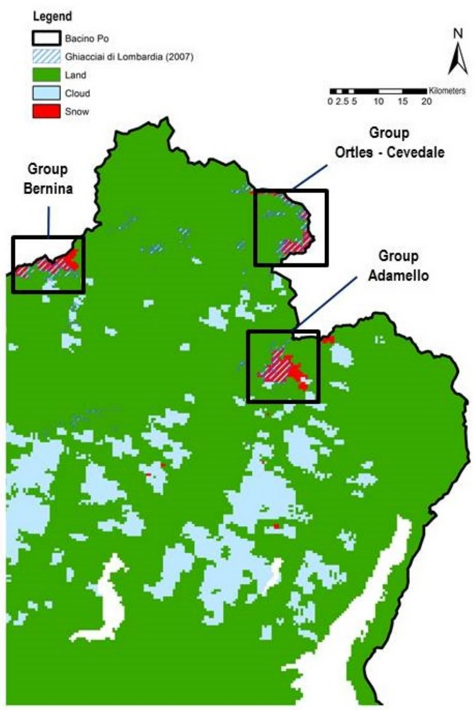

Figure 11:
Comparison between the digital map of the Lombardy's glaciers (source Arpa Lombardia) and the snow distribution from MYD10A1 at the end of June 2005.

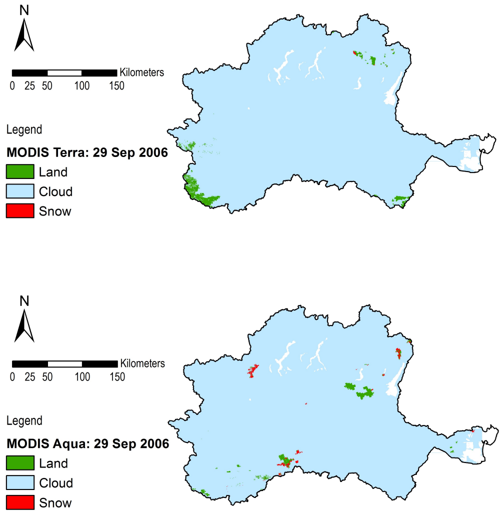

Figure 12:
Cloud mask on September 29th, 2006 affecting both Terra and Aqua sensing.

Analyzing the most cloud-free days without snowfalls in the lowlands of the 2004/2005 and 2005/2006 winter months, the percentages between 20% and 30% seem a representative range for the long-lasting snow covered fraction of the basin. Notice that the hypsographic curve of the Po Valley had shown that about 30% of the area lies above 1000 m a.s.l. Figure 11 shows a comparison between snow observed by the Aqua MODIS on June 28th, 2005 and a digital map of the Lombardy glaciers. The latter is the result of processing and comparison of areal data taken from orthophotos (1999 - 2007), and from glaciological registers. Given that at the end of June the snow cover extension has not yet achieved its annual minimum size, it is possible to notice how the cores of the glaciers are contained in boundaries identified as snow by MODIS. Digital maps of glaciers can be an important tool for the validation of MODIS SCA Products.

We studied the issue of cloudiness to get an idea of how much it would restrict the fruition of a product with daily temporal resolution. Once reclassified each snow map in three classes (cloud C, snow S, not snow (or land) L), let N_c, N_s, N_l be the number of cloud, snow and land pixels included in the daily map. We get that

$$C_d = \frac{N_c}{(N_s + N_l + N_c)} = \frac{N_c}{N_{tot}} \qquad (1)$$

represents the percentage of area hidden by clouds within the basin, observed on the day d. The variable C_d ranges from 0 to 1 over the year, depending on cloudiness. The absolute frequency histogram of C_d is plotted on Figures 13, 14 for the years 2005 and 2007. The mean

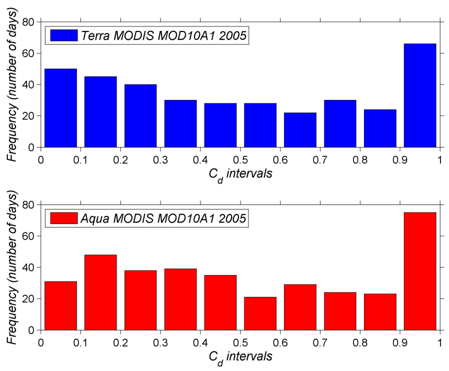

Figure 13:
Absolute frequency of the daily cloud percentage C_d, year 2005.

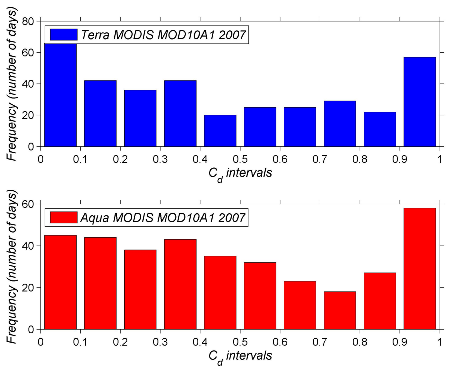

Figure 14:
Absolute frequency of the daily cloud percentage C_d, year 2007.

annual value C_a is obtained as

$$C_a = \langle C_d \rangle = \frac{\sum_{d=1}^{N_d} C_d}{N_d} \tag{2}$$

where N_d is the number or recorded days for that year. Processing MOD10A1 and MYD10A1 products of four years (2004 - 2007) we got that the mean annual cloud-covered part of the basin corresponds to a percentage between 48 and 54% for the Terra MODIS and between 50% and 56% for the Aqua MODIS. These values are slightly lower than those found by [31], who estimated that clouds obscured 63% of Austria in the period from February 2000 to December 2005. The higher values found in the Aqua images depend on the fact that Aqua crosses northern Italy few hours later, in the afternoon, when cloudiness usually increases. In both cases these rates exceed the 60% analysing only the Alpine regions located at elevations higher than 2000 m a.s.l., confirming the evidence that clouds tend to insist especially over mountain areas. Named N_{tot} the sum of N_c, N_l and N_s:

$$C_d(H > h_t) = \frac{N_c(H > h_t)}{N_{tot}(H > h_t)} \tag{3}$$

where h_t is the threshold altitude above which the relative extension of the cloud mask C_d is calculated, and H is the DEM. The frequency of $C_d(H > h_t)$ (year 2005) is plotted on Figures 15, 16, 17, 18 for four threshold altitudes h_t.
The mean annual value of the area hidden by clouds, for the part of the basin which lies above h_t, is provided by

$$C_a(H > h_t) = \langle C_d(H > h_t) \rangle \tag{4}$$

In figures 19 and 20 are proposed the relations h_t - $C_a(H > h_t)$ for the year 2004 and 2006. The upper threshold is bordered to 3500 m a.s.l. to keep an acceptable number of observed cells, since the number of pixels over which the spatial mean is calculated decreases for higher h_t. The trend of the mean annual cloudiness confirms an increase in the probability of being masked by clouds for pixels in the uplands. Since such areas are also those where snow is expected with greater frequency, the problem of cloudiness has a significant (and adverse) impact on the number of days in which the presence of snow can be detected. In order to preserve a daily temporal resolution of the products, cloud removal methodologies [10, 30, 32, 33] should be taken into considerations.

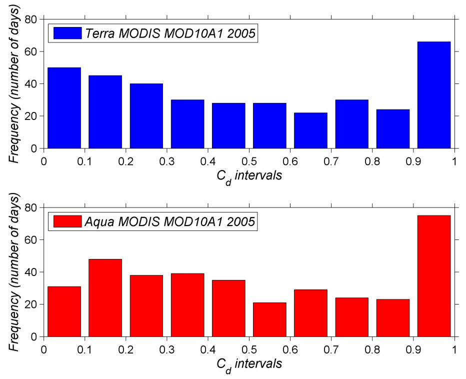

Figure 15:
Absolute frequency of the daily cloud percentage C_d, year 2005, of the whole basin.

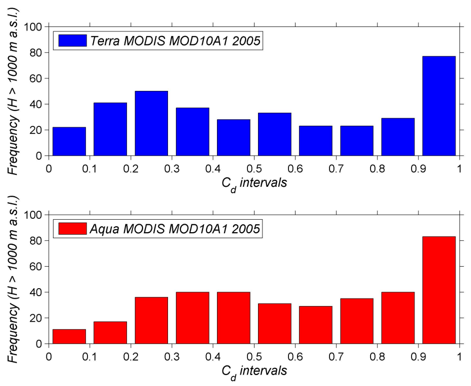

Figure 16:
Absolute frequency of the daily cloud percentage $C_d(H > h_t)$, year 2005, calculated on that part of the basin higher than 1000 m a.s.l.

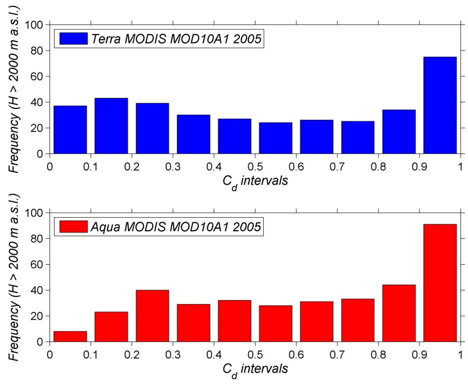

Figure 17:
Absolute frequency of the daily cloud percentage $C_d(H > h_t)$, year 2005, calculated on that part of the basin higher than 2000 m a.s.l.

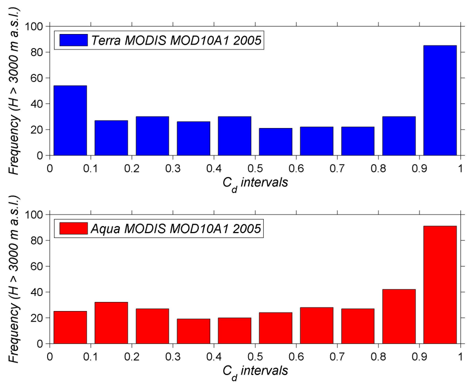

Figure 18:
Absolute frequency of the daily cloud percentage $C_d(H > h_t)$, year 2005, calculated on that part of the basin higher than 3000 m a.s.l.

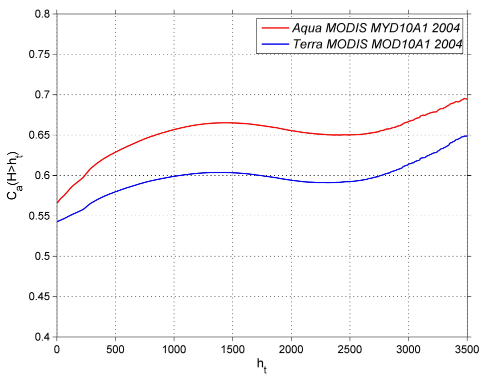

Figure 19:
Mean annual cloud cover percentage and its dependence on altitude, 2004.

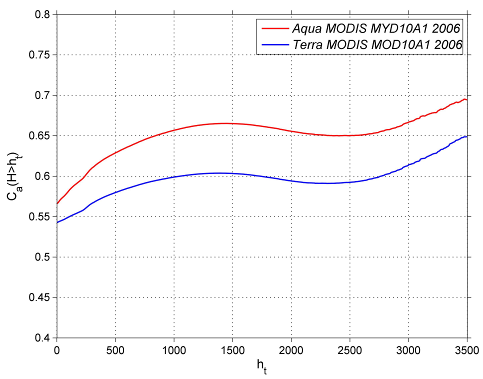

Figure 20:
Mean annual cloud cover percentage and its dependence on altitude, 2006.

10. DISCUSSION AND FURTHER APPLICATIONS

MODIS daily Snow Cover Area (SCA) Products have been considered, highlighting advantages and disadvantages connected with its use. The purpose was to understand if such processed images, available free of charge, could be of interest for mapping snow cover extension and distribution over the Po Valley. The issue descends from the impacts that the processes of snow accumulation and snowmelt has on the hydrologic regime of the major Italian river. The projected changes in the climatic forcings (e.g. temperature and precipitation) is expected to affect snow cover duration, amounts and extension. Changes in such variables will affect the hydrology of mountain areas and, as consequence, that of lowlands.

We reviewed the main studies available in literature, with the aim of assessing the accuracy of MODIS snow maps. The product can be considered reliable, due to the high degree of agreement showed when compared with ground truths. Even if a validation has been recently carried out in Austria [31], we did not find comparison between snow maps and ground data performed in northern Italy. In this regional context, a further evaluation of the accordance between SCA Products (derived from the processing of remote sensing images) and ground observations (from weather station or cameras) at different longitudes and altitude should be performed. In prospective, digital maps of glaciers provided by the Italian local administrations are usually available and might be an interesting tool.

After a pre-processing which allowed to interface MODIS maps with the DEM of the study area, we got and analyzed daily maps throughout five years (2003 - 2007) both for Terra and Aqua satellite. MOD10A1 and MYD10A1 products have 500 m spatial resolution, therefore for our wide study area the grid results properly dense. This high resolution allows to display snow distribution with a good level of detail. This seems a considerable advantage in terms of compatibility with distributed hydrologic models, which generally have a relatively high spatial resolution compared to the study area.

Even if cloudiness usually blinds large areas, through some clear-sky days it was possible to highlight the whole snow cycle from the begin of the accumulation season to the end of the snowmelt season, which is ruled by different timing depending on the altitude. Also occasional snowfall could often be detected outside the winter months, when snow cover lasts a few days. In Lombardia, summer cloudless remote sensing showed how the permanent snowfields and glaciers are correctly individuated, even if the resolution of the snow maps is relatively low for a careful reproduction of small snow-covered areas.

As expected, the main limitation of the SCA products is related to cloudiness. On average, a cell spends more than 50% of the year hidden by clouds. For these reasons a procedure for cloud removal should be involved whether the purposes is to investigate snow extension and distribution over a complete annual cycle. In literature some methodologies for reproducing ground conditions beneath the clouds have been proven to be effective and easy applicable. The application and adaptation of one of these could be an interesting starting point for future researches on this topic.

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