Geogr. Fis. Dinam. Quat.
35 (2012), 91-99, 5 figg., 8 tabb.

DOI 10.4461/GFDQ.2012.35.9

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ANALYSIS OF SNOW PRECIPITATION DURING THE PERIOD 2000-09 AND EVALUATION OF A MSG/SEVIRI SNOW COVER ALGORITHM IN SW ITALIAN ALPS

ABSTRACT: TERZAGO S., CREMONINI R., CASSARDO C. & FRATIANNI S., *Analysis of snow precipitation in 2000-09 and evaluation of MSG/SEVIRI a snow cover algorithm in SW Italian Alps*. (IT ISSN 0391-9838, 2012).

The automatic meteorological station network of Piedmont (North-West Italy), whose realization started in 1988, together with the pre-existing manned stations are now providing snow depth and fresh snow depth measurements in more than 100 sites spread out over Western Alps, also outside the geographical borders of the Region. The high spatial resolution network in combination with satellite devices can be used for an integrated monitoring of snow cover that combines information on snow depth, amount of snow precipitation and snow cover extension. In particular satellites can provide complementary knowledge on snow cover over large scale with spatial continuity, supplying the lack of data where surface measurements are not available.

This study focus the attention on the decade 2000-2009, for which both surface and satellite data are accessible. The high density of meteorological stations in Western Italian Alps makes this area appropriate for testing a novel snow cover algorithm using Meteosat Second Generation (MSG) satellite data. In the first part the analysis of the mean condition of snow precipitation over South Western Italian Alps is presented. Ground-based automatic daily total and fresh snow depth measurements provided by the Regional Agency for the Environmental Protection (ARPA Piemonte) have been used to determinate snow indices and the snow precipitation variability over the 10 years period. In the second part a novel method to estimate the snow cover extension using satellite data from the SMG Spinning Enhanced Visible and Infrared Imager (SEVIRI) is described and discussed. The snow cover algorithm minimizes the number of unclassified pixel due to cloud obscuration taking advantage of the MSG high frequency of acquisition, which provides daylight images over the investigated area every 15 minutes. The algorithm has been tested for 19 case-studies referring to the period 2007-2009 using surface stations data and then it has been applied to assess and compare the snow cover extension during the 2006-07 and 2007-08 snow seasons.

KEY WORDS: Snow cover, Alps, Satellite, MSG SEVIRI, Climate change.

RIASSUNTO: TERZAGO S., CASSARDO C., CREMONINI R. & FRATIANNI S., *Analisi delle precipitazioni nevose nel periodo 2000-09 e valutazione di un algoritmo per il rilevamento della copertura nevosa tramite MSG/SEVIRI sulle Alpi Sud-Occidentali*. (IT ISSN 0391-9838, 2012).

La rete di stazioni meteorologiche automatiche del Piemonte (Nord-Ovest Italia) realizzata a partire dal 1988 insieme con le preesistenti stazioni manuali fornisce misure di altezza della neve fresca e di spessore del manto nevoso in più di 100 siti sparsi sulle Alpi occidentali, anche al di fuori dei confini geografici della Regione. Questa rete ad alta risoluzione spaziale puo' essere utilizzata in combinazione con i dispositivi satellitari per un monitoraggio integrato del manto nevoso che combini le informazioni di profondità del manto, quantità di precipitazione ed estensione della copertura nevosa. In particolare i satelliti sono in grado di fornire informazioni sull'estensione delle aree innevate su larga scala e con continuità spaziale, anche laddove non si hanno misure al suolo.

Questo studio focalizza l'attenzione sul decennio 2000-2009 per il quale sono disponibili sia i dati delle stazioni superficiali sia quelli satellitari. L'alta densità di stazioni meteorologiche sulle Alpi Occidentali Italiane rende questa zona appropriata per testare un nuovo algoritmo di copertura nevosa che utilizza i dati del satellite Meteosat di Seconda Generazione (MSG). Nella prima parte e' presentata l'analisi delle condizioni medie di precipitazione nevosa sulle Alpi Sud-Occidentali italiane. Le misure giornaliere di altezza della neve fresca e di spessore del manto nevoso fornite dall'Agenzia Regionale per la Protezione Ambientale (ARPA Piemonte) sono state utilizzate per determinare gli indici nivologici nella decade 2000-09. Nella seconda parte viene descritto un metodo per stimare l'estensione della copertura nevosa usando i dati satellitari dello Spinning Enhanced Visible and Infrared Imager (SEVIRI), sensore del Meteosat Second Generation (MSG). L'algoritmo di copertura nevosa permette di ridurre il numero di pixel non classificati a causa dell'oscuramento da nubi sfruttando l'elevata frequenza di acquisizione di SEVIRI, che fornisce immagini ogni 15 minuti. L'algoritmo è

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The authors would like to thank two anonymous referees who gave valuable help in improving the text. This work has been carried out as a part of the RISKNAT project funded by Arpa Piemonte.

stato testato per 19 casi di studio relativi al periodo 2007-2009 utilizzando i dati delle stazioni al suolo e quindi applicato per valutare e confrontare l'estensione del manto nevoso durante le stagioni 2006-07 e 2007-08.

TERMINI CHIAVE: Copertura nevosa, Alpi, Satellite, MSG SEVIRI, Cambiamento climatico.

INTRODUCTION

Snow cover in the Alpine region influences climate both at local and large scale as it reflects most of the solar radiation varying surface radiation and energy budgets (Romanov & *alii*, 1999) and alters the atmospheric circulation by modifying the overlaying air masses. Moreover snow represents a resource for hydro-power generation, irrigation, domestic and industrial water supply and for tourism based on winter sports.

The investigation on snow precipitation and snow cover variability is fundamental in the frame of climate change studies and in developing strategies for the mitigation of climate change effects. At local scale the need of information about snow precipitation amount, duration and variability is required for a correct socio-economic planning which takes into account the changing environment. Literature on snow climatology is rich for the Swiss Alps (Laternser & Schneebeli, 2003; Beniston, 1997; Scherrer & *alii*, 2004) and French Alps (Durand & *alii*, 2009; Martin & *alii*, 1994). Concerning Italian Alps Valt & *alii* (2005) analyzed the Standardized Anomaly Index (SAI, Giuffrida & Conte, 1989) of snow precipitation over the Southern Alps over the period 1920-2005, while regional studies have been performed for example by Biancotti & *alii* (1998), who considered snow precipitation climatology over Piedmont over the period 1966-1996, and Barbolini & Ferro (2004), who analyzed snow precipitation distribution in Friuli, Eastern Alps. Over Western Italian Alps daily snow depth observations were performed since the 1920's by the personnel of the *Ufficio Idrografico del Bacino del Po* (Po basin Hydrographic Office) and a big effort is currently being accomplished to digitize, recover, homogenize and analyze these valuable historical time series. First results for the Northern sector of Piedmontese Alps (Ossola Valley) have been published by Canevarolo & *alii* (2011) who carried out an in depth analysis of temperature, liquid and solid precipitation records over the maximum period 1933-2009 and determined the climatic indices and trends finding significant decrease in snow depth and increase in minimum and maximum temperatures. Similar results have been found by Fratianni & *alii* (2009, 2010) and Terzago & *alii* (2010) for several stations in Southern Piedmontese Alps.

The present work is a contribution to the determination of the average conditions of snow precipitation in South-Western Italian Alps (Province of Cuneo) focused on the decade 2000-2009 for which both surface and satellite data are available. This area has a high meteorological station density and so it is suitable to test a novel method to estimate snow cover extension through Meteosat Second Generation (MSG) satellite data. The use of both surface meteorological stations and satellites can provide complementary information on snow cover: the former collect climatological parameters which allow to evaluate climate indices and trends at local scale, the latter allow to evaluate the extension of snow cover, its temporal evolution, the snow level (the altitude above which the ground is covered by snow), the snow albedo at large scale, etc...

The purpose of this study is to present and test the MSG snow cover algorithm accuracy validating snow cover daily maps through the surface station measurements. The algorithm is applied to evaluate and compare the snow cover extension at two different times during the 2006-07 and 2007-08 snow seasons.

THE DATA

In Piedmont the meteorological station network controlled by the Regional Agency for the Environmental Protection (ARPA Piemonte, hereafter simply referenced to as ARPA) counts more than 350 automatic and manual stations, of which more than one hundred perform snow measurements on a daily basis. Most automatic stations started recording data in the 1990s, thus supplying a large dataset for the analysis of the last one-two decades.

The South Western Piedmont (Provincia of Cuneo) has been chosen for our investigation as here the spatial density and distribution of meteorological stations is adequate to represent properly the features of the area. The length of the records varies for different stations, so for this study only station with continuous records over the decade 2000-09 where chosen. Total and fresh daily snow depth measurements performed in 10 automatic meteorological stations located between 575 and 2135 m a.s.l. (table 1) have been considered in order to calculate the snow indices over the period January 2000-December 2009. Figure 1 reports the geographical position of all the nivometrical stations of the ARPA Piemonte network: those considered in the first part of this study have been put in evidence.

TABLE 1 - Snow measurements sites considered in this study: station name, elevation above sea level and UTM coordinates

Station	Elevation (m a.s.l.)	UTM_x (m)	UTM_y (m)
Boves	575	385442	4910296
Paesana	1265	362370	4947015
Valdieri	1390	361709	4896272
Pontechianale	1575	345555	4941889
Acceglio	1610	339567	4927939
Piaggia	1645	398488	4880823
Argentera	1680	335978	4918048
Castelmagno	1755	354208	4918133
Rifugio Mondovì	1760	398757	4894142
Pian delle Baracche	2135	351816	4934725

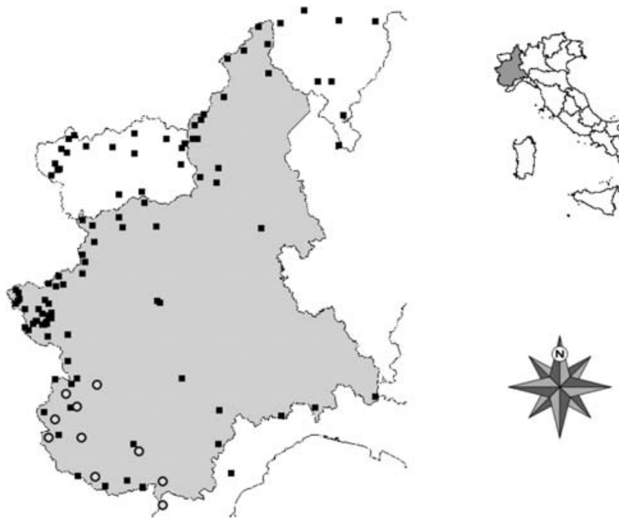

FIG. 1 - Location of all the ARPA Piemonte nivo-meteorological stations considered in this work. The stations considered in the first part of the study are displayed as circles, the others as squares).

CUMULATED SNOW AND NUMBER OF SNOWY DAYS

Fresh snow depth measurements have been used to calculate the monthly cumulated snow precipitation and the number of snowy days. The mean values over the period 2000-2009 are reported in table 2 and table 3.

December is the snowiest month in all observation sites but the highest one, Pian delle Baracche (2135 m a.s.l.), where solid precipitation is most abundant at the end of the snow season (April), and Paesana (1265 m a.s.l.), where the snowfall amount is comparable in December and February.

The occurrence of the monthly cumulated snow precipitation maximum in December is in contrast with the general features outlined by Biancotti & *alii* (1998) over the 1966-1996 period: according to their study in South Western Alps the monthly cumulated snow precipitation maximum occurs in January at elevations between 800 and 1600 m a.s.l.. Our observations show that in the last decade snow precipitation has become most abundant in December, thus suggesting a shift in the peak of the snow precipitation distribution one month earlier. This hypothesis is supported by a recent study (Terzago & *alii*, 2010) on the historical data of three manned stations located in the surroundings of those here considered: it has been found that in the last decade the snow precipitation maximum occurred in December, one month earlier with respect to the reference period 1971-2000.

TABLE 2 - Average monthly cumulated snow precipitation for each station referring to the period January 2000-December 2009: the maximum values are written in bold

Station	Cumulated snow precipitation (cm)							
	Nov	Dec	Jan	Feb	Mar	Apr	May	Seas
Boves	8± 15	**33±24**	20±19	29±24	4±7	0	0	**95**
Paesana	36±32	49±42	40±39	**51±48**	29±21	14±16	0	**219**
Valdieri	77±44	**100±69**	69±51	69±49	56±25	61±44	1±3	**433**
Pontechianale	58±43	**67±58**	47±43	45±37	43±33	44±36	0	**304**
Acceglio	64±41	**75±52**	53±41	55±34	48±28	44±38	1±3	**339**
Piaggia	33±28	**72±60**	58±53	47±42	37±17	44±33	2±4	**293**
Argentera	75±45	**90±63**	62±44	57±34	59±31	65±57	5±7	**414**
Castelmagno	80±44	**93±55**	54±38	69±45	57±35	79±64	4±6	**436**
Rifugio Mondovì	69±36	**96±73**	61±48	57±49	61±26	80±54	12±18	**436**
Pian delle Baracche	87±55	73±40	44±36	50±36	60±36	**90±69**	17±15	**422**

TABLE 3 - As in table 3 but for the number of snowy days

Station	Number of snowy days							
	Nov	Dec	Jan	Feb	Mar	Apr	May	Seas
Boves	2±2	**3±2**	3±2	2±2	1±1	0	0	**11**
Paesana	3±1	**5±3**	4±3	3±2	3±2	2±2	0	**20**
Valdieri	5±2	**7±3**	5±3	4±2	5±3	5±3	0±1	**31**
Pontechianale	4±2	**7±3**	5±4	4±2	5±1	5±3	0	**31**
Acceglio	5±2	**6±3**	5±3	4±2	5±2	5±3	0	**30**
Piaggia	4±2	**6±3**	5±3	3±2	5±3	4±2	0±1	**27**
Argentera	6±2	**8±3**	6±3	5±2	6±3	6±1	1±1	**38**
Castelmagno	6±2	**7±3**	5±3	4±2	5±2	6±3	0±1	**34**
Rifugio Mondovì	**7±3**	**7±3**	5±2	4±2	6±2	7±4	1±1	**37**
Pian delle Baracche	7±2	7±3	6±4	4±2	7±3	**8±4**	2±2	**41**

The seasonal distribution of the mean monthly cumulated snow precipitation has been investigated to analyze the geographical variability of snow precipitation. The lowest station, Boves (575 m a.s.l.), presents a bimodal distribution, with an absolute maximum in December and a secondary maximum in February. Also at Paesana (1265 m a.s.l.) the monthly snowfall distribution is bimodal but the absolute maximum is observed in February. At middle elevation, between 1300 and 1700 m a.s.l., snow distribution is unimodal, with a winter maximum occurring in December and comparable snow amounts occurring in January, February and March in most of the sites, as in the French side of the Alps at about 1000 m a.s.l. (Besancenot, 1990). It is remarkable the case of the station Valdieri, which is situated at 1390 m a.s.l. but has more abundant snowfalls than any other considered station in December and January. Monthly accumulated snow precipitation derived by the Acceglio automatic station is compared to that evaluated by Fratianni & *alii* (2009) in the Acceglio Saretto manned measurement site nearby over the period 1930-2008 and the distributions result to be similar.

At elevation about 1700 m a.s.l. (Castelmagno, 1755 m a.s.l., Rifugio Mondovì, 1760 m a.s.l) the snowfall distribution is bimodal with an absolute maximum in winter (December) and a secondary maximum in spring (April). Above 2000 m the position of the maxima is reversed, with the absolute maximum in spring. This bimodality has also been observed in Northern Piedmont (Lepontine Alps, Toggia, 2200 m; Vannino 2177 m) over the period 1966-1996 and on the French side, where the absolute maximum in April, the secondary in December (Biancotti & *alii*, 1998).

The analysis of the seasonal distribution of the monthly mean number of snowy days (table 2) has that, in the sites at low elevation the number of snowy days reaches its maximum in December and afterward decreases. At higher elevation the absolute maximum occurs still in December but there is a secondary maximum in March/April. At the only station located above 2000 m a.s.l. the absolute maximum occurs in April.

SNOW DEPTH

In the successive analysis the average monthly snow depth and the corresponding standard deviation have been calculated (table 4). The highest snow depth is registered in February in almost all the measurements sites. In the lowest one (Boves) and the two highest (Rifugio Mondovì, Pian delle Baracche) comparable snow depths are registered in January-February and February-March respectively. In all stations the standard deviations are generally large due to the strong interannual variability of snowfalls in Piedmont.

TABLE 4 - Monthly mean snow depth and corresponding standard deviation in each station referring to the period January 2000-December 2009

Station	**Monthly average snow depth (cm)**						
	Nov	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**
Boves	1±2	9±10	**15±17**	14±18	4±5	0	0
Paesana	7±11	20±25	32±39	**38±41**	31±32	4±6	0
Valdieri	18±16	66±35	89±55	**108±58**	101±64	45±52	5±15
Pontechianale	10±11	28±23	28±30	**29±29**	18±18	5±6	0
Acceglio	12±13	38±28	48±34	**53±38**	37±29	9±19	0±1
Piaggia	3±4	28±31	47±48	**58±59**	46±52	18±31	1±3
Argentera	15±14	55±35	68±43	**74±50**	58±42	20±38	3±9
Castelmagno	16±15	50±27	58±41	**65±46**	51±38	22±41	4±11
Rifugio Mondovì	16±10	52±37	71±54	**84±56**	**84±57**	62±53	13±27
Pian d. Baracche	28±21	70±41	87±57	**98±56**	97±55	91±67	38±51

The snow season 2008-2009 has been characterized by heavy snowfalls over Piedmont and the exceptionality of the winter snowfalls has been documented in several studies (Valt & Cianfarra, 2009; Cordola & *alii*, 2009, Terzago & *alii*, 2010; Pelosini & *alii*, 2011). The anomalies of this season with respect to the mean values in the period 2000-2008 have been here investigated. The case study of Acceglio manned station is presented as an example of the general behavior. The 2008-2009 monthly cumulated fresh snow has been compared to the corresponding value averaged on the period 2000-2008. During November the amount of snow precipitation was just above the mean value, while in December the cumulated snow precipitation exceeded the mean value by three standard deviations. In January the mean value was exceeded by one standard deviation while in February the cumulated fresh snow was just above the average. The variability of snow cover extension during this snow season will be here analyzed using satellite images. Meteorological satellites provide images of the Earth at particular spectral bands and allow to investigate snow cover variability over large scale, thus overcoming the scarcity of surface observations. A method to discriminate the presence of snow at ground is now presented and discussed.

MSG SNOW COVER ALGORITHM

Radiometric measurements performed by imagers carried onboard meteorological satellites are used to reconstruct the spatial distribution of snow cover at large scale with spatial continuity even where ground observations are not available. In fact the radiances and reflectances of the Earth-Atmosphere system collected in selected bands of the electromagnetic spectrum allow to identify the emitting and reflecting surfaces (Kidder & *alii*, 2005).

The Meteosat Second Generation (MSG) geostationary satellite, located at an altitude of 36'0000 km on the equatorial plane at 0° longitude, provides images of its entire field of view every 15 minutes with 3 km spatial resolution (1 km for High Resolution Visible Channel) at the sub satellite point. Its higher temporal resolution with respect to polar satellites represents a considerable advantage in snow cover monitoring, in fact the problem of the satellite field of view obscuration by clouds can be considerably reduced by detecting the changes in cloud cover between successive images. The use of several images with different cloud cover increases the probability to have clear sky observations at the cost of lower spatial resolution respect to polar satellites. Other sensors have been used for snow studies and the selection of the appropriate one depends on a trade off between spatial and temporal resolution (Rott, 1987). Swamy & Brivio (1997) used Landsat Multispectral Scanner System (MSS) and Thematic Mapper high spatial resolution data to model run off in high mountainous Alpine catchment, while Rossi & *alii* (1986) and Ranzi & *alii* (1999) considered NOAA-AVHRR polar satellites imagery to model snow cover evolution and the snow water equivalent in selected area of Italian Alps.

In this study the MSG snow cover algorithm developed by ARPA Piemonte is presented. It allows to discriminate in real time cloud- and snow-covered surfaces using the Spinning Enhanced Visible and Infrared Imager (SEVIRI) carried onboard the Meteosat Second Generation platform (Schmetz & *alii*, 2002). The algorithm is based on classes of threshold tests carried out on radiance and reflectance of surfaces at different spectral bands: each surface can be identified by the corresponding class of tests passed. The input data for the snow detection are:

- cloud mask;
- 4 MSG bands daytime (0.6 μm, 0.8 μm, 1.6 μm, 10.8 μm);
- ECMWF atmospheric model temperature at 2 m and at 850, 700 and 500 hPa levels;
- threshold tests selected by the user.

The tests for snow detection are applied to daylight land pixels and they are based on the Normalized Difference Snow Index (NDSI) and other conditions commonly used (Dozier & *alii*, 2004; Salomonson & *alii*, 2006; Ruyter de Wildt & *alii*, 2006; Hall & *alii*, 2007):

$$255 < T_{10.8} < 285K \qquad (1)$$

$$R_{0.8} > 0.2 \tag{2}$$

$$NDSI = \frac{R_{0.8} - R_{1.6}}{R_{0.8} + R_{1.6}} > 0.2 \tag{3}$$

where $T_{10.8}$ is the brightness temperature at 10.8 μm and $R_{0.8}$ and $R_{1.6}$ are the reflectances at 0.8 μm and 1.6 μm.

If these conditions are satisfied, the pixel is labeled as snowy. In this way, considering the MSG resolution over Alps, it is possible to create snow cover maps with about 3200 m spatial resolution. A further step consists in processing only snowy pixels through a test on the High Resolution Visible (HRV) SEVIRI reflectance at 1600 m spatial resolution over the area of study. This procedure makes available four HRV pixels for each 3200 m pixel and allows to refine the snow identification:

$$R_{HRV} > 0.2 \tag{4}$$

The final product is a set of 1600 m resolution georeferenced snow cover maps, generated every 15 minutes, for each SEVIRI data acquisition. The possible values of these maps are snow-covered, snow-free or cloudy surface. When the field of view of the imager is cloud-covered multiple data acquisitions can be used to create a daily snow cover product where a pixel is classified as snowy if, during that day, it results snowy in at least one of the SEVIRI acquisitions. In this way the number of unclassified pixels can be consistently reduced. Fig. 2 shows an example of a MSG SEVIRI image relative to April, 05^{th} 2008 at 1200 UTC and the corresponding daily snow cover obtained using all the daylight SEVIRI acquisitions. Even if clouds do not allow to see the Earth surface in each of the images during the day, the daily product has few unclassified pixels. The map obtained with this method gives binary information on presence or absence of snow at surface and represents the «mean condition» within a 1600 m pixel, so it may be affected by an error due to partially snow covered pixels, mainly at the snow edges.

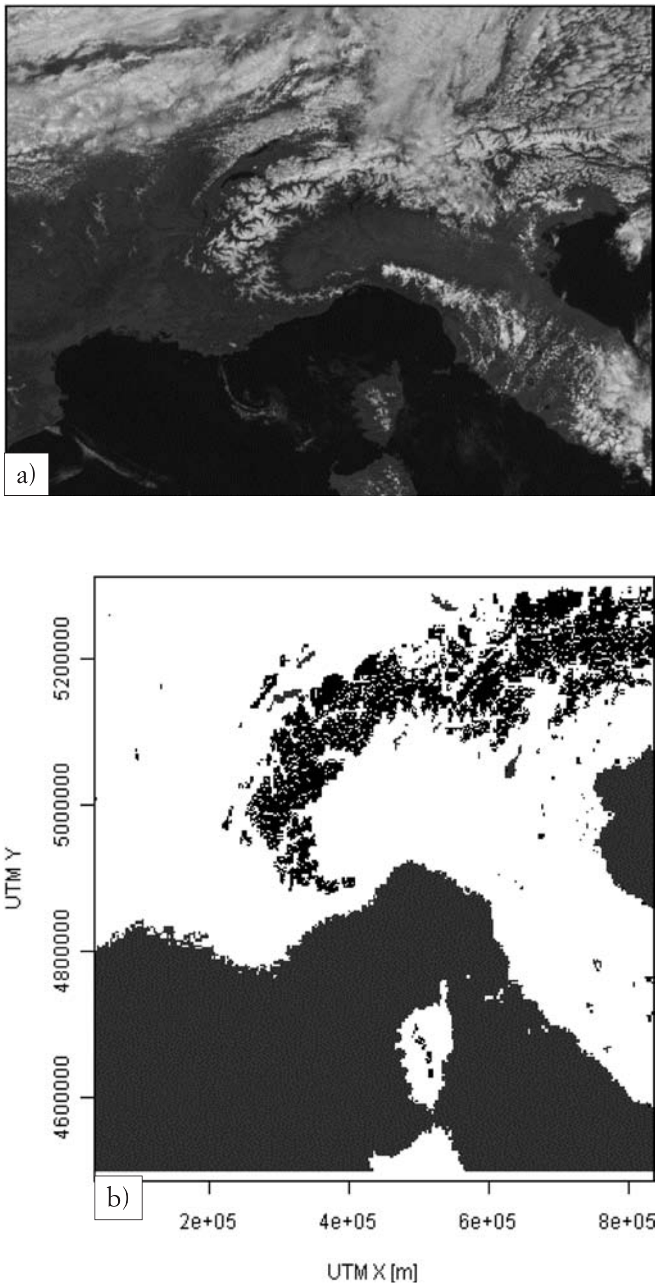

FIG. 2 - (a) MSG SEVIRI acquisition referring to April 05^{th} 2008, 1200 UTC in the HRV channel; (b) Daily snow cover map obtained by processing all the MSG SEVIRI maps referring to April 05^{th} 2008. Snow is represented in black, snow-free surfaces in white. The map is georeferenced in UTM coordinates.

VALIDATION OF THE ALGORITHM

The accuracy of the daily snow cover maps obtained using this method has been assessed through validation with in-situ snow depth measurements in Western-Italian Alps (Piedmont and Aosta Valley): the ground stations considered in the former part of this study, together with all the others belonging to the ARPA Piemonte network (111 in total, fig. 1) have been used. 19 case studies in the period 2007-2009 have been chosen to represent different snow cover conditions and different seasons.

For each case study the daily snow cover was generated and validated using all the 111 daily measurements of the surface network by comparing the snow cover value to the surface observation at the corresponding pixel. Of course this procedure assumes that the information on presence or absence of snow got by an individual station could be representative of the whole 2.56 km^2 area of the corresponding pixel in the snow cover map. This assumption may lead to an error in the estimation of the real snow cover in case of shallow and discontinuous mantle but the validation of the satellite product using the surface measurements is objective and thus commonly used to represent the «ground truth» (Hall & Riggs, 2007).

For each case study, the satellite snow map and the surface observations data have been reduced to «snow», «no snow» and «not available» and contingency table and its relative statistical indices (table 5) have been calculated. The results, comprehensive of all case studies, are reported in table 6. The overall accuracy of the algorithm, here expressed by the Critical Success Index is 0.74. The algorithm tends to overestimate the snow covered area (FAR= 0.17) rather than underestimate it (BIAS=1.04). In order to have more quantitative information on the algorithm performance, the case studies were considered separately according to the season. In the period November-February (NDJF) the Critical Success Index is much higher (CSI=0.84) than in the period March-June (MAMJJ, CSI= 0.54): while in winter the algorithm performance is good, in spring the algorithm estimates poorly the snow cover with many overestimation and underestimation errors (FAR=0.39, BIAS=1.38).

TABLE 5 - Contingency table and relative statistical indices used for the validation of SEVIRI snow cover through surface observations

	SURFACE OBSERVATIONS	
SEVIRI	**NO SNOW**	**SNOW**
NO SNOW	correct negatives	missing
SNOW	false alarm	hit

Statistical Indices
POD = hit / (hit + missing)
FAR = false alarm / (hit + false alarm)
CSI = hit / (hit + false alarm + missing)
BIAS = (hit + false alarm) / (hit + missing)

TABLE 6 - Statistical indices relative to all the 19 case studies during the complete snow season (November-June), during winter (November-February) and during spring (March-June)

	November-June	November-February	March-June
POD	0.87	0.88	0.84
CSI	0.74	0.84	0.54
FAR	0.17	0.04	0.39
BIAS	1.04	0.92	1.38

This result is apparently surprising because in spring the surface illumination is better than in winter and one could expect that the snow cover detection would be easier and that the algorithm would give a more accurate estimation: this finding may be due to the use of threshold values optimized for winter season and constant throughout the year while solar illumination conditions change. Moreover classification errors occur mostly at sunrise and sunset, i.e. when the solar zenith angle is high. Thus the quality of the daily snow maps should be improved using only satellite images with good condition of illumination.

ALGORITHM ACCURACY IN PRESENCE OF FRESH SNOW

The snow cover daily product has been tested in order to determinate its accuracy when there is fresh snow at the surface. Daily fresh snow measurements have been used to validate the snow cover daily products. Only the stations which registered a fresh snow depth larger than 1 cm have been considered in this study because where snow depth is equal or lower than 1 cm the snow mantle can be discontinuous over the considered area of 1600 m x 1600 m. Checking whether the algorithm identifies the corresponding pixel as snow covered it has been found that the probability of a correct identification of snow covered areas is 0.95 which is a good estimation. In this case the higher reflectivity of the snowpack allows the correct snow identification.

ALGORITHM ACCURACY FOR DIFFERENT SNOW DEPTH CLASSES

A further aspect investigated is the algorithm accuracy in snow cover detection considering different classes of snow depth: all the ground measurements where snow depth (HS) is higher than 1 cm are considered. The following three classes were considered: $1\,cm < HS < 10\,cm$, $10\,cm \leq HS < 30\,cm$ and $HS \geq 30\,cm$. The performance of the MSG snow cover algorithm has been verified for each of these classes.

The results show that the probability that the algorithm correctly identifies snow increases with the increasing of snow depth, varying from a minimum of 0.56 for the lowest depth class to a maximum of 0.95 for the highest depth class (fig. 3).

APPLICATION OF THE SNOW COVER ALGORITHM

In order to use the MSG snow cover products to investigate the variability of snow cover extension over the area considered in this study, the algorithm has been evaluated over South Western Piedmont using the smaller surface

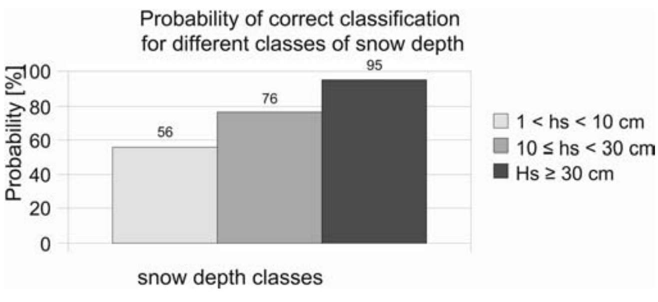

FIG. 3 - Variation of the probability of correctly detecting snow cover with increasing snow depths.

containing all the automatic stations reported in table 1 (this area is about 4300 km^2 wide). The nivometrical measurements performed in those sites in the 19 case studies previously considered have been used to validate the algorithm. Its accuracy (table 7) resulted higher than the corresponding one obtained for the whole region.

TABLE 7 - Accuracy of the snow cover algorithm over the South Western Italian Alps during the whole snow season (November-June) and the winter season (November-February)

	November-June	November-February
POD	0.96	0.96
CSI	0.80	0.94
FAR	0.17	0.02
BIAS	1.16	0.98

The analysis was repeated in order to determine the algorithm accuracy during the winter season. The estimation of snow cover during the period November-February is very good (TS=0.94) and both overestimation and underestimation are negligible. This encouraging result allows to make considerations on the temporal variability of snow cover over the South Western Piedmont, in order to integrate those results with the information given by the ground stations.

Four cases studies have been chosen to compare the snow cover extension in 2006-07 and 2007-08 snow seasons: for this purpose the nearest cloud-free scenes in January and April have been selected in order to analyze the evolution of the snow pack during the two seasons.

During January 2008 snow cover was much more extended than during January 2007 (fig. 4) because snow cover was present also at low altitudes. In fact during January 2008 (2007), 84% (11%) of the area here considered (South Western Alps, surrounded by the white rectangle) was covered by snow. In April (fig. 5), the percentage of snow covered area in 2008 (26%) is comparable with that in 2007 (28%). The extension of snow covered area calculated from the georeferenced snow maps is reported in table 8.

The analysis of the temperatures registered in the surface stations showed that the monthly average maximum temperatures in the period February-March 2008 were higher with respect to those in the previous year in the sites above 1600 m a.s.l.. In conclusion, in the South Western Piedmontese Alps, a larger amount of snowfall occurred in the early 2008 snow season but the snow ablation was faster than in the previous year, due to the higher maximum temperatures recorded in late winter and early spring.

TABLE 8 - Snow cover area (SCA) extension over Alps and over South Western Italian Alps during the 4 considered cases of study

Data	SCA Alps (km^2)	SCA SW Alps (km^2)
13/01/2007	47150	330
17/01/2008	79839	3779
17/04/2007	41303	1193
05/04/2008	59374	1139

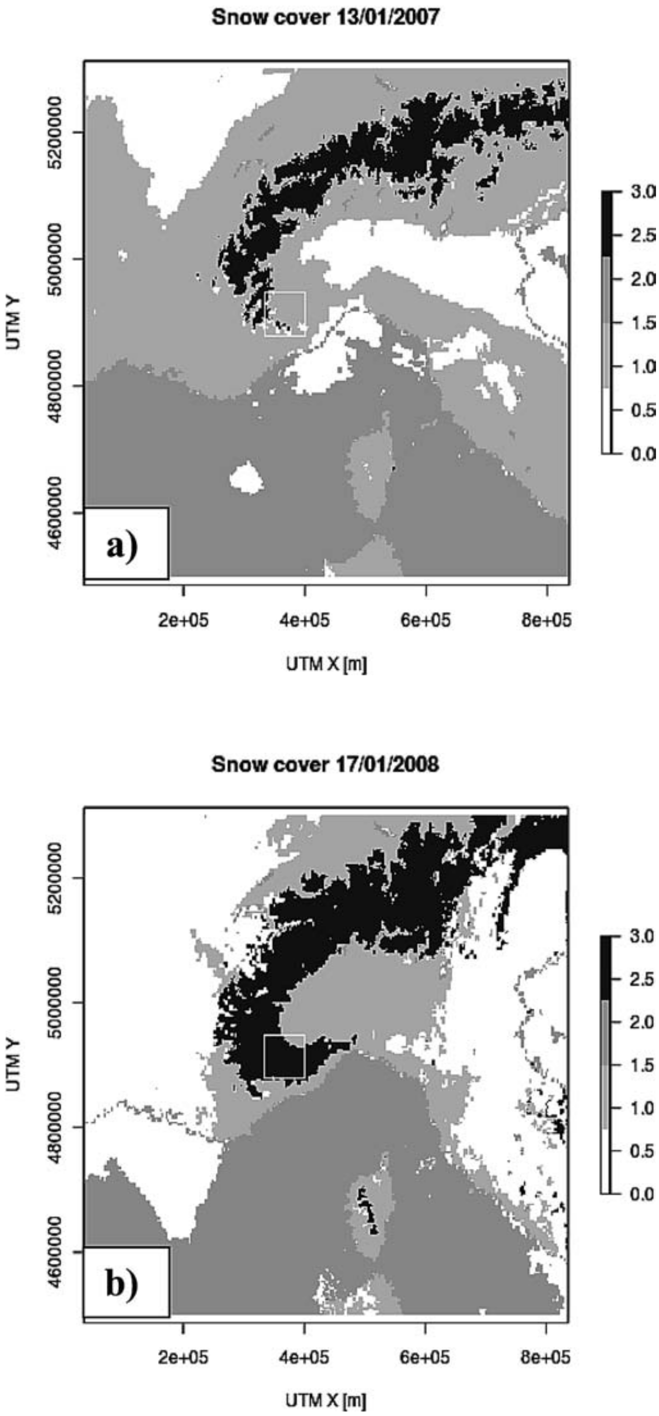

FIG. 4 - Snow cover evaluated on January 13th 2007 (a) and January 17th 2008 (b) represented in dark. The studied area is surrounded by a white rectangle.

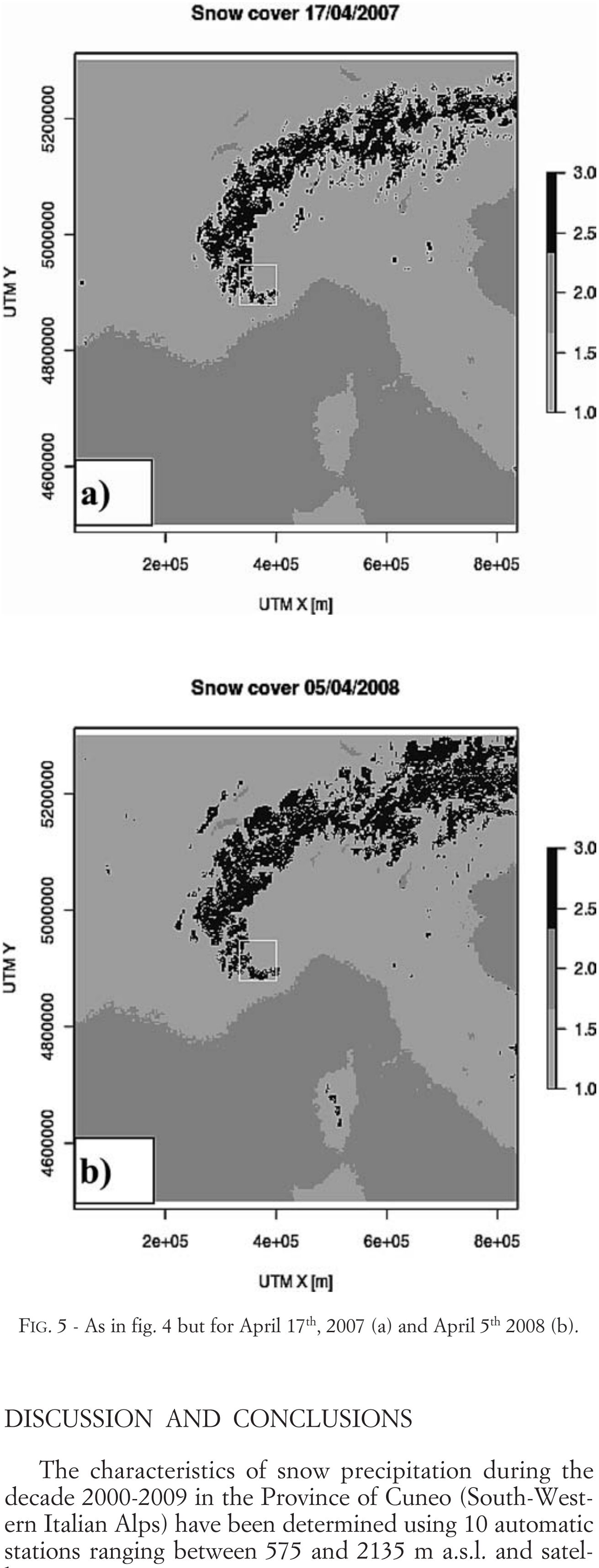

FIG. 5 - As in fig. 4 but for April 17th, 2007 (a) and April 5th 2008 (b).

DISCUSSION AND CONCLUSIONS

The characteristics of snow precipitation during the decade 2000-2009 in the Province of Cuneo (South-Western Italian Alps) have been determined using 10 automatic stations ranging between 575 and 2135 m a.s.l. and satellite snow cover images.

A new method to estimate the snow cover extension over large scale through MSG satellite data has been presented and validated using all the 111 surface stations belonging to the ARPA Piemonte network. The accuracy of the snow cover algorithm has been assessed using the snow depth and fresh snow measurements performed in Piedmont and Aosta Valley in 19 case studies in the period 2007-2009.

The algorithm gives a very good estimation of snow cover in presence of fresh snow and when the snow layer is thick. The algorithm performs better in winter (NDJF) than in spring (MAMJ). The overestimation of snow cover during spring is partly caused by the misclassification at sunrise and sunset, when the solar zenith angle is high and the illumination is scarce. Each pixel incorrectly classified as snowy will result in an error in the daily product. This problem can be overcome by reducing the time range for the generation of the daily product, so that only scenes with good illumination are considered. Another problem could be that too mild thresholds can lead to snow cover overestimation, so following steps will be the reduction of the time interval for the generation of the daily snow cover maps in order to avoid errors of classification occurring at sunrise and sunset, and the optimization of the test thresholds for the Alpine area.

The analysis has highlighted a low algorithm accuracy in detecting shallow snow cover. However this deficiency may be due not only to an error of the method but also to the presence of discontinuous snow cover over an area 2.56 km^2 wide. In this case the «mean information» on presence/absence of snow cover over that pixel may be in contrast with the local information of the stations measurements.

Another limit of the validation of satellite snow cover through surface stations is that stations are generally located on low vegetation terrains and can not provide information on the algorithm accuracy over forested area where snow detection is in general more critical (Hall & Riggs, 2007). Future analysis will be addressed to assess and improve MSG algorithm's classification accuracy over different soil types and aspects over large scale by the validation with the MODerate Resolution Imaging Spectroradiometer (MODIS) snow cover products at 500 m spatial resolution.

Current MSG algorithm has proven to be able to represent the snow cover with high accuracy over the South Western Piedmont, so it has been possible to make quantitative considerations and comparisons about the persistence of snow cover during the 2006-2007 and 2007-2008 snow seasons.

An accurate snow cover estimation will be the basis for many applications in meteorology for supplying the initial conditions for weather forecasts, in environmental monitoring and management of natural risks and in climatology. As a complete and high quality daily snow cover dataset will allow to analyze variability and extremes of snow cover extension with spatial continuity even where ground based measurements are not available.

REFERENCES

BARBOLINI M. & FERRO F. (2004) - *Distribuzione degli innevamenti sulla montagna friulana.* Regione Autonoma Friuli Venezia Giulia, Direzione delle Risorse Agricole, Naturali e Forestali, 51 pp.

BESANCENOT J.P. (1990) - Climat et Tourisme. Masson, Paris, 223 pp.

BENISTON M. (1997) - *Variations of snow depth and duration in the Swiss Alps over the last 50 years: links to changes in large-scale climatic forcings.* Climatic Change, 36, 281-300.

BIANCOTTI A., CAROTTA M., MOTTA L. & TURRONI E. (1998) - *Le precipitazioni nevose sulle Alpi piemontesi. Trentennio 1966-1996.* Collana Studi Climatologici in Piemonte*,* 2, 11-80.

CANEVAROLO N., TESTA D, FRATIANNI S., ACQUAOTTA F. & TERZAGO S. (2011) - *Variabilità climatica e rischio valanghivo in Valle Ossola.* Neve e Valanghe, 72, 24-33.

CORDOLA M., TURRONI E., PROLA M.C., BERTEA A., ZACCAGNINO M., TURCO M. & MARTORINA S. (2009) - *Piogge e nevicate intense del 14-17 dicembre 2008 in Piemonte*. Neve e Valanghe, 67, 28-37.

DOZIER J. & PAINTER T.H. (2004) - *Multispectral and hyperspectral remote sensing of Alpine Snow Properties.* Annual Reiew of Earth Planet Sciences, 32, 465-494.

DURAND Y., GIRAUD G., LATERNSER M., ETCHEVERS P., MÉRINDOL L. & LESAFFRE B. (2009) - *Reanalysis of 47 Years of Climate in the French Alps (1958-2005): Climatology and Trends for Snow Cover.* Journal of Applied Meteorology and Climatology, 48, 2487-2512.

FAZZINI M. (2009) - *Caratterizzazione generale dei fenomeni di innevamento nel territorio italiano.* Neve e Valanghe, 60, 36-49.

FRATIANNI S., BRUNATTI S., ACQUAOTTA F. & TERZAGO S. (2009) - *Tendence de temperatures et precipitations neigeuses en Vallée Maira (Piemont Sud-Occidental, Italie)*. Geographia Technica, Numero Special 2009, 187-192.

FRATIANNI S., BRUNATTI S. & ACQUAOTTA F. (2010) - *Contributo allo studio del cambiamento climatico nelle Alpi Occidentali: il caso della Valle Maira*. Neve e Valanghe, 69, 20-25.

FRATIANNI S., MOTTA L., TURRONI E. & CAGNAZZI B. (2002) - *Andamento climatico in alta Val di Susa.* Collana Studi climatologici in Piemonte*,* 4, 45-50.

HALL D.K. & RIGGS G.A. (2007) - *Accuracy assessment of the MODIS snow products.* Hydrological Processes, 21, 1534-1547.

JOHNSON D.B., FLAMENT P. & BERNSTEIN R.L. (1994) - *High-Resolution Satellite Imagery for Mesoscale Meteorological Studies.* Bulletin of the American Meteorological Society, 75, 1.

KIDDER S.Q. & VONDER HAAR T.H. (1995) - *Satellite Meteorology: an introduction*. Academic Press, 466 pp.

LATERNSER M. & SCHNEEBELI M. (2003) - *Long-term snow climate trends of the Swiss Alps (1931-99)*. International Journal of Climatology, 23, 733-750.

MARTIN E., BRUN E. & DURAND Y. (1994) - *Sensitivity of the French Alps snow cover to the variation of climatic variables*. Annales Geophysicae, 12, 469-477.

PARAJKA J. & BLOESCHL G. (2006) - *Validation of MODIS snow cover images over Austria.* Hydrology and Earth System Sciences, 10, 679-689.

PELOSINI R., BOVO S. & CORDOLA M. (2011) - *Lessons learnt from the snow emergency management of winter season 2008-2009 in Piemonte.* Advances in Geosciences, 26, 149-153.

RANZI R., GROSSI G. & BACCHI B. (1999) - *Ten years of monitoring areal snowpack in the Southern Alps using NOAA-AVHRR imagery, ground measurements and hydrological data.* Hydrological Processes, 13, 2079-2095.

RUYTER DE WILDT M., SEIZ G. & GRUN A. (2006) - *Snow mapping using multi-temporal Meteosat-8 data.* EARSeL eProceedings 5, 1/2006.

ROMANOV P., GUTMAN G. & CSISZAR Z. (1999) - *Automated monitoring of snow cover over North America with multispectral satellite data.* Journal of Applied Meteorology, 39, 1866-1880.

ROSSI G., TOMASINO M., DELLA VENTURA A., RAMPINI A., SERANDREI BARBERO R. & RABAGLIATI R. (1986) - Landsat registration for a snowmelt model of the Piave Basin. In Modeling Snowmelt Induced Processes. Morris EM (ed.) IAHS Publ., 155, 215-229.

ROTT H. (1987) - "*Remote sensing of snow*". In: Goodison B.E., Barry R.G. & Dozier J. (Eds), Large Scale Effects of Seasonal Snowcover, IAHS Publ. No. 166. IAHS Press, Wallingford., pp. 279-290.

SALOMONSON V.V. & APPEL I. (2006) - *Developement of the Aqua MODIS NDSI fractional snow cover algorithm and validation results.* Geoscience & Remote Sensing, 44, 1747-1756.

SCHERRER S.C., APPENZELLER C. & LATERNSER M. (2004) - *Trends in Swiss Alpine snow days: the role of local and large scale climate variability.* Geophysical Research Letters*,* 31, L13215.

SCHMETZ J., PILI P., TJEMKES S., JUST D., KERKMANN J., ROTA S. & RATIER A. (2002) - *An introduction to Meteosat Second Generation (MSG).* Bulletin of the American Meteorological Society, 83, 977-992.

SWAMY A.N. & BRIVIO P.A. (1997) - *Modeling run-off using optical satellite remote sensing data in high mountainous alpine catchment of Italy.* Hydrological Processes, 11, 1475-1491.

TERZAGO S., CASSARDO C., CREMONINI R. & FRATIANNI S. (2010) - *Snow Precipitation and Snow Cover Climatic Variability for the Period 1971-2009 in the South Western Italian Alps: The 2008-2009 Snow Season Case Study.* Water, 2(4), 773-787; DOI:10.3390/W2040773.

VALT M. & CIANFARRA P. - *Lo straordinario inverno 2008-2009.* Neve e Valanghe, 67, 4-15, 2009.

VALT M., CAGNATI A., CREPAZ A. & CATBERRO D. (2008) - *Variazioni recenti del manto nevoso sul versante meridionale delle Alpi.* Neve e Valanghe*,* 63, 46-57.

VALT M., CAGNATI A., CREPAZ A. & MARIGO G. (2005) - *Neve sulle Alpi.* Neve e Valanghe, 56, 23-41.

(Ms. received 1 January 2011; accepted 30 March 2012)