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CLIMATIC CHANGE IN WESTERN ITALIAN ALPS: ANALYSIS OF SNOW PRECIPITATION VARIABILITY DURING THE PERIOD 1925-2010 USING HISTORICAL AND SATELLITE TIME SERIES

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INTRODUCTION

Alpine glaciers have been identified as one of the European climate tipping elements, *i.e.* a climatic subsystem whose changes may have large-scale impact on Europe (Levermann *et al.*, 2012). In fact snow and ice have high reflectivity and the shrinkage of Alpine glaciers and snow cover is increasing the fraction of the surface absorbed radiation, thus leading to amplified temperature increase in the region, with consequences on environmental and socio-economic systems. Furthermore the Alps are the source of the river systems that supply water to the Po, Rhine, Rhone and Danube basins, thus playing a key role in the hydrological cycle. A shift in climatic regimes, particularly winter precipitation and snow cover duration, would impact heavily on the river systems originating in that area with consequences on water availability for agriculture, industries and hydroelectrical power production, but also on winter tourism that sensitively depends on a reliable snow cover throughout the skiing season.

Despite its outcomes on the society, the climate change at high elevation sites in Italian Alps is an under-explored field of research and the information on snow precipitation variability is very scarce compared to the Swiss, French and Austrian Alps. One of the reasons for this "gap of knowledge" is the uneasy availability of long term high quality time series for this region (Schöner *et al.*, 2009).

This work has been conducted in the frame of the MEditerranean climate DAta REscue (MEDARE) initiative, born under the auspice of the World Meteorological Organization, with the main goal of developing, consolidating and progressing climate data and metadata rescue activities across the Greater Mediterranean Region (GMR). The present study gives a contribution to the assessment of the temporal and spatial snow precipitation variability in Western Italian Alps over the period 1925-2010 taking advantage of three different data sources: the historical records registered at the manned stations, the automatic meteorological station network data and the meteorological satellites data. In particular the objectives are: *i*) to assess the average conditions of snow precipitation using a set of newly recovered historical time series registered in the Piedmontese Alps, *ii*) to investigate extremes, temporal variability and trends of snow precipitation in relation to the main climatic variables, *i.e.* temperatures and total precipitation, *iii*) to investigate the connections between the large scale atmospheric forcings (the North Atlantic Oscillation) and snow precipitation at local scale, *iv*) to explore snow cover extension temporal and spatial variability using EOS Terra/MODIS satellite data, *v*) to estimate the spatial variability of the snow parameters combining satellite data and surface observations.

SNOW CLIMATOLOGY IN PIEDMONTESE ALPS (1925-2010)

The first part of the work aimed to the recovery of several historical daily climatic time series from the paper archives of the Ufficio Idrografico del Bacino del Po (Po basin Hydrographic Office) and the Servizio Idrografico e Maregrafico Nazionale (National Hydrographic and Mareographic Service, SIMN), operational since 1920's up to 1990 and then merged to the Agenzia Regionale per la Protezione dell'Ambiente (ARPA) Piemonte. For the purpose of this study only stations located in the mountains were considered. The other criteria used for the selection of the analyzed stations have been the length, continuity and homogeneity of the series, the representativeness of different altitude ranges and the representativeness of different alpine sectors.

The data finally analyzed refer to the 14 stations covering the whole Piedmontese Alps and ranging between 700 and 2300 m a.s.l. (Table 1, Fig. 1).

Table 1 - Denomination, elevation and UTM (32N) coordinates of the measurement sites considered in the study.

STATION	ALTITUDE [m]	UTM X [m]	UTM Y [m]	PERIOD
1 - Rosone	701	376375	5032521	1938-2010
2 - Lago Piastra	960	371372	4898574	1926-2010
3 - Alpe Cavalli	1500	431707	5104302	1932-2010
4 - Acceglio Saretto	1540	335855	4927442	1925-2010
5 - Ceresole Reale	1573	362763	5032442	1926-2010
6 - Lago Castello	1589	345381	4942026	1943-2010
7 - Agaro	1600	422567	5094533	1961-2010
8 - Alpi Devero	1634	443114	5129624	1951-2010
9 - Malciaussia	1800	354672	5007898	1936-2010
10 - Rochemolles	1950	324427	5000105	1925-2010
11 - Lago Toggia	2165	456227	5142763	1932-2010
12 - Lago Vannino	2177	451230	5137189	1951-2010
13 - Lago Serrù	2283	354236	5035990	1955-2010
14 - Camposecco	2316	426645	5101275	1951-2010

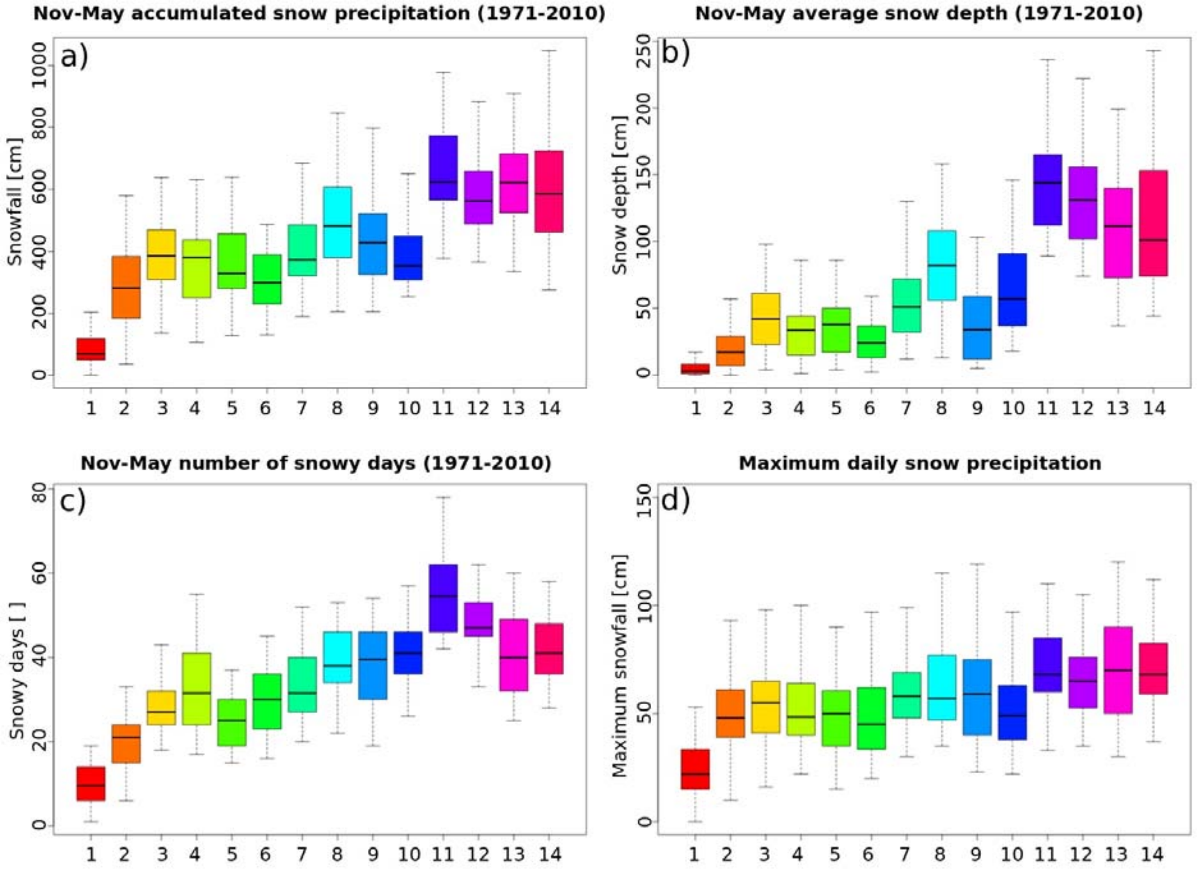
Fig. 1 - Geographical position of the selected stations plotted against the sectors of Piedmontese Alps.

The data originally reported over bulletins were digitized, quality controlled, checked for inhomogeneities and then analyzed to assess present conditions of snow precipitation over Piedmontese Alps at seasonal (November-May) scale. For each measurement site it has been derived the average seasonal distribution of the snow precipitation, the number of snowy days, the snow depth and the snow cover duration in order to represent the nivometrical features in Piedmontese Alps and give the reference values to support environmental and economical planning in the Region, for example for a rational use of water resources and for the development of a sustainable winter tourism. The statistics over the 1971-2000 standard reference period (Fig. 2) are here summarized:

- snow precipitation (HN) median is about 70 cm at 700 m a.s.l., 300-400 cm at about 1500 m a.s.l. and 600 cm at about 2000 m a.s.l.;
- snow depth (HS) median is about few centimeters at 700 m a.s.l., about 50 cm at about 1500 m a.s.l. and 100-150 cm at 2000 m a.s.l.;

- days with snow precipitation (SD) median is about 10 days/season at 700 m a.s.l., 30 days at about 1500 m a.s.l. and 40 days at about 2000 m a.s.l.;

- days with snow cover (HS0) median is about 65 days per season at 700 m a.s.l., 150 days at 1500 m a.s.l. and 200 days at 2000 m a.s.l.


Nov-May accumulated snow precipitation (1971-2010)

Nov-May average snow depth (1971-2010)

Nov-May number of snowy days (1971-2010)

Maximum daily snow precipitation

Fig. 2 - Statistics of the November-May accumulated snow precipitation (a), average snow depth (b), number of snowy days (c) and maximum daily snow precipitation (d) over the period 1971-2000. Each box represents one station, ordered by increasing elevation (ref. Table 1). The lower hinge, the median, the upper hinge correspond to the 1st, 2nd, 3rd quartiles respectively, the lower and upper whiskers represent the minimum and the maximum of the sample.

An important application of historical daily snow data analysis is the evaluation of the snow avalanche hazard and the potential effects on mountain communities. Extreme values of daily snowfall and snow depth have been analyzed for each site in order to provide essential climatological information for planning defences for mountain security. The maximum daily snow precipitation in the November-May season shows small variability in the elevation range between 1000 and 2300 m a.s.l., in fact its median spans between 50 and 70 cm and the extreme maxima vary between 90 and 120 cm (Fig. 2d). Unlike snow precipitation, the seasonal snow depth maxima show a clear altitude dependence: at 700 m a.s.l. the median is 30 cm; at about 1000 m a.s.l. the median is 100 cm; around 1500 m a.s.l. the median is 100-130 cm; around 2000 m a.s.l. the median is 120-180 cm; above 2000 m a.s.l. the median is much higher and ranges between 250 and 290 cm.

Looking at the altitudinal variation of snow parameters, the seasonal averages increase with height h in the range $700 < h < 2300$ m according to the following relations:

$$\mathrm{HN}(h) = -116.74 + 0.32h \tag{1}$$
$$\mathrm{HS}(h) = 2.25\ \mathrm{e}^{0.0018\,h} \tag{2}$$
$$\mathrm{SD}(h) = -2.83 + 0.02h \tag{3}$$
$$\mathrm{HS0}\ (h) = 6.79 + 0.09h \tag{4}$$

Concerning the seasonal distribution of snow precipitation, at altitude below 2200 m a.s.l. the largest monthly snowfall amount is concentrated in January. After January, HN rapidly decreases below 1000 m a.s.l., while above this altitude spring snowfalls become relevant. Above 2200 m solid precipitation are most abundant in spring and in particular in April.

The seasonal distribution of HN is mainly dependent on the elevation:

- below 2000 m a.s.l. it is unimodal, with an absolute maximum in winter (January);
- between 2000 and 2200 m a.s.l. January is still the month with maximum snow precipitation but a sensible amount of snow falls in March/April;
- above 2200 m a.s.l. the distribution is unimodal with a maximum in spring (April).

The length of the snow season increases with elevation: precipitation starts in November and ends in May in the lowest station (701 m a.s.l.), while in the highest site (2316 m a.s.l.) the snowfalls are registered from September to June, but occasionally may occur also in July/August.

The analysis of snow precipitation and snow depth temporal variability has been carried out using the Standardized Anomaly Index SAI (Giuffrida & Conte, 1989) which expresses the anomaly of the studied parameters respect to the mean value over a reference 30-year period, in this case the 1971-2000. An anomaly index with value 0 means a season lined up with the reference period, a positive or negative anomaly mean respectively an excess or a deficit compared to the normal value. The SAI allowed to highlight sequences of positive snow anomalies in the late 1930's, from the end of the 1950's to the beginning of the 1960's and during all the 1970's (Fig. 3). Consecutive seasons of below average snow depth were recorded during the early 1930's and a strong reduction is registered from the mid 1980's up to the end of the record. During the last 25 years almost all seasons were characterized by negative anomalies. Only few isolated exceptions occurred: among them the 2008-2009 snow season, that registered the third highest snow depth of the record after 1936 and 1960.

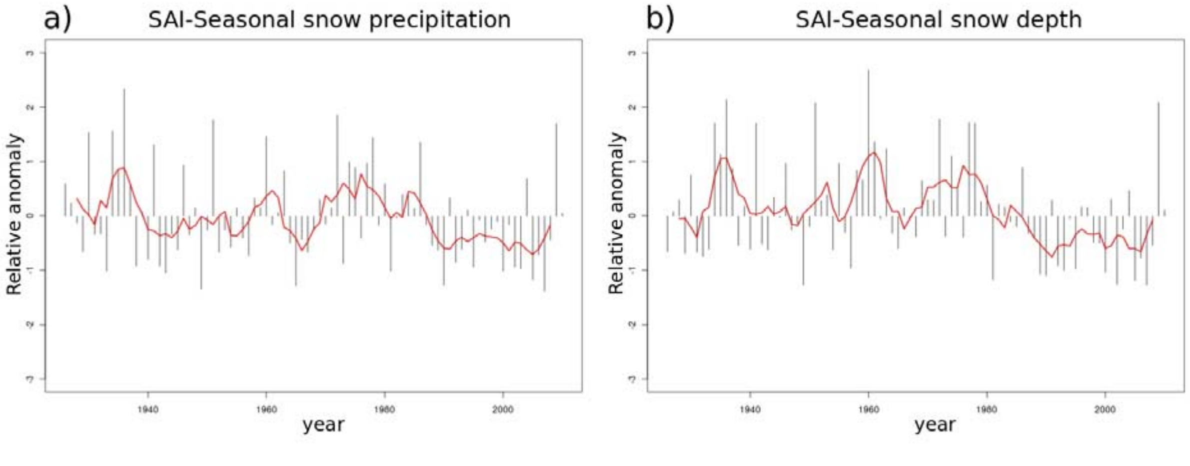


Fig. 3 - Standardized Anomaly Index of November-May accumulated snow precipitation (a) and average snow depth (b) for Piedmontese Alps over the period 1925-2010 calculated using all 14 time series. The red line represents the 5 year moving average.

The strong snow depth reduction in the last decades is highlighted also by the trend analysis (Table 2): over the maximum period 1925-2010 snow depth has significantly reduced by -0.25 ÷ -0.43 cm/y. Over the 1951-2010 common subperiod 11 out of 14 stations show a significant decrease of snow depth ranging from -0.19 cm/seas in the most Southern station at 960 m a.s.l. and -1.40 cm/seas in the most Northern station at 2165 m a.s.l..

Table 2 - Trends in seasonal (November-May) snow depth (HS), accumulated snowfall (HN) and number of snowy days (SD) over the maximum period available and over the 1951-2010 common period. The statistically significant trends (Mann Kendall, 95% confidence level) are highlighted in bold.

Station	**Elev [m a.s.l.]**	**Max Period**	**Trend Max Period**			**Trend 1951-2010**		
			HS [cm/y]	HN [cm/y]	SD [days/y]	HS [cm/y]	HN [cm/y]	SD [days/y]
Camposecco	2316	1951-2010	-	-	-	**-1.05**	-0.56	-0.04
Lago Serrù	2283	1955-2010	**-2.01**	-0.80	0.12	-	-	-
L. Vannino	2177	1951-2010	-	-	-	**-1.39**	-1.54	-0.10
Toggia	2165	1932-2010	**-0.96**	0.74	0.08	**-1.40**	0.59	-0.02
Rochemolles	1950	1925-2010	**-0.43**	**-2.65**	0.06	**-1.01**	**-3.71**	-0.08
Malciaussia	1800	1936-2010	-0.01	-0.47	-0.05	**-0.29**	**-2.16**	-0.15
Alpi Devero	1634	1951-2010	-	-	-	**-0.75**	-0.37	0.02
Agaro	1600	1961-2010	-0.33	**-0.51**	**-0.28**	-	-	-
L. Castello	1589	1943-2010	-0.15	-0.51	0.07	**-0.27**	-0.85	0.03
Ceresole R.	1573	1926-2010	-0.15	-0.08	-0.08	**-0.32**	-0.94	-0.08
Acceglio S.	1540	1925-2010	**-0.25**	-0.73	-0.03	**-0.41**	-1.31	-0.09
Alpe Cavalli	1500	1932-2010	-0.30	-0.52	**-0.08**	**-0.58**	-1.41	**-0.16**
Lago Piastra	960	1926-2010	-0.06	-0.61	-0.02	**-0.19**	**-1.92**	-0.05
Rosone	701	1938-2010	0.02	0.02	-0.01	0.02	**0.10**	-0.01

Several climatic parameters were considered in order to explain these findings in terms of a change in either the abundance of snow precipitation or the frequency of meteorological perturbations favourable to solid/total precipitation or the increase of surface temperatures. The main causes of the observed snow depth reduction were identified in the temperature increase rather than in the precipitation decrease. In general, November-May accumulated total (liquid+solid) precipitation does not show significant changes over the period 1951-2010 probably because of its high interannual variability. On the contrary, minimum and maximum temperatures show positive, highly significant trends: minimum temperatures increased by 0.05 ÷ 0.06 ±0.01 °C/y (99% confidence level), with almost the same contribution from winter and spring months; maximum temperatures increased by 0.02÷0.03 ±0:01 °C/y especially in winter. The number of frost days (T_{min} < 0 °C, potentially snowy days) significantly decreased by -0.29 ÷ -0.82 days/y, especially at middle and low elevations, with strongest reduction in spring. As well the number of ice days (T_{max} < 0 °C, day without snow melting) generally decreased mainly in winter at the middle-low elevation and mainly in spring at the highest site. The decrease in the potentially snowy days and the increase in the number of days with snow melting are the main causes of the observed snow precipitation and snow depth decrease.

SNOW PRECIPITATION LINKS WITH LARGE SCALE FORCINGS

The second part of the work consists in the analysis of the connections between winter (DJF) snow precipitation and snow depth over Piedmontes Alps and large scale atmospheric forcings, in particular the North Atlantic Oscillation (NAO, defined as the mean normalized sea level pressure difference between Ponta Delgada (Azores) and Stykkisholmur/Reykjavik (Iceland)) which is the dominant mode of atmospheric variability over the North Atlantic (Hurrell, 1995). In recent years several works investigated the patterns of interannual variability of winter precipitation in the Alps using different methods and they obtained results somehow contrasting (Beniston & Jungo, 2002; Schmidli *et al.*, 2002; Bartolini *et al.*, 2009). Here the aim is to clarify the type of dependence existing between the large scale climate forcing and the local response. The classical methodology of the correlation analysis showed that a significant anticorrelation exists between snow depth and NAO: negative (positive) NAO is favourable (unfavourable) to snow pack persistence. Snowfall amount is anticorrelated only at middle/low altitudes, where small changes in temperature and precipitation may largely affect snowfall frequency and amount. Middle and low elevation area result thus the most sensitive to the NAO external forcing. A more detailed description of the similarities between NAO and snow precipitation time series has been obtained using spectral analysis that allowed to determinate the periodic components embedded in the time series. Two different methods were used, the Monte Carlo Singular Spectral Analysis (MCSSA) and the MultiTaper Method (MTM) (Ghil *et al.*, 2002). Both techniques allowed to test the significant oscillations against the null hypothesis of red/white noise background and they provided almost the same results: all 14 long term time series present significant (0.05 significance level) 2.7/2.3 year period oscillations that are typical cycles of the North Atlantic Oscillation (Table 3, Fig. 4).

Table 3 - Oscillatory modes of DJF cumulated snowfall and average snow depth obtained using MultiTaper Method (MTM) and Monte Carlo Singular Spectrum Analysis (MCSSA).

		HN MODES		HS MODES	
Station	**Elev [m a.s.l.]**	MTM	MCSSA	MTM	MCSSA
Camposecco	2316	2.6	-	2.9	2.8
L. Vannino	2177	2.6 -	- -	2.7 7.1	2.7 -
Toggia	2165	2.4 4.8 -	2.4 4.8 -	2.4 4.8 8.3	2.4 - 8.2
Rochemolles	1950	5	5	2.3	-
Malciaussia	1800	2.4	2.5	2.6	2.7
Alpi Devero	1634	4.3	4.3	2.6	2.7
L. Castello	1589	2.5	2.5	2.5	2.5
Ceresole R.	1573	2.5	2.5	2.6	2.8
Acceglio S.	1540	2.4 - 5.9	2.4 - 5.9	2.3 2.8 5.9	2.3 2.8 5.9
Alpe Cavalli	1500	2.4	2.4	2.4	2.4
Lago Piastra	960	2.5 -	2.4 -	2.4 5.9	2.4 5.9
Rosone	701	2.5	-	2.5	-

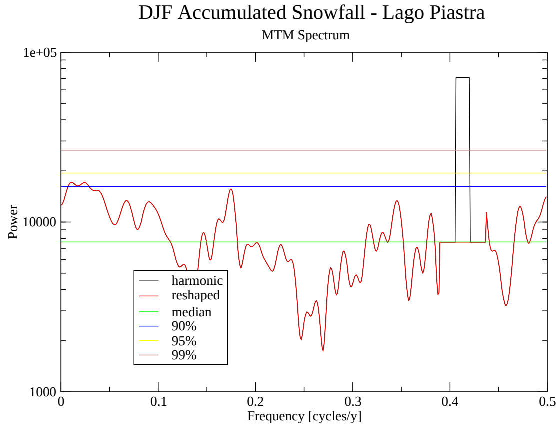


Fig. 4 - MTM power spectrum (red line) of DJF cumulated snowfall in Entracque Lago Piastra station, Southern Piedmont. The estimated red noise background and associated 90%, 95%, and 99% significance levels are shown by the four smoothed curves, in this order, from the lowest to the highest curve in the figure. The harmonic peak at frequency f = 0.41 y^{-1} corresponds to a periodicity of 2.4 years.

The similarity of snow depth and NAO waveforms has been evaluated through the cross-correlation analysis: in almost all cases the signals are significantly anticorrelated at lag L = 0 and L = 5 years, corroborating the hypothesis of the existence of a ciclicity of about 2.5 years that can be observed after two oscillations. The Spectral Coherence Analysis showed that the squared coherency between NAO and snow depth always reaches a maximum at the frequencies corresponding to about 2.3 and 2.7 year periods, so it can be concluded that the 2.7/2.3 year period oscillations are synchronized. This procedure shows that a direct cause-effect relation can be established between the atmospheric large scale patterns and the local climate. In particular the NAO drives the high frequency oscillations of snow precipitation in Piedmontese Alps. The knowledge of the mechanisms underlying snow precipitation is the prerequisite for prediction and may be of valuable help in climate models. Current efforts in the improvement of the NAO seasonal prediction will have positive outcome in seasonal snow climatic forecasts.

SATELLITE DATA

Snow cover is among the most important characteristics of the Earth's surface that influence surface radiation, energy and hydrologic budgets (Romanov *et al*., 2002). Meteorological observations at the surface are an excellent way for studying the long term climate variability at local scale, but especially in mountain area their number is too limited to describe the snow cover spatial variability. On the contrary, satellite remote sensing enables observations at large scale and in remote areas where no surface measurement is available. EOS Terra satellite was launched in orbit on December 18, 1999 and it is part of the Earth Observing System (EOS) mission of the US National Aeronautics and Space Administration (NASA). It is located at an altitude of 705 km on a sun-synchronous near-polar orbit and it carries on board the MODerate Resolution Imaging Spectroradiometer (MODIS). MODIS acquires data in 36 spectral channels in the range 0.4-15 µm, with an average 500 m spatial resolution and a return time period of 1 day. The availability of the MODIS snow cover data since 2000 allowed to study snow cover variability over the Alps, and in particular over Western Italian Alps during the last decade. The temporal variability of the snow cover extension, its extreme values and average characteristics over the period 2000-2011 are investigated. The seasonal distribution of the average snow cover extension is unimodal (Fig. 5a). It increases from September to January when it reaches the absolute maximum and after decreases to reach the absolute minimum in August. January is the month with the maximum probability to have snowfall at low elevation and in the plains, in agreement with the surface historical records. The percentage of the area that is interested by January snowfalls ranges between a minimum of 57% and a maximum of 93%, slightly lower values are registered in December, followed by February and March.

The satellite information on the snow cover extension over large scale has been integrated to the snow precipitation abundance surface data given by the meteorological stations of the Regional Agency for Environmental Protection (ARPA) of Piedmont (Italy) and the results have been related to the temperatures in order to achieve a global view on the last snow seasons. In this way the features of each snow seasons have been described in terms of temperature, snow abundance and snow cover extension anomalies. A quite clear linear relation exists between winter accumulated snow precipitation and snow cover extension: positive anomalies in snow precipitation over Western Alps correspond to above average snow cover extension also at low elevation and in the plain. Snow cover extension (SCA) anomaly results in linear relation also with both minimum and maximum temperatures anomalies (TN, TX respectively) according to:

$$TN = -0.75SCA - 0.01 \qquad (5)$$

$$TX = -0.81SCA - 0.02 \qquad (6)$$

In particular negative temperature anomalies are associated to widespread snow precipitation over the plain, while positive temperature anomalies generally do not allow low elevation snow precipitation.

Satellite snow cover maps combined with the Digital Elevation Model data allowed to determinate several parameters of interest for both meteorological monitoring and climate studies, *i.e.* the seasonal evolution of the snow level and the speed of the snow cover retreat (*snow depletion*) for each sector of the Piedmontese Alps (Fig. 5b). These information are needed also for studying the impact of climatic change on ecosystems and for planning a sustainable development of winter tourism.

MODIS monthly snow maps were processed in order to calculate, for each pixel, the frequency of snow occurrence over the 2000-2010 period. This frequency, representing how many times in the 10 year period a pixel results snow covered in monthly maps, can be interpreted as the probability to have snow cover at least once in a given month over a given area. An example is reported in Fig. 5c that represent the snow cover probability map for March. These information will help a rational planning of the resources needed for the road security throughout the Region.

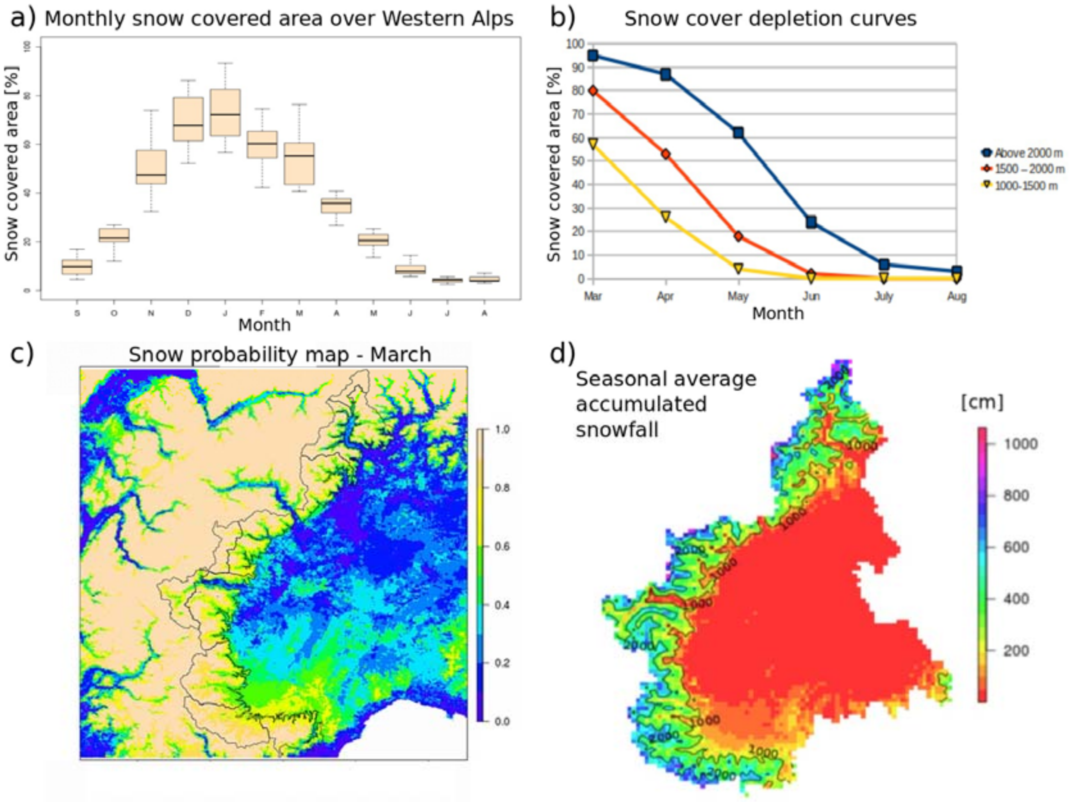


Fig. 5 - Statistics of the maximum monthly snow cover extension over Western Alps (a), snow depletion curves for different altitude zones in Piedmontese Alps (b); snow cover probability map for the month of March (c) derived from MODIS data over the 2000-2010 period. Average seasonal accumulated snowfall map derived by Kriging interpolation of nivo-meteorological station network data (d).

Monthly aggregations of MODIS snow cover were used in combination with surface data from 111 nivo-meteorological stations operated by ARPA to estimate the spatial distribution of the monthly average snow depth and the accumulated snowfall over Piedmont where no observation is available. The Kriging method has been applied to interpolate the measurements and estimate spatial averages. Two approaches were examined, the first using only meteorological stations data, the second using both satellite snow cover and surface stations data. The objective was to investigate the added value of using satellite observations in generating high spatial resolution snow fields. The accuracy of the estimate has been calculated each time by cross-validation technique which provides the difference between the measure and the predicted values and thus the model accuracy. An analysis of several case studies shows that the use of satellite data improves the estimation of the spatial variability of snow parameters and allows to determine snow fields more accurately with respect to the station-only method. The Kriging interpolation technique has been applied to all available stations to calculate the spatial distribution of the average seasonal snow precipitation and number of snowy days over Piedmont in the last decade 2000-2010 (Fig. 5d). All these maps provide information with spatial continuity where surface stations are not available and they can be used in combination with historical record reference values for supporting political decisions on socio-economical and energetic planning in mountainous area.

Finally the potential of using Meteosat Second Generation (MSG) satellite for snow cover estimation has been assessed. MSG is a geostationary satellite launched in orbit in 2002 and it carries the Spinning Enhanced Visible and Infrared Imager (SEVIRI). It is located at an altitude of 36.000 km and its field of view is the Earth disk centered in the equatorial plane at 0° longitude. The MSG-SEVIRI 15 minutes temporal resolution allows to have frequent image acquisitions, thus increasing the probability to have clear sky observations. This characteristic makes this satellite suitable for snow monitoring on a daily basis. A novel snow cover algorithm based on MSG/SEVIRI data and developed by ARPA Piemonte is presented. The algorithm exploits the SEVIRI high temporal resolution to combine multiple acquisitions and generate daily snow maps that minimize the number of cloud covered pixel. SEVIRI daily snow maps may thus provide a more complete representation of the snow cover over the Alps respect to MODIS that relies on a single daily acquisition. Several applications are presented, including the determination of the daily snow level and the fraction of snow covered area for each sector of Piedmontese Alps. The advantage of using MSG satellite is thus to have a daily resolution snow cover dataset, that is profitable for weather forecast and environmental monitoring applications.

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