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Article

Snow Precipitation and Snow Cover Climatic Variability for the Period 1971–2009 in the Southwestern Italian Alps: The 2008–2009 Snow Season Case Study

Silvia Terzago [1,*], Claudio Cassardo [2,3], Roberto Cremonini [4] and Simona Fratianni [1]

[1] Department of Earth Sciences, University of Torino, Via Valperga Caluso, 35-10125 Torino, Italy; E-Mail: simona.fratianni@unito.it

[2] Department of General Physics "A. Avogadro", University of Torino, Via Giuria, 1-10125 Torino, Italy; E-Mail: claudio.cassardo@unito.it

[3] CINFAI, National Inter-University Consortium for Physics of the Atmosphere and Hydrosphere, 1-10121Turin, Italy

[4] Regional Agency for Environmental Protection (ARPA) of Piemonte, Via Pio VII, 9-10135 Torino, Italy; E-Mail: r.cremonini@arpa.piemonte.it

* Author to whom correspondence should be addressed; E-Mail: silvia.terzago@unito.it; Tel.: +39-011-670-5102; Fax: +39-011-670-5146.

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Abstract: Snow cover greatly influences the climate in the Alpine region and is one of the most relevant parameters for the climate change analysis. Nevertheless, snow precipitation variability is a relatively underexplored field of research because of the lack of long-term, continuous and homogeneous time series. After a historical research aiming to recover continuous records, three high quality time series of snow precipitation and snow depth recorded in the southwestern Italian Alps were analyzed. The comparison between the climatological indices over the 30 years reference period 1971–2000 and the decade 2000–2009 outlined a general decrease in the amount of snow precipitation, and a shift in the seasonal distribution of the snow precipitation in the most recent period. In the analysis of the last decade snow seasons characteristics, the attention was focused on the heavy snowfalls that occurred in Piedmont during the 2008–2009 snow season: MODerate resolution Imager Spectroradiometer (MODIS) snow cover products were used to evaluate snow cover extension at different times during the snow season, and the results were set in relation to the temperatures.

Keywords: snow cover; Alps; climate change; MODIS; satellite; snow map

1. Introduction

Snow cover and duration are among the major controlling factors for a range of environmental and socio-economic systems in mountainous regions. During the coldest part of the winter, snow cover protects dormant plants from frost damage, therefore a shorter snow season may influence the survival rates of numerous species at high altitudes [1,2]. Moreover, snow represents a resource for hydro-electrical energy production, for agricultural and human drinking water supply and for winter sports tourism.

Snow abundance depends on both temperature and precipitation: snow depth, snow cover extension and duration are not only related to the diurnal values of temperature and precipitation, but they are also based on the history of these variables over a period preceding the observation itself. For this reason, snow records, averaged over monthly or yearly periods, provide a useful insight into inter-annual or longer time scale climatic fluctuations [3]. Furthermore, on a larger scale, the snow cover can affect the climate as snow has a major impact on the surface energy balance, due to its high albedo and low thermal conductivity, and it may also alter the atmospheric circulation by modifying the overlaying air masses [4]. As a consequence, snow can be considered as a main parameter, both as indicator and controlling factor, for studying the climate change in the Alpine area.

There have been some major studies carried out on the snow precipitation variability over the Swiss Alps by Beniston [3-5], Laternser and Schneebeli [6] and Scherrer *et al.* [7], and over the Austrian Alps by Hantel *et al.* [8]. Concerning Italy, Valt *et al.* [9,10] analyzed the snow cover variability, abundance and duration over the southern Alps, while Fazzini [11] outlined general features of snow precipitation over the entire national territory. Even though some regional studies have already been produced (for Piedmont [12,13] and Trentino [14]), this field can still be considered as underexplored due to the difficulty in finding long term, continuous and homogeneous time series.

In the Piedmontese region, the meteorological station network controlled by the Regional Agency for the Environmental Protection (ARPA Piemonte, hereafter simply referred to as ARPA) counts for more than 350 automatic and manual stations, of which about one hundred perform snow measurements on a daily basis. Most automatic stations started recording data around 1990, thus supplying a large dataset for the analysis of the last two decades. However, in order to perform a long term analysis, the manual measurements recorded by the *Ufficio Idrografico del Bacino del Po* (Po basin Hydrographic Office), an independent institution only recently inglobated in the ARPA, must also be considered.

For this reason, an historical survey and research of the paper archives was performed, and records of daily fresh snow and snow depth measurements in the Cuneo province, southwestern Piedmont, were found and digitized. The resulting continuous and high quality time series were used to evaluate and analyze the snow precipitation indices over the 30 year period 1971–2000, and over the decade of 2000–2009. The aim of this study is to compare the snow precipitation characteristics of the last decade with those of the 30 year reference period. An in-depth analysis was carried out to evaluate the

2008–2009 snow season, when heavy snow precipitations occurred over the western Alps. Maps from the Earth Observing System (EOS) satellites, reproducing the snow cover extension over a large scale, were used to integrate the ground stations information and to achieve a global view on the features of the 2008–2009 snow season.

2. Materials and Methods

2.1. Meteorological Stations at the Earth Surface

The paper archives of ARPA contain the bulletins reporting daily temperatures, rainfall, snow precipitation and snow depth data recorded at a set of Piedmontese stations maintained by the personnel of the *Ufficio Idrografico del Bacino del Po*. In this work the attention is focused on snow depth and snow precipitation: the measurements were performed over a flat field where a vertical graduated scale was fixed at the ground and a small tablet, usually made of wood, was available. At approximately 8:00 am local time, the observer measured the snow depth (as the depth between the ground and the snow surface top) using the graduated scale and the fresh snow (evaluated as the snow precipitation accumulated in the prior 24 hours over the tablet placed over an horizontal surface). In a few cases, snow precipitation records cover more than 50 years, with some measurement sites still in operation, under the supervision of ARPA.

In this study, three measurement sites located in southwestern Piedmont, in the Cuneo province, were chosen (Figure 1 and Table 1), and the corresponding data were digitized.

Figure 1. Map of Piedmont. The geographical position of the three stations selected for this study, located in the southwestern sector and highlighted by red squares.

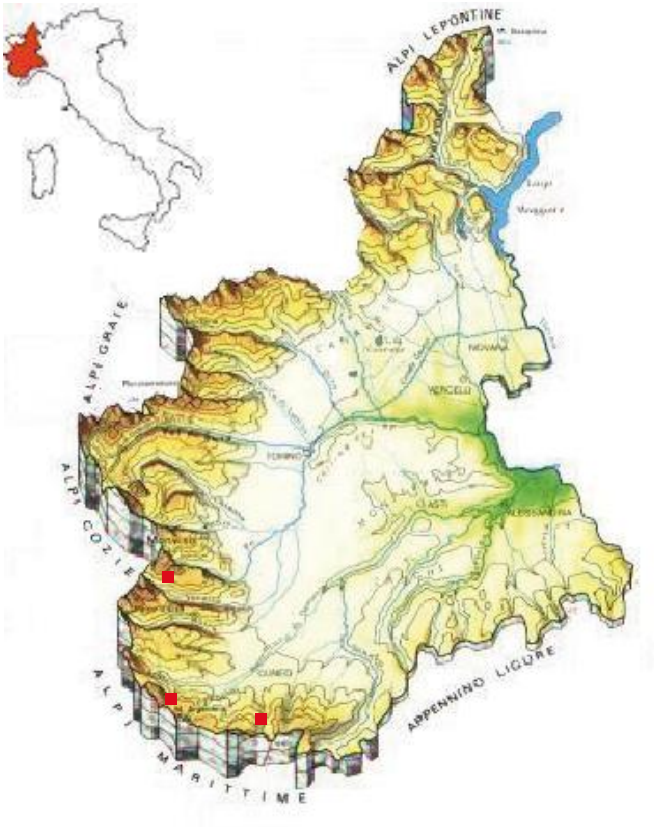


Table 1. Denomination, elevation and UTM coordinates of the three measurement sites considered in this study.

	Elevation [m. a. s. 1]	**UTM_x[m]**	**UTM_y[m]**
Entracque L. Piastra	960	371372	4898574
Vinadio Riofreddo	1200	354258	4905036
Ponte chianale L. Castello	1589	345381	4942026

Several missing data in the original datasets were discovered. After a historical research in the Electric Power company (ENEL) archives containing a copy of the original observation forms, some missing bulletins were found and missing data were filled in. This operation provided snow depth and fresh snow datasets which are continuous for the whole period of 1971–2009 and suitable for the statistical analysis.

A preliminary in-depth historical research was carried out in order to acquire information on the location and characteristics of the measurement sites and to detect eventual changes undergone during the stations lifetime, which could reflect in relevant changes in the data not related to climatic factors [15]. This inspection did not reveal relevant variations. The quality of daily data was subsequently checked using the RClimdex software [16], in order to identify and eventually correct errors due to the digitization. The obtained dataset, composed of quality controlled and continuous time series, was analyzed to evaluate the snow climatological features of the area.

2.2. Satellite Data

In order to integrate the information given by ground observations, satellite snow cover derived by the MODerate Resolution Imaging Spectroradiometer (MODIS) measurements was used. MODIS employs a cross-track scanning mirror and a set of detector elements to provide imagery of the Earth's surface and clouds in 36 discrete and narrow spectral bands, extending from approximately 0.4 to 14.0 μm [17]. The spatial resolution of MODIS varies with the spectral band, and ranges between 250 m and 1 km at the nadir. The device is a component of the Earth Observing System (EOS) Terra and Aqua satellites, orbiting on a near-polar sun-synchronous orbit, at 705 km from the Earth surface. Operational data collection from the Terra MODIS began on 24 February 2000, and from the Aqua MODIS on 24 June 2002. Using the radiometric measurements performed by the satellites, it is possible to observe the snow cover every day.

Hall *et al.* [18] developed an algorithm using the MODIS spectral measurements to identify the snow cover from its spectral properties. The algorithm is based on a series of threshold tests able to identify the emitting/reflecting surfaces of the Earth-Atmosphere system looking at their spectral properties [19-21] and requires the following input data:

- MODIS Level 1B bands 1, 2, 3, 4, 5, 6, 31 and 32 [22];
- MODIS Cloud-Mask [23,24];
- MODIS 1 km geolocation product for latitude, longitude, viewing geometry data and water/land mask [25].

The cloud mask filters the areas resulting cloud covered at the moment of the MODIS acquisition: in fact clouds obscure the MODIS field of view and the spectral method cannot give any information

on the presence of snow at the surface. Cloud-free land pixels are then processed for snow detection, and a daily 500 m spatial resolution snow cover map is generated. The daily product accuracy was determined comparing MODIS maps with ground measurements (absolute validation), or with other snow maps (relative validation). An overview of the validation of MODIS snow products is given by Hall *et al.* [4] which report the results of the comparison between MODIS daily snow products and SNOwpack TELemetry (SNOTEL is an automated system to collect snow pack and other related data over the western United States) measurements performed in 15 sites in the upper Rio Grande basin during the 2000–2001 snow season [26]: the MODIS overall accuracy was estimated to be 94.2%. Another study performed by Simic *et al.* [27] compared MODIS daily snow cover maps acquired over Canada with observations carried out at approximately 2000 meteorological stations: the overall percentage of agreement with the *in situ* data over a 160 day period during 2001 was 93%, with the lowest agreement over evergreen forests (80%), where MODIS maps tended to overestimate snow cover.

For the relative validation, the 500 m MODIS daily snow cover was degraded in order to match the resolution of the National Operational Hydrological Remote Sensing Center (NOHRSC) products (1 km): the agreement was 95.1% in the study area (the Great Plains) [28]. The best agreement was found in winter, when snow cover was more continuous. Some differences were found in the forested area, where MODIS maps show more extended snow cover than did the NOHRSC products.

In this study, 8-day composite snow products (MOD10A2) available on the National Snow and Ice Data Center (NSIDC) website [29,30] were considered: MOD10A2 reports as "snow covered" all pixels that were recorded as snow covered at least once during the 8-day period; the number of unclassified pixels due to cloud obscuration is therefore minimized.

3. Results

Daily total and fresh snow depth measurements performed at the three meteorological observation sites during the period of January 1971 to December 2009 were analyzed in order to evaluate the following snow indices:

- Monthly cumulated fresh snow [HN];
- Average number of snowy days per month [SD] (fresh snow depth ≥ 1cm);
- Monthly mean snow depth [HS]

Those indices were evaluated over the thirty year reference period 1971–2000 and over the last decade 2000–2009. Details are provided in Table 2.

3.1. Snow Climatic Indices during the 1971–2000 Reference Period

At each observation site, the monthly values show a strong interannual variability, evidenced by the large standard deviation. During the 1971–2000 period, the cumulated snowfall (HN) presents an absolute maximum in January at all sites. After January, HN rapidly decreases at lowest elevations (Entracque Lago Piastra, 960 m a.s.l. and Vinadio Riofreddo, 1,200 m a.s.l.). At these locations, the snow rate (seasonal distribution of HN) is unimodal, with a single winter maximum: this behavior

confirms the results outlined by Biancotti *et al.* [12] and Fazzini [11] relative to the stations located in the western Alps at low altitude, below 1,300 m a.s.l.

Table 2. Mean monthly cumulated snow precipitation (HN), average number of snowy days per month (SD) and mean monthly snow depth (HS) over the periods 1971–2000 and 2000–2009 at the Entracque Lago Piastra (a), Vinadio Riofreddo (b), and Pontechianale Lago Castello (c) stations, with their standard deviations (σ). The 30 year seasonal averages include November and December 1970 measurements.

(a)	**Entracque Lago Piastra**											
	1971-2000						**2000-2009**					
	HN [cm]		**SD [cm]**		**HS [cm]**		**HN [cm]**		**SD [cm]**		**HS [cm]**	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Nov	23	24	3	2	3	4	35	26	3	2	4	4
Dec	51	44	4	2	14	12	62	55	5	2	18	25
Jan	84	69	6	3	39	33	50	40	4	2	28	32
Feb	57	59	5	2	47	43	47	41	3	2	27	36
Mar	41	35	4	2	30	35	21	12	2	1	11	16
Apr	21	21	2	2	4	7	9	11	1	2	1	1
May	2	4	0	1	0	0	0	0	0	0	0	0
Seas	279	129	20	7	20	15	224	104	18	5	13	15

(b)	**Vinadio Riofeddo**											
	1971-2000						**2000-2009**					
	HN [cm]		**SD [cm]**		**HS [cm]**		**HN [cm]**		**SD [cm]**		**HS [cm]**	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Nov	30	28	4	3	6	7	46	35	4	2	7	7
Dec	65	52	5	2	21	18	76	71	6	3	34	38
Jan	88	80	7	3	44	33	58	54	5	3	49	57
Feb	68	74	7	3	56	44	48	39	4	2	49	58
Mar	54	47	6	2	44	41	33	25	3	2	30	42
Apr	36	28	3	2	13	19	19	18	3	2	2	1
May	4	12	1	1	1	1	0	0	0	0	0	0
Seas	339	159	25	9	26	17	268	144	24	7	26	32

(c)	**Pontechianale Lago Castello**											
	1971-2000						**2000-2009**					
	HN [cm]		**SD [cm]**		**HS [cm]**		**HN [cm]**		**SD [cm]**		**HS [cm]**	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Nov	37	35	4	3	7	9	58	44	4	2	12	14
Dec	45	35	6	2	21	17	72	66	6	3	37	30
Jan	65	54	7	3	41	33	46	38	4	3	44	39
Feb	54	47	7	3	49	36	42	37	4	2	44	34
Mar	51	44	6	1	41	36	33	34	4	2	32	27
Apr	46	41	4	2	14	13	35	30	4	2	9	13
May	7	15	1	1	1	2	0	0	0	0	0	0
Seas	305	103	30	7	25	15	275	107	26	9	28	22

At higher elevation (Pontechianale Lago Castello, 1,589 m a.s.l.), HN show a maximum in January as well, but cumulated snow amounts in February, March and April are comparable, as recorded on the French side of the Alps at about 1,000 m a.s.l. [31].

It is also remarkable that the maximum amount of seasonal snowfall does not occur at the highest station (Pontechianale Lago Castello), but at Vinadio Rifreddo. This behavior can be perhaps explained by the geographical position of the two sites: the lower station is located in the Stura di Demonte Valley, which is west-east oriented and exposed to the southeastern flows (favorable to snow precipitation), while the highest station is located at the end of a lateral valley with respect to the main west-east oriented Varaita Valley, thus, it is in a relatively more unfavorable position for snow precipitation.

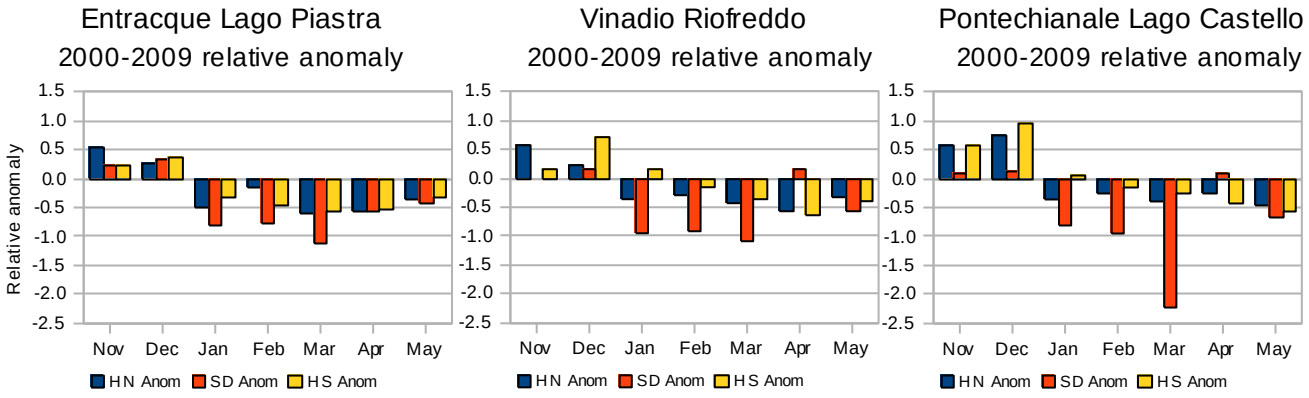
The SD shows a maximum in January or February, while the HS shows its maximum in February at all the measurements sites. The seasonal number of SD increases with elevation, while comparable seasonal average snow depth is found at Pontechianale and at Vinadio Riofreddo, although the elevation difference is larger than 350 m.

3.2. Snow Indices during the 2000–2009 Decade

The 2000–2009 decade show relevant differences with respect to the general features outlined for the 30 year reference period.

All measurement sites show that snowfalls are most frequent and abundant in December when HN and SD reach their maxima. This suggests the presence of a shift in the period of maximum precipitation, which occurs earlier in the snow season. By looking at the relative anomalies of HN, SD and HS [calculated as the difference between the mean monthly values in 2000–2009 and the corresponding reference values over the 1971–2000 period, divided by the corresponding standard deviation] (Figure 2), a positive anomaly in November and December and a negative anomaly from January to the end of the snow season are evident.

Figure 2. The relative anomaly [adimensional] of average monthly cumulated snowfall (HN), snowy days (SD), and snow depth (HS), for the 2000–2009 decade with respect to the 1971–2000 reference period in the three stations considered in this study.



Moreover, in May, average HN, SD and HS and corresponding standard deviations are constantly zero; thus, the increased early winter and decreased spring snow precipitation are associated with shorter snow seasons with respect to the 30 year reference period. These characteristics have been found at each measurement site, regardless of its altitude.

Looking at the absolute values, the strongest anomalies were registered at the highest elevation station (Pontechianale Lago Castello): positive in November and December, when snow precipitations and snow depth are more abundant than in the reference period, and negative during the remaining months. Another remarkable characteristic is that, with respect to the reference period, the mean number of snowy days (SD) is only slightly higher in November and December, but is much lower during the remaining period (especially in March, when it exceeds the mean value by more than two standard deviations), suggesting a drastic reduction in the total number of days with snowy precipitation in the whole season.

When examining the seasonal averages, a considerable decrease in the cumulated snowfall (HN) and a slight decrease in the number of snowy days (SD) are evident. These findings are in agreement with the unprecedented series of low snow winters registered over the Swiss Alps since the end of the 1980s [32]. Regarding the snow depth (HS), a decrease is found in the seasonal average at low elevations where snow cover amount and duration is extremely sensitive to changes in temperatures. At middle and high elevations, the last decade seasonal snow depth is comparable to the climatic averages, but the higher standard deviations suggest an increased interannual variability. Similar characteristics relative to the HS have been outlined over the French Alps [33].

The significance of these results was investigated using the non-parametric Wilcoxon Rank-Sum Test, applied to HN, SD and HS seasonal values (see Table 3). The results show that there were no statistically significant differences at the confidence level of 95%.

Table 3. List of the *p-values* referring to the Wilcoxon Rank-Sum Test for the HN, SD and HS variables. In this test, the null hypothesis (H_0) is that the 2000–2009 and the 1971–2000 seasonal values belong to the same distribution, and the alternative hypothesis (H_1) is that the last decade distribution shifts to the left with respect to the 30 year reference distribution, implying a decrease in the mean value. Given that all *p-values* are greater than 0.05, the hypothesis H_0 of statistical equality among the means of two samples is accepted with a confidence level of 95%.

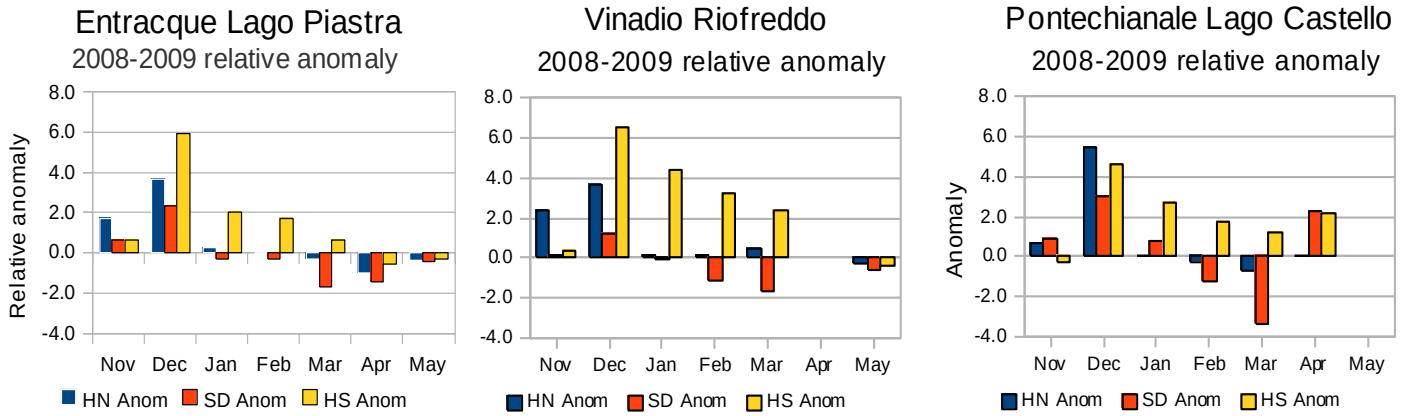
	$\mathbf{P_{HN}}$	$\mathbf{P_{SD}}$	$\mathbf{P_{HS}}$
Entracque L. Piastra	0.08	0.17	0.06
Vinadio Riofreddo	0.10	0.33	0.21
Ponte chianale L. Castello	0.17	0.12	0.55

3.3. The 2008–2009 Snow Season Case-Study

During the 2008–2009 snow season, abundant snowfalls occurred over the western Alps and over the Po Valley. An in-depth analysis on the features of this peculiar snow season was therefore carried out. The relative anomalies of the HN, SD and HS monthly values with respect to the 1971–2000 averages are reported in Figure 3. Abundant snowy precipitations (HN) occurred in

November and especially in December, producing large anomalies in HS. In particular, in December, HN exceeded the mean value by 3.7 standard deviations (σ) at the Entracque Lago Piastra and Vinadio Riofreddo stations, and by 5.5σ at the Pontechianale Lago Castello station. Also the anomaly of SD was positive at all measurement sites; in fact, the highest one exceeded the mean value by 3.0σ. The strongest anomalies were those of the snow depth (HS), whose departures from the average value in December exceeded 5.9σ at Entracque Lago Piastra, 6.5σ at Vinadio Riofreddo, and 4.6σ at Pontechianale Lago Castello.

Figure 3. The relative anomaly [adimensional] of average monthly cumulated snowfall (HN), snowy days (SD), and snow depth (HS), for the period 2008–2009, compared with the reference period 1971–2000. April and May anomalies are not available for Vinadio Riofreddo and Pontechianale Lago Castello, respectively.



In order to help the reader in classifying the 2008–2009 values in the frame of the snow climatology in that area, a comparison with the data referring to the 1971–2000 reference period was performed. The results show that the seasonal snow cumulated at each site during 2008–2009 exceeds in each observational site the corresponding 90th percentile threshold. These findings allowed the researchers to conclude that the snowfall during the 2008–2009 season was exceptional.

3.4. Further Considerations on the 2008–2009 Snow Season Using Satellite Data

In order to achieve a deeper knowledge of the snow precipitation features and of the duration of snow cover during the 2008–2009 snow season, satellite images derived from the MODerate Resolution Imaging Spectroradiometer (MODIS) were analyzed. MODIS 8-Days snow cover, which reports the maximum snow cover over eight days, was used to evaluate the extension of snow covered areas at two different times during the 2008–2009 season: (1) after heavy winter snowfalls occurred in December, and (2) at the beginning of the successive spring.

Cloud cover is more persistent in winter. In order to minimize the number of unclassified pixels in MODIS acquisitions, a monthly composite was created: It reports as snowy all the pixels classified as snow covered in at least one of the 8-day snow products used for the composition. In this way, a map of maximum snow cover for December 2008 (most specifically, the period taken into account is from 2nd December 2008 to 3rd January 2009, with a total of four 8-day composites) was created. This map

considers the heavy precipitation events that occurred on the 9th, 10th, 13th, 14th, 15th and 25th of December. Concerning the early spring, the persistence of cloud cover during the period 14–21 March 2009 was negligible, so a single 8-day snow cover product was analyzed. The snow cover products referring to these two periods were compared to the corresponding products obtained for the 2003–2004 season (Figures 4 and 5), which also proved remarkable for the heavy snowfalls by analyzing the ground stations data.

Almost all the Italian Alps were covered by snow at least once in December 2008 (Figure 4a). Snow cover was consistent also at low elevations over the Western Po Valley, Apennines and Corsica. Snow cover was more extensive than it was in December 2003 (Figure 4b), when it was continuously present only at higher elevations.

Figure 4. MODIS derived maximum snow cover extent during December 2008 (a) and December 2003 (b). Snow covered areas are colored in white, snow-free areas in green, and water surfaces in turquoise.

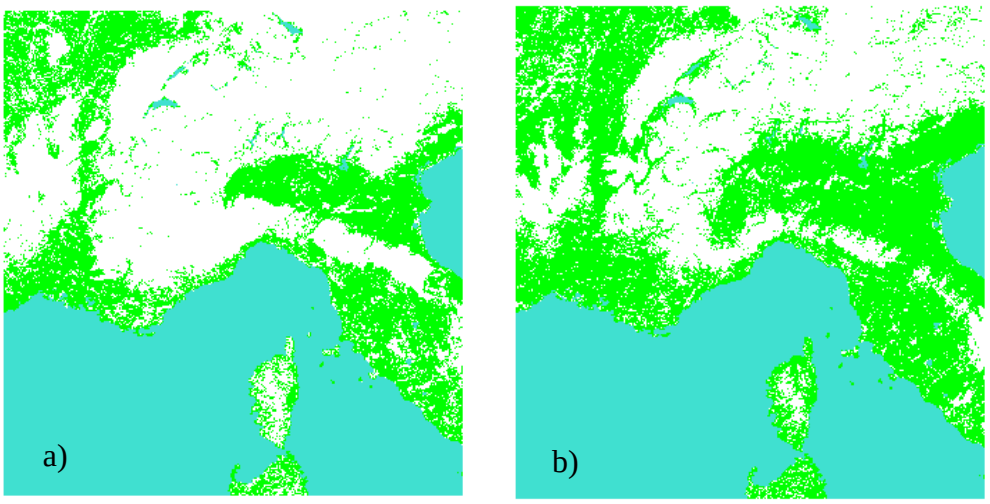
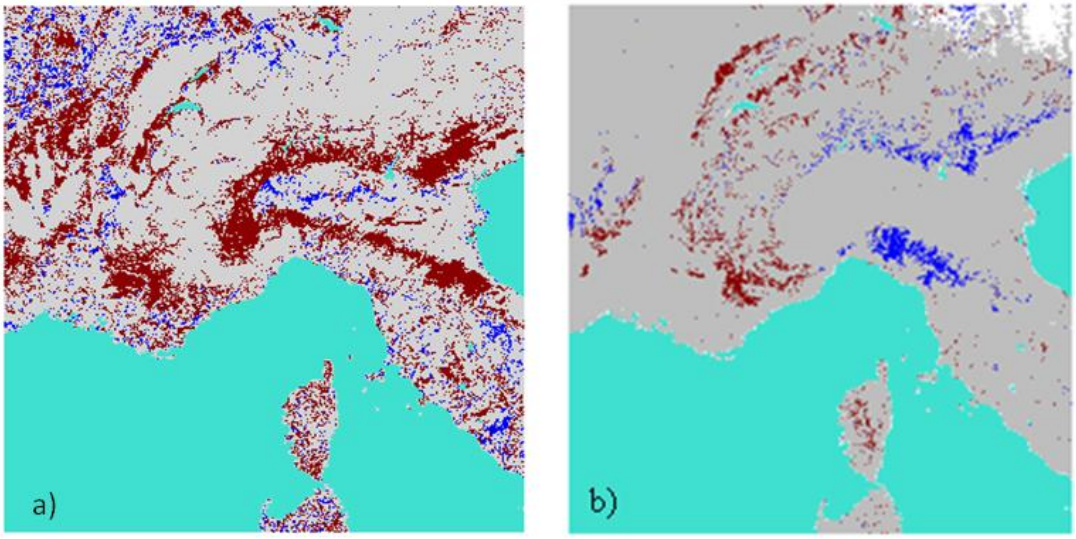


Figure 5a reports the difference between the two December snow cover maps (2008 minus 2003). Low elevation mountains (pre-Alps) on the Italian slope of the Alps, the Western Po Valley, and the northern side of the Apennines were snow covered in December 2008 but not in December 2003. On the other hand, only a few isolated areas (located in France and Switzerland, along the Po River and in central Italy) were snow free in December 2008 but snow covered in December 2003.

The comparison between early spring snow maps shows few differences in the snow cover extension in March 2009 and in March 2004 (Figure 5b) especially over the Piedmont region. In 2009, snow was slightly more abundant than in 2004 over the French and Swiss slope of the Alps, and Corsica, and slightly less abundant over the Central and Eastern Italian Alps, and Emilian Apennines. This comparison shows that the snow surplus that was found during the early part of the 2008–2009 snow season over the Alps was already almost completely melted in March.

Figure 5. Difference between the snow cover maps of December 2008 and December 2003 (a), and of March 2009 and March 2004 (b). The areas where snow cover was present in 2008–2009 but not in 2003–2004 are represented in red, and those with snow cover in 2003–2004 but not in 2008–2009 are represented in blue. Pixels representing snow covered or snow free zones in both maps are gray; pixels representing water surfaces are turquoise, and cloudy pixels in one of the two images are white.



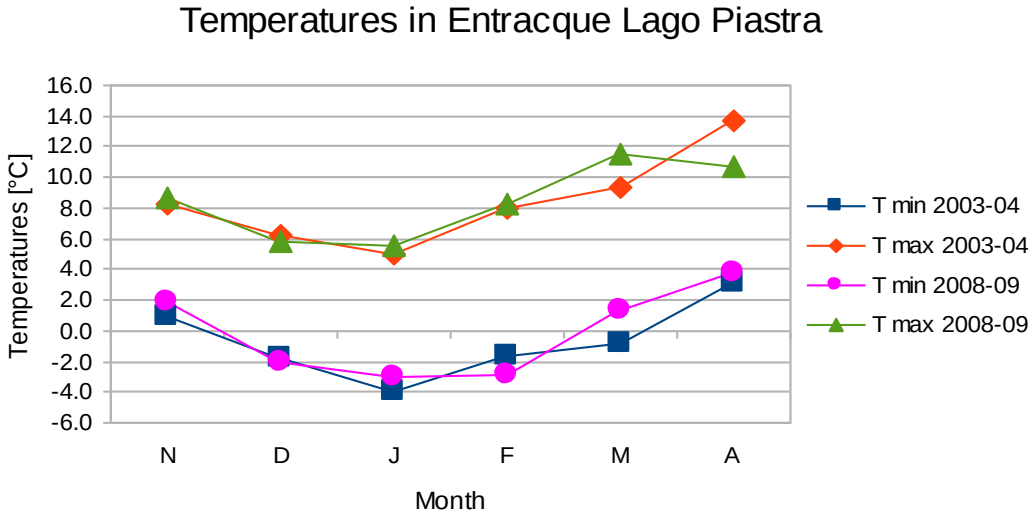
These findings suggested another investigation to determine which factor affected the rapid melting of the snow pack: the analysis of the minimum and maximum temperatures recorded during the 2008–2009 winter and spring.

The lowest elevation site, Entracque Lago Piastra, was chosen to check the daily minimum and maximum temperatures. This site possesses a complete quality controlled database of air temperatures for the period 1971–2009. The mean monthly temperatures, as well as the corresponding anomalies with respect to the 1971–2000 reference period (Figure 6a, b), were evaluated for the 2003–2004 and 2008–2009 snow seasons.

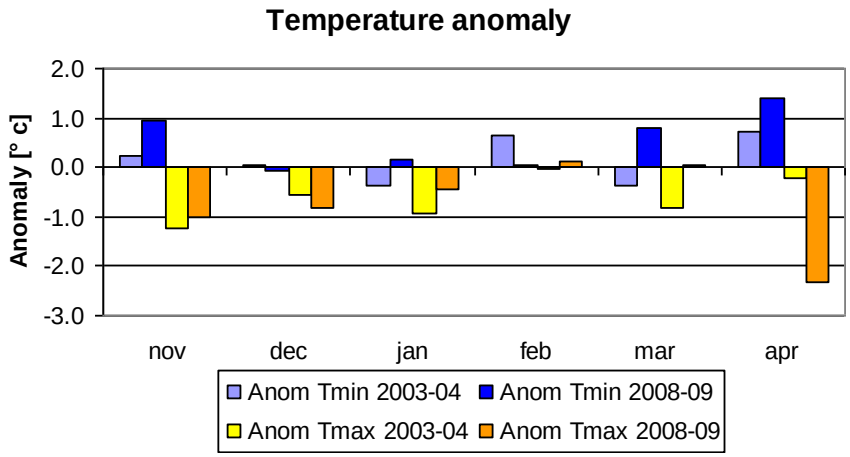
The result shows that for both the 2003–2004 and 2008–2009 seasons, the maximum monthly temperature anomalies were negative in November, December and January, and that the minimum temperatures were negative in December, January and February. These conditions allowed for the occurrence of heavy winter snowfalls. On the other hand, it is important to outline the positive anomaly in March 2009 for minimum temperatures. March 2004 was colder than the average, with a monthly mean minimum temperature below 0 ℃, and presented negative maximum and minimum temperatures anomalies, while March 2009 registered a monthly mean minimum temperatures above 0 ℃, with an anomaly of +0.8 ℃. The temperature anomalies, especially for minimum temperatures in March, can explain why the exceptional snow cover in December 2008 did not last until March 2009, when snow cover extension was comparable to that recorded during March 2004.

Figure 6. (a) Minimum and maximum temperatures recorded at Entracque Lago Piastra during the 2003–2004 and 2008–2009 snow seasons (November-April). (b) Minimum and maximum temperatures anomalies recorded at Entracque Lago Piastra during 2003–2004 and during 2008–2009 with respect to the 1971–2000 reference period.

a.



b.



4. Conclusions

Three newly digitized snow series derived by direct observations carried out in the southwestern Italian Alps (in Piedmont) during the period 1971–2009 were analyzed to determine the main snow climatic indices over the 1971–2000 reference period. These values were compared with corresponding values recorded during the decade 2000–2009. Relevant differences were found concerning the distribution and amount (the latter not statistically significant) of snowfalls in the most recent decade. The analysis of the snowfall distribution showed that, in the recent period, the maximum occurs one month earlier in the snow season, as compared with the 1971–2000 average: the peak of the cumulated snow precipitation shifts from January to December. As a general feature, positive anomalies in monthly snow precipitation, number of snowy days, and snow depth were found during November and December, while negative anomalies were found during the remaining months. Snow seasons appeared to be shorter than in the 30 year reference period, as neither snow cover nor

snow precipitation were recorded in May. These results are in agreement with the studies of Durand *et al.* [33] over French Alps. They also appear to confirm the more general trend in the extension of snow cover at large scale outlined by IPCC 2007 [34]: since the late 1970's, the snow coverage in the Northern Hemisphere has declined in spring and summer (during the months from February to August) but not substantially in winter. This has resulted in a shift in the month of maximum snow cover from February to January, in a shift toward early spring melt and in a statistically significant decline in the annual mean SCA.

This study found a considerable decrease in the seasonal cumulated snowfall and in the number of days with snow precipitation, which was associated with a decrease in the seasonal average snow depth at low elevations. Other recent studies documented these features over the Swiss and French slope of the Alps [6,7,32]. This highlights that, at lower elevation, the temperatures determine whether the precipitation falls as rain or snow and influence the snow pack behavior [7]. In the southwestern Italian Alps, the decrease is not statistically significant; this is most likely due to the high interannual variability of snow precipitation.

Focusing attention on the 2008–2009 snow season, when the Piedmont region and, generally speaking, most of the Alps were affected by heavy snowfalls, the monthly values evaluated during this period were compared to the corresponding values for the 30 year reference period (1971–2000). The results showed that, in December 2008, the cumulated snowfall exceeded the mean value by more than 3σ at all the measurements sites, and by 5.5σ at the highest one. The results also showed that the seasonal cumulated fresh snow exceeded the 90th percentile threshold at each station.

Finally, MODIS satellite data allowed for the examination of the extension of snow cover in 2008–2009 and to make a comparison with the corresponding snow cover in the 2003–2004 season, also characterized by heavy snowfalls. The comparison showed that even though the 2008–2009 snow precipitation amount was exceptional, the snow pack melted almost completely during the first three months of 2009, due to the temperatures recorded on the Piedmontese Alps, which were higher than the corresponding temperatures recorded in 2004 and with respect to the mean conditions.

In conclusion, this work aimed to give an overview of the snow precipitation and snow cover characteristics over the Western Italian Alps during the last 40 years, and in particular during the last decade, for the purpose of providing further documentation in the study of climatic change and its impact on the Alpine Region.

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