SNOW PRECIPITATION AND SNOW COVER VARIABILITY IN PIEDMONTESE ALPS IN THE PERIOD 2000-2009

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ABSTRACT
This study aims to define snow precipitation and snow cover features over Western Italian Alps during the decade 2000-2009. A new approach integrating ground meteorological stations and satellite information is used. Daily measurements performed in Piedmont by the Regional Agency for Environmental Protection (ARPA) network together with the MODerate resolution Imager Spectroradiometer (MODIS) 8-day snow cover product allow to have a general overview on both snow abundance and snow cover extension during the last decade.

1. INTRODUCTION

Snow is an essential component of Earth system physics and any changes in the amount, duration and extension of the snow pack can have environmental and economics consequences (Beniston et al., 2003). Snow cover influences the percentage of the solar radiation reflected by the Earth surface and subsequently the energy budget and the atmospheric circulation over large scale (Romanov et al. 1999). Moreover the variation in frequence and amount of snow precipitation plays a key-role in the water availability for agriculture, hydroelectric power production and human drinking water supply, so a better knowledge of the snow precipitation features over the Alps would have applications in different fields of research and positive social and economic outcomes.

Snow precipitation over Piedmont Alps is here analyzed using ground measurements provided by 10 automatic and manned stations of the Regional Agency for Environmental Protection (ARPA Piemonte) network (Figure 1).

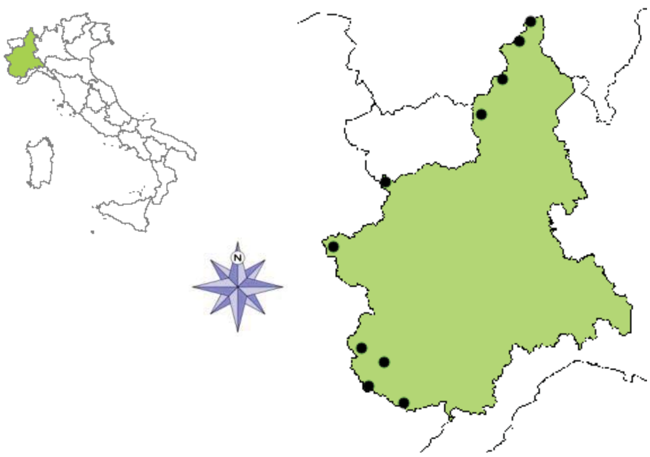


FIGURE 1. Location of the 10 snow measurement sites considered in this study.

The stations are located along the Piedmont slope of Italian Alps: their spatial distribution and elevation above sea level (Table 1) allows to have a general overview of the snow precipitation in Piedmontese mountains. The period considered in this study ranges from January 2000 and December 2009: the daily measurements recorded during the snow season November-May were used to calculate snow indexes over the decadal period.

The information given by the snow time series is integrated by the temporal variability of the snow cover extension derived by the MODerate resolution Imager Spectroradiometer flying on board Earth Observing System Terra and Aqua polar satellites.

The National Snow and Ice Data Center (NSIDC) made available MODIS Snow Cover 8-Day L3 Global 500m Grid (MOD10A2/Terra, MYD10A2/Aqua) datasets, which contain data fields for maximum snow cover extent over an eight-day compositing period. Terra dataset covers a longer period than Aqua's, as the satellite imagers became operational respectively in 2000 and 2002: in order to have a longer record MOD10A2 products are used to investigate the maximum extension of snow cover over the period 2001-2009.

TABLE 1. Stations considered in this study (M=manned station, A=automatic station) and corresponding sector in Piedmont, elevation above sea level and UTM coordinates. The background colour indicates low, middle and high elevation altitude stations.

Station (type)	Alpine sector	Elevation [m a.s.l.]	UTM x [m]	UTM y [m]
Alagna Cap. (M)	N-W	1180	417574	5078442
Vinadio Bagni (M)	S-W	1270	346152	4905614
Prerichard (A)	W	1353	320334	4994017
Alpe Cheggio (A)	N	1460	431711	5104080
Saretto Acceglio(M)	S-W	1540	335855	4927442
Chiappi-Castelmagno (M)	S-W	1630	354894	4917985
Alpe Devero (A)	N	1634	443114	5129624
Chiotas-Entracque (M)	S-W	1970	366898	4892107
Lago Agnel (A)	W	2304	354620	5036811
Formazza (A)	N	2453	450779	5142603

2. METHODOLOGY AND RESULTS

Ground snow measurements and satellite derived snow cover have been used to determinate snow climatological indexes over the last decade and to investigate the temporal evolution of the maximum amount of snow precipitation and the maximum snow cover extension over the period 2001-2009.

2.1 Analysis of ground measurements

Daily snow depth and fresh snow depth records performed in 5 manned measurements sites and 5 automatic stations in the snow season November-May were considered to calculate the monthly average cumulated snow precipitation, the monthly mean number of snowy days and the monthly average snow depth over the period 2000-2009.
Each monthly value is calculated using the corresponding daily values only if the 80% of measurements per month is available (Klein Tank et al., 2002).
In Chiappi-Castelmagno and Vinadio-Bagni manned stations the measurements are usually performed from December to April and in Alagna Cap. from November to April, so in these cases the seasonal value was calculated over a shorter period.
For each measurement site considered, the monthly mean cumulated fresh snow was determinated and reported in Table 2, together with the corresponding seasonal value, calculated as sum of the monthly values. The stations are ordered according to the increasing elevation above sea level.

Table 2. Average monthly cumulated fresh snow and seasonal values in the period 2000-2009: the "*" highlights the seasonal value calculated over a shorter period. Bold font highlights the maxima.

Station	**Monthly average cumulated snow**							
	Nov	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Seas**
Alagna Cap.	**107**	54	49	62	32	23	NA	327*
Vinadio Bagni	NA	57	**68**	61	36	31	NA	253*
Prerichard	42	**51**	43	35	27	7	0	205
Alpe Cheggio	57	**74**	47	61	51	43	4	337
Saretto Acceglio	54	**92**	67	59	44	41	0	357
Chiappi	NA	**105**	72	88	50	56	NA	371*
Alpe Devero	**105**	98	63	79	74	64	13	496
Chiotas	125	**140**	78	87	82	129	19	660
Lago Agnel	125	122	93	90	111	**136**	57	734
Formazza	**172**	102	87	106	112	117	72	768

The results shows that in 8 out of 10 sites the amount of snow precipitation is maximum at the beginning of the snow season, in November or December, in particular the stations located in N and N-W Piedmont have a maximum in November and those located in W and S-W Piedmont in December. The exception is Alpe Cheggio station which is in the Northern sector and presents a maximum in December.
This behaviour may be due to the orientation of the valley, which is mainly in N-S direction in Northern Piedmont and in E-W direction in the South. Alpe Cheggio station is in the Northern sector at the end of a valley with E-W orientation and presents a maximum in December.
Vinadio-Bagni, which is located below 1300 m a.s.l., presents the snow precipitation maximum in January as the stations situated in the plain such as Torino (Biancotti et al., 1998) and the monthly values are similar to those calculated over the period 1981-2004 by Fazzini (2009). Lago Agnel, located above 2000 m a.s.l., presents similar amount of snow precipitation in November, December and April.

The seasonal distribution of the mean monthly cumulated snow precipitation, or snow rate, can be considered unimodal below 1600 m, while at higher elevation there is the transition to a bimodal snow rate, with comparable amount of snow precipitation in November, December and April and a minimum in January. In the highest site the snow rate presents an absolute maximum in December and approximative the same amount in February, March and April.
The number of snowy days (Table 3) reaches the maximum in the first months of the snow season, in most of cases in December, and afterwards it decreases. Around 2000 m a.s.l. the absolute maximum is earlier, in November, and a secondary maximum in March/April arises. As a general feature both seasonal cumulated fresh snow and seasonal number of snowy days increases with the increasing of elevation above sea level.

Table 3. Monthly average number of snowy days in the period 2000-2009: the "*" highlights the seasonal value calculated over a shorter period. Bold font highlights the maxima.

Station	**Monthly average number of snowy days**							
	Nov	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Seas**
Alagna Cap.	**5**	4	4	3	3	2	NA	21*
Vinadio Bagni	NA	4	**5**	3	3	3	NA	18*
Prerichard	**5**	**5**	**5**	4	3	2	0	24
Alpe Cheggio	5	**6**	5	4	5	4	0	29
Saretto Acceglio	4	**8**	5	4	5	4	0	30
Chiappi	NA	**7**	5	4	4	3	NA	23*
Alpe Devero	7	**8**	7	6	6	6	1	41
Chiotas	8	**9**	6	5	7	8	3	46
Lago Agnel	**10**	9	7	6	9	8	5	54
Formazza	**11**	9	8	9	10	10	6	63

Snow depth daily measurements were used to calculate the monthly average snow depth and its standard deviation. In each site snow depth has a strong variability respect to the mean value, as results by the high standard deviation. In February snow depth is maximum in most of the stations: those above 2000 m a.s.l. register a maximum in April, Chiappi (1630 m a.s.l.) in January. The curve of the snow depth is always unimodal.
The mean values on Prerichard can be compared to the ones referred to the decade 1990-1999 (Fratianni et al., 2002): in the last decade monthly snow depth is slightly higher than in the previous one at the beginning of the snow season (November and December), but in January and February a decreasing in mean snow depth occurred.

Table 4. Monthly average snow depth in the period 2000-2009. Bold font highlights the maxima.

Station	**Monthly average snow depth and standard deviation**

	Nov	Dec	Jan	Feb	Mar	Apr	May
Formazza	68±65	114±84	146±78	177±84	202±75	**222±74**	195±79
Alpe Devero	26±25	70±39	82±44	**98±49**	87±51	48±46	14±23
Alpe Cheggio	8±12	36±26	44±31	**53±41**	38±41	9±15	0±0
Alagna Cap.	17±NA	23±24	35±30	**41±31**	26±30	4±5	NA
Lago Agnel	44±39	81±70	84±78	86±78	99±71	**125±86**	89±93
Prerichard	8±10	19±14	**24±25**	**24±30**	8±10	0±1	0±0
Saretto Acceglio	9±11	31±21	45±37	**46±41**	26±21	7±14	0±0
Chiappi	NA	42±25	**58±68**	52±61	30±35	11±22	NA
Vinadio Bagni	NA	42±21	61±48	**81±60**	58±49	12±24	NA
Chiotas	34±29	97±59	108±75	**115±73**	111±66	91±79	20±33

2.2 Analysis of MODIS snow cover

MODIS Terra scans the Alps twice a day, once during the daylight: this acquisition provides measurements used by a snow mapping algorithm that employs a Normalized Difference Snow Index (NDSI) and other criteria tests (Hall et al., 1995). In order to minimize cloud obscuration problems and subsequently the number of unclassified pixels, the 8-day composite snow cover MOD10A2 (Hall et al., 2006) is used: it classifies as snowy all the pixel that have been snow covered at least once in the 8-day period. Starting from the first day of the year, groups of eight consecutive daily snow cover products are aggregated. MOD10A2 consists of 1,200 km by 1,200 km tiles of 500 m resolution data gridded in a sinusoidal map projection.

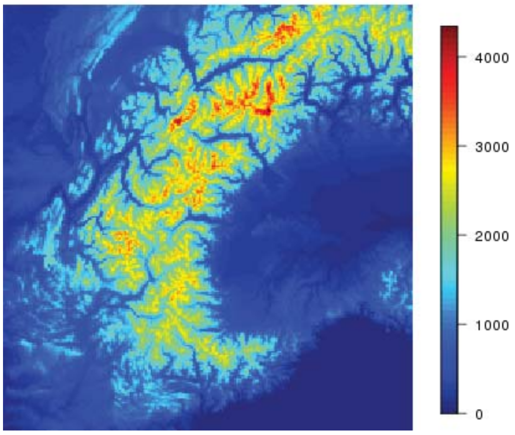
These data allow the analysis of the temporal evolution of the extension of snow covered area over large scale: for our purpose an area of about 123,000 km^2 centred on the Western Alps was selected (Figure 2).

As the 8-day snow cover may contain unclassified pixel due to cloud obscuration, four consecutive 8-day products were aggregated to create a maximum monthly product, where a pixel is classified as snowy if snow cover is detected at least in one of the weekly product.

As we found for most of the sites whose records have been considered, in February the monthly average snow depth is maximum: MODIS products are used to investigate the variability of the extension of snow cover over the period 2001-2009 in the month of its maximum extension (February).

The aggregation to create February snow cover is done using four 8-days products beginning on the 33rd, 41th, 49th, 57th day of the year.

The results are reported in Figure 3.



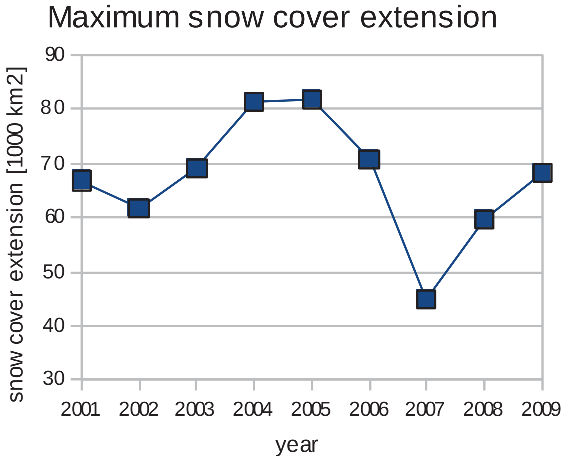


FIGURE 2. Digital elevation model of the area considered for snow cover extension analysis.
FIGURE 3. Maximum snow cover extension during the period 02 February-05 March (02 February-04 March in leap years) over the area of study in the period 2001-2009.

The maximum extension of snow cover over Western Alps during the period 2001-2009 is reached in 2005 (Figure 4), followed by 2004, with snow covered area more than 80,000 km^2 wide in both cases: snow precipitation at low elevation occurred, both over Italian and French side, in particular over the Padan Plain.
The minimum snow cover extension were registered in 2007 when snow covered area were around 44,000 km^2 wide (Figure 5) and snow was present only at middle-high elevation.
The average snow cover extension is about 67,000 km^2.

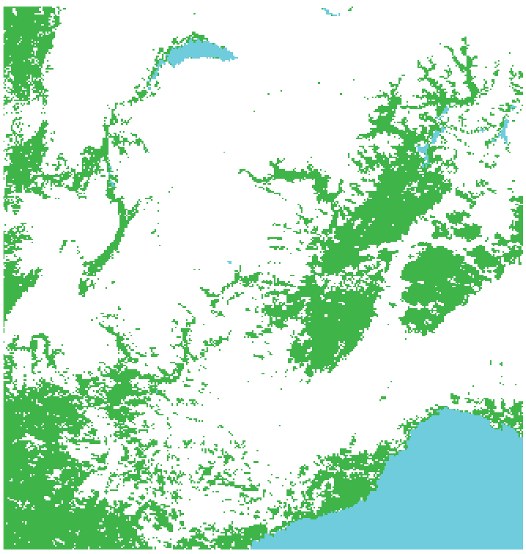


Figure 4. Maximum snow cover in the period 02 February-05 March 2005: snow is represented in white.

Figure 5. Maximum snow cover in the period 02 February-05 March 2007: snow is represented in white.

For each snow season in the period 2000-2009 it was considered the maximum snow cover extension in February and the corresponding total snow precipitation occurred during December-January-February registered by the ground measurement sites: it was investigated the features of each snow season both in terms of amount of snow precipitation and extension of snow covered area.
The results for three measurements sites representative of low, middle and high elevation are reported in Figure 6.

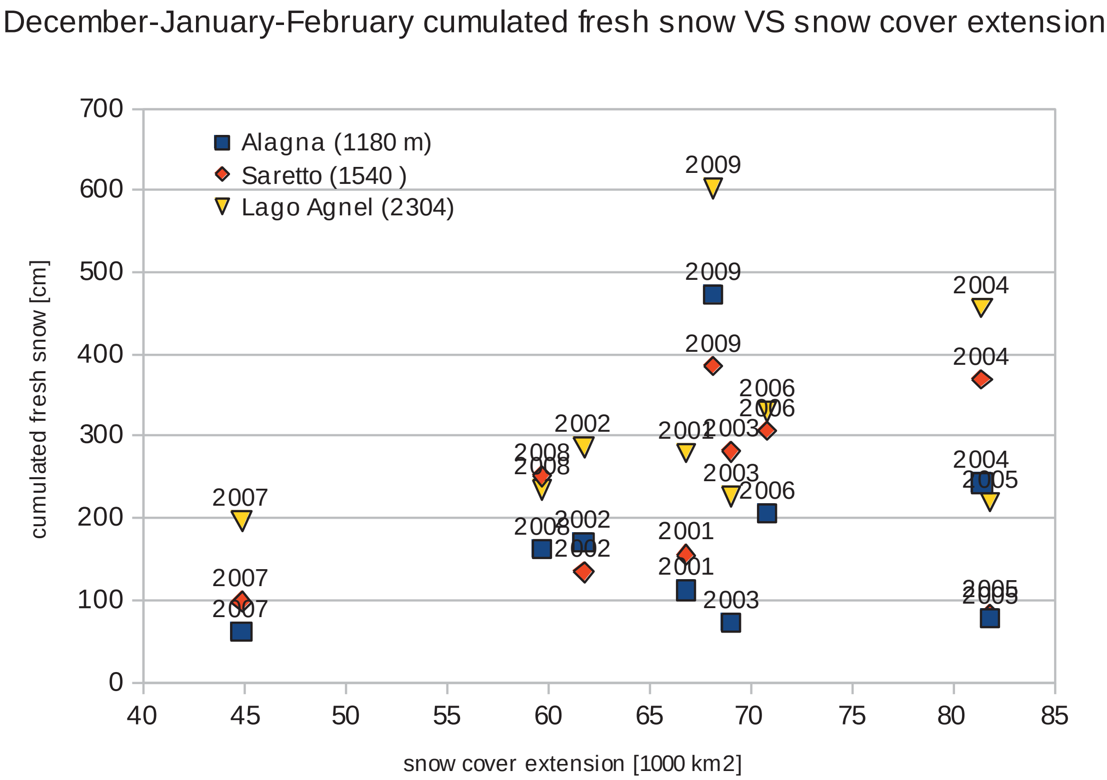


FIGURE 6. Cumulated snow precipitation in December January and February in 3 stations (low, middle and high elevation) and corresponding maximum snow cover extension over Western Alps for each snow season in the period 2000-2009.

It was found that the large snow cover extension registered in February 2005 was not associated to abundant snow precipitation in the previous months and that the total snow amount occurred in 2005 is comparable to the one registered in 2007, the year of the minimum in snow cover extension. The scarce snow cover extension in February 2007 was effectively due to the scarce snow precipitation occurred during the all period December 2006-February 2007.
The winter 2003-2004 was characterized by an extended snow cover and a considerable amount of snow precipitation especially at middle and high elevation.
The snow season 2008-2009 was exceptional for the total amount of snow precipitation occurred in December-January-February: in all the measurement sites it was registered the maximum cumulated snow precipitation over the period 2000-2009 and the snow abundance corresponded to a snow cover extension exceeding the mean value.

3. CONCLUSIONS

The analysis of ground snow measurements performed throughout Piedmont during the period 2000-2009 allowed to have a general overview on the average amount and frequence of snow precipitation along the Italian slope of Western Alps in the last decade. Moreover the temporal variability of snow cover extension over Western Alps was investigated using MODIS Terra snow cover product. The analysis of February maximum snow cover was put in relation to the total amount of corresponding winter snow precipitation (December-January-February) registered in the ground based measurements sites. This approach allowed to integrate the local information on snow depth and the large scale information on the snow cover extension in order to have a global view on the features of the last decade snow seasons.

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