SNOW COVER AND CLIMATE CHANGES IN THE ITALIAN ALPS (1930-2018)

Valt Mauro[1,2]*, Cianfarra Paola[3]

[1] *AINEVA, Trento Italy*
[2] *ARPAV -Avalanche Centre Arabba, Italy*
[3] *Università degli Studi Roma Tre, Dipartimento di Scienze Roma, Italy*

ABSTRACT: The Fifth AR5 report of the working group of the Stockholm IPCC panel confirmed that the snow cover extent in the Northern Hemisphere has been gradually decreasing, and that in March and April high correlation exists between such decrease and anomalous temperature values.
Recent works have already proved that also in the Italian Alps (6.6-13.7 E and 47.1-44.1 N) the snow cover extent and the amount of fresh snow have been gradually reducing, especially in March and April, at altituders ranging between 800 and 1,500 m.
The present work analyses temperature data, snowfalls and snow cover duration with more than 30 cm thickness (skiable snow) in the 1930-2017 period.
The explored 1987-1988 period highlighted a variation of regime for all the three parameters analysed. Furthermore, in the 1991-2000 period, the largest deficit was observed in the last 10 years. In the 2004-2013 period a lower temperature rise was observed in December-February compared with the 1961-1990 average, and almost standard snowfalls.
Temperature ranges in March-April have been instead steadily increasing, with a major snow deficit (approximately -30%) especially at low altitudes, and resulting lower snow cover duration.
As for the snow reliability line (LAN), altitude rose by over 300 m following a seasonal temperature rise of +0.7 ℃, amounting to a much higher value than that recorded in other studies, i.e. 150 m for +1.0 ℃.

KEYWORDS: Snow cover, Snow reliability, Alps, Climate

1. INTRODUCTION

Snow cover extent reduction in the Northern Hemisphere (NH) has been proved by several works, being also confirmed by the fifth AR5 WGI I report of the IPCC approved in Stockholm on 28 September 2013 (http://www.ipcc.ch/).
In fact, satellite data show, for the 1967-2012 period, a reduction of annual snow cover extent, especially in March – April (MA) (IPCC-WGI 4.52, 2013). In March and April, the average decennial reduction in the 1922-2012 period amounted to 0.82%, to 1.59% in the 1967-2012 period and even higher, to 2.24% in the most recent period, 1979-2012, (IPCC-WGI 4.52, 2013).
Moreover, always in MA months, in the areas between 40°N-60°N of the NH, a high linear correlation was demonstrated (R=0.76) (Brow and Robinson, 2011) between anomalous surface temperatures of the NH (Jones et al., 2012) and snowfalls (Snow Covered Areas).
This snow cover extent reduction was also demonstrated for alpine regions (Micu 2009; 2009; Morin et al., 2008; Xu et al., 2008), and particularly in European Alps (Wielke et al., 2004; Hantel and Hirtl-Wielke, 2007; Schoner et al,. 2009; Valt and Cianfarra, 2010). A reduction of maximum snow cover height values was shown for both the northern (Marty and Blanchet 2012) and the southern side (Valt et al., 2010) of the Alps.
Several studies have shown that the average snow cover thickness and number of days of snow have been decreasing in the Alps in the last 20 years (Marty, 2008; Durand et al., 2009; Valt and Cianfarra, 2010), mainly at altitudes lower than 1500 m (Laternser and Schneebeli, 2003; Scherrer et al., 2004).
The average earth surface temperature rose by about +0.89 ℃ in the 1901-2012 period, and by about +0.72 ℃ in the 1951-2012 period. In any case, and particularly for the Alps, the high interannual variability of precipitation and the NAO impact gave rise to some difficulties in quantifying the impact of temperature increase on snow cover (Serguet et al., 2011; Scherrer and Appenzeller, 2006; Scherrer et al., 2004; Marty, 2008; Schoner et al., 2009; Morin et al., 2008; Durand et al., 2009).
Variations of snow cover duration, including its annual variations, have a major impact on alpine regions, not only from a hydrological, geological and glaciological viewpoint, but also from a social-economic point of view for winter tourism.
It has been estimated that a rise of +1 ℃ of average air temperature results in a rise of 150 m of the LAN limit, with direct consequences on winter tourism (Haubner-Köll, 2002).

* *Corresponding author address:*
Valt Mauro,
Via Pradat-Arabba, 5
32020 Livinallongo del Col di Lana (BL)-Italy.
email: mauro.valt@arpa.veneto.it

The present work illustrates the preliminary studies on the recent variations of air temperature in the Italian Alps in the period between December and April (DJFMA), variations of snowfalls and snow cover, and variations of snow reliability line.

2. DATA AND METHOD

Average monthly temperature values, monthly accumulation data and average snow cover thickness data were used in the present work.
Observation and measurement stations were chosen based on the availability of historic time series already homogenized or published areal and altimetric geographical distribution and length of historic series.
Air temperature values are taken from 12 stations located between 254 m and 2200 m altitude, in the southern side of the Alps and operated by different agencies. Online datasets from Provincia Autonoma di Trento, Provincia Autonoma di Bolzano, Società Meteorologica Italiana, Meteosuisse, Arpa Veneto, Arpa Piemonte, Progetto Histalp, Progetto RiskAlp, and Osservatorio di Oropa were consulted, along with the Hydrological Annals published by the Ministry of Public Works and several publications (Mercalli et al., 2003, 2006; Tarolli et al., 2007; Bellin and Zardi, 2004; Barbi et al., 2013; Faletto et al., 2013). Average monthly air temperature data were also used, such as aggregation of minimum and maximum temperatures (WMO n. 100, Cap. 5.2.4.1.1.).
Temperature values of the Northern Hemisphere are taken from website http://www.cru.uea.ac.uk/cru/data/temperature/ (Climatic Research Unit, University of East Anglia).
The average monthly value was also used for these studies.
Analyses of monthly fresh snow accumulations (calculated as the sum of daily values measured at 8 am) were carried out using 18 snow measurement stations, located between
750 m and 2529 m altitude. Monthly fresh snow accumulation was used in calculations.
The study of average snow cover thickness was carried out considering the number of days in which snow cover height was higher than a preset value. This pre-set thickness value is chosen based on the kind of activities carried out on snow at different heights, for example 5 cm for a snowman, 30 cm for Nordic skiing or 50 cm for snowboarding (Marty, 2008). The limit thickness of 30 cm is used to determine skiable conditions for a certain geographic area as a function of the number of days in which snow thickness exceeds the limit of 30 cm in the December – April period. This limit is called “Snow Reliability Line (LAN)” (OECD, 2007).

For the present study the above-said limit thickness of 30 cm was used. On this basis the minimum altitude was calculated for duration of snow cover exceeding 30 cm thickness for at least 100 days in a winter season (Laterser e Schneebeli, 2003; Uhlmann et al., 2008). The stations used were 22, located between 750 m and 2529 m of altitude.
All data on snow was taken from databases of regional and provincial monitoring networks of AINEVA Avalanche Services and from the Hydrological Annals published by the Ministry of Public Works (Ministry of Public Works, 1927-1996). Data collected from dam sites operated by different hydroelectric companies in the alpine range was also used. Specifically for the Canavese area, data was supplied by the online monthly resolution databank of Società Meteorologica Italiana, with financial support of Fondazione Vodafone Italia.
In all the series analysed, the missing data, never exceeding 10% of the whole historic time series, were reorganized as specified in Cap.5.2.7.3.2 of WMO.100, using near homogenized historical series with linear correlation coefficient R higher than 0.7 as a benchmark (Auer, 1992).
Having sufficiently long series of snow data for almost all the stations considered, elaborations were carried out based on the thirty-year 1961-1990 period taken into account as a reference, as indicated by WMO (WMO, Climate Normals, CLINO, technical note 847, 1998).
In all the diagrams and tables of the present work the reference year is the hydrological year (for example year 2018 starts on 1 October 2017 and ends on 30 September 2018).
The analysis of data trends was carried out using different statistical methods such as simple linear regression, mobile average and regime shift analysis with the library Strucchange (Bai e Perron, 2003) within software R (Zeileis et al., 2003), which enables finding a point of discontinuity (regime shift) of two contiguous climatic phases (Chiaudani et al., 2008; Marty and Blanchet, 2012).

3. RESULTS

3.1 Air temperature

It is widely proved that air temperature in the NH is steadily increasing (IPPC 2007, 2013).
Some recent works have also quantified temperature variations in the Alps. For Switzerland, Marty and Meister (2012) indicate an annual temperature rise of +0.8 ℃ for the last 30 years at six significant stations at high altitude, a lower value compared with medium-low altitude stations: +1.2/+1.4 ℃.

In Austria, in the Carinthia region, from 1900 to 2008, a temperature rise of 1.5-1.7 ℃ was observed (Stockinger, 2010).
Cacciamani et al. (2003) have determined a rise of +1.1 ℃ /+0.9 ℃ for the Italian Alps for the DJF period and 0.8-1.0 ℃ for the MAM period (March-April-May).
Compared with the average of the 1961-1990 period, air temperature deviation DJFMA shows a positive trend with a linear correlation coefficient R= 0.90 with NH temperature (Fig. 1).

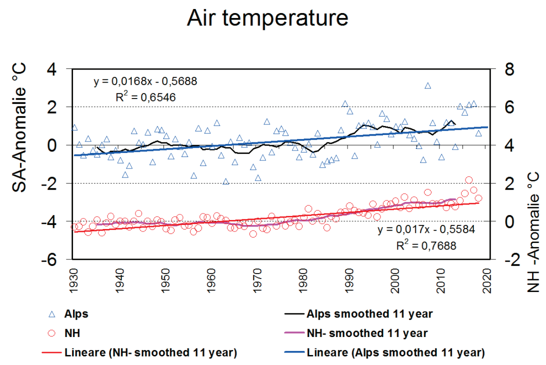

Fig. 1. Air temperature. Trend North Emisfere and Italian Alps.

The preliminary results of the average air temperature trend, for the southern side of the Alps, show a temperature rise of 1.0 ℃ (DJFMA) in the last 30 years (1989-2018).
The most likely year of climate discontinuity found in the 11-year mobile average of the historic series is 1987 (Fig. 2). At a synoptic level such discontinuity coincides with the sharp shift of phase of Atlantic circulation as shown by the NAO index (Werner et al. 2000).

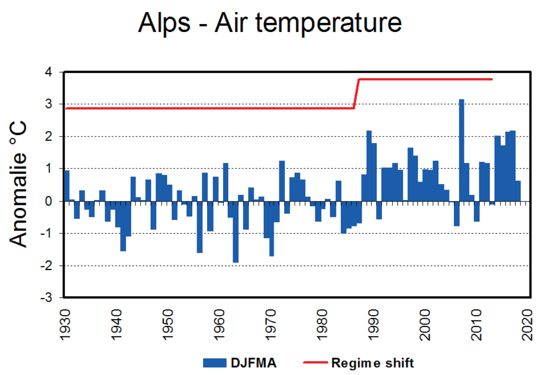

Fig.2 Italian Alps: Air temperature. Difference from the average 1961-90.

From 1987 onward, average temperature values have been always exceeding the 1961-1990 reference value, save in winter seasons of 1991, 2005, 2006, 2010 and 2013.
However, in the last 10 years (2009-2018) 3 relatively colder winter seasons were observed, and also 4 winter seasons were characterized by "very mild" temperatures, with values exceeding 0.90 percent (2014=+2.0 ℃, 2016=+2.1℃ e 2018= 2.2 ℃).
The 1991-2000 and 2001-2010 decades, DJFMA, show nearly a tenth of degree of difference from each other (+0.82 ℃ /+0.62 ℃) (Tab. I).

	DJFMA	DJF	MA
1961-1990	**+/-°C**	**+/-°C**	**+/-°C**
1991-2010	0,72	0,62	0,95
1991-2000	0,82	0,82	0,91
2001-2010	0,62	0,43	0,98
2009-2018	0,96	0,69	1,45

Tab. I. Italian Alps: Temperature trend. Difference between the average 1961-1990.

Temperatures of DJF 2001-2010 show a lower positive deviation (+0.43 ℃) compared with the DJF 1991-2000 period (+0.82 ℃), whereas the MA 2001-2010 period shows a higher positive deviation (+0.98 ℃) compared with the previous ten-year period (+0.84 ℃).
Moreover, the 2009-2018 periods still shows a milder in DJF (+0.69 ℃) and in MA (+1.45 ℃).

3.2 Fresh snow seasonal accumulation

On the southern side of the Alps, in the 1990-2009 period, seasonal fresh snow accumulation (DJFMA) decreased, especially between 800 and 1500 m of altitude (Valt e Cianfarra, 2010). Snow cover duration also decreased, mainly in the MA period (Valt and Cianfarra, 2010), as it happens in the NH (Dye, 2002).
For 18 Italian stations, the standardized anomaly index (SAI index) was calculated (Giuffrida and Conte, 1989) compared with the 1961-90 average of snowfalls and the point of regime shift (Bai and Perron, 2003). The 1987 year was found to be the most likely discontinuity year of climate (Fig. 3).

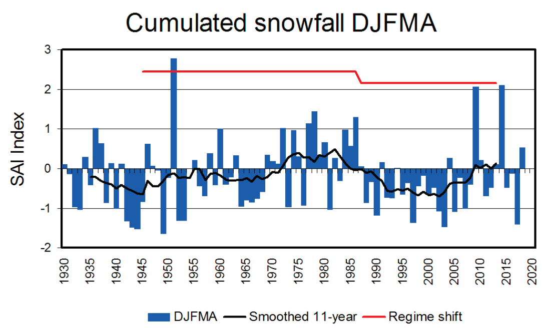

Fig.3 Italian Alps: Cumulated snowfall. SAI Index. Anomalie. Difference from the average 1961-90.

However, from 1987 onward and then up to 2008, the index moving average has always been negative.
The quantitative variation in cm of seasonal fresh snow accumulation was calculated for the

altimetric ranges between 800 - 1500 m and between 1500 – 2500 m.
The average precipitation values for the different DJFMA periods are shown in Tab. II.

(cm)	DJFMA	DJF	MA
1961-1990	**306**	**407**	**218**
1991-2010	-44	-46	-44
1991-2000	-54	-54	-54
2001-2010	-34	-37	-35
2009-2018	-3	10	-25

Tab.II. Difference of fresh snow (cm) compared to the average 1961-1990.

3.3 Snow cover thickness, snow reliability line

Laternser and Schneebeli (2003) determine snow reliability line (LAN) at 1300 m of height for Switzerland. This altitude limit is referred to an altitude where there are at least 100 days with 30 cm snow cover thickness in the DJFMA period. This limit is not fixed but changes with time and geographically depending on climatic zones. For example Wielke et al. (2004), compared snow cover duration values between Austria and Switzerland and calculated an altitude of 1,050 m for eastern Austria. This difference is due to a transition between the Atlantic maritime climate of western Switzerland and the continental climate of eastern Austria. In addition to a west-east variation of the snow reliability line, Marty (2008) also showed a variation between the northern and southern sides of Swiss Alps. Referring to a minimum snow height of 50 cm, he found a 20% decrease of days on the southern side, as opposed to the north side of the Alps. This indicates that the snow reliability line in the southern side of the Alps, affected by the Mediterranean climate, is higher compared with the north side of the Alps.
For the Italian Alps, OECD (2007) determines the LAN at 1,500 m of height, like Canton Ticino in the Swiss Alps.
Fhoen (1990) and Haeberli and Beniston (1998) also estimated a variation of 150 m of height for every 1°K of warming in the Alps.
The present study considered the daily snow height values taken from 22 stations of southern Alps located between 850 and 2600 m.
For these stations, the number of days with snow cover thickness exceeding 30 cm was calculated and days were analysed in groups according to months DJFMA (Fig. 4), DJF and MA and according to two altitude interval, 800-1500 m and 1500 - 2500 m.
For each group, a deviation from the 1961-90 average was calculated for the two subsequent decades and the recent 2009-2018 period, respectively. The moving average and its trend line, which decreased for both altitude ranges, were also calculated.

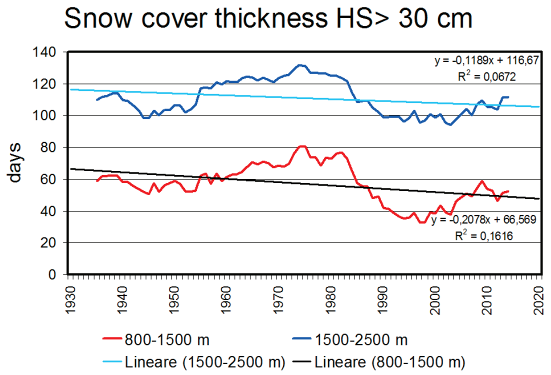

Fig. 4. Duration of snow cover for decades and altitude.

Tab. III shows the average snow cover duration values by altitude range for the 1961-90, 1991-2000, 1991-2001, 2001-2010 and 2009-2018 periods, respectively.

DJFMA	800-1500 m		1500-2500 m	
1961-1990	**61**	**+/- day**	**123**	**+/- day**
1991-2010	42	-19	107	-16
1991-2000	36	-25	105	-18
2001-2010	49	-13	109	-14
2009-2018	48	-13	114	-9

Tab.III. Duration of snow cover for decades (December to April-DJFMA) (HS> 30 cm). Difference from the average value 1961-90.

Values calculated in DJFMA underline a lack of snow in the 1991-2000 period, which was characterized by relatively lower snowfalls, and an increase in snowfalls in the subsequent 2001-2010 decade. The recent 2009-2018 period shows a steady snowfall increase, though still being lower than the 1961-90 average.
In Tab. IV and V the situation for DJF e MA.

DJF	800-1500		1500-2500	
1961-1990	**40**	**+/- day**	**72**	**+/- day**
1991-2010	31	-8	66	-6
1991-2000	28	-12	65	-7
2001-2010	35	-5	67	-5
2009-2013	33	-7	69	-3

Tab. IV. Duration of snow cover for decades (DJF) (HS> 30 cm). Difference from the average value 1961-90.

MA	800-1500		1500-2500	
1961-1990	**22**	**+/- day**	**51**	**+/- day**
1991-2010	11	-11	41	-10
1991-2000	8	-14	40	-11
2001-2010	14	-8	42	-9
2009-2018	15	-7	45	-6

Tab. V. Duration of snow cover for decades (MA) (HS> 30 cm). Difference from the average value 1961-90.

For the MA period, Tab. V, only a few variations are observed at a higher altitude, where the deficit is almost stationary and larger than the DJF period.
According to thiese data, the Snow Reliabiliy Line (LAN) for the southern side of the Alps was recomputed (Fig. 5, Tab VI)

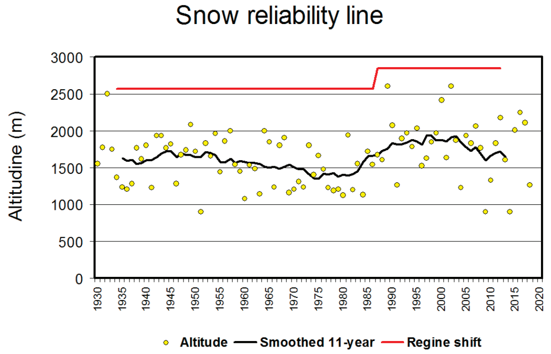

Fig. 5. Italian Alps. Snow Reliability Line (LAN).

1961-1990	1534	+/- altitude
1991-2010	1774	240
1991-2000	1834	300
2001-2010	1714	180
2009-2018	1637	103

Tab.VI. Snow Reliability Line trend (m a.s.l.).

In the period 1991-2010, the LAN increased by 240 m (Tab. IV) and the air temperature was 0.72 ℃ (Tab. I).

In the last 10 years (2008-2018), the temperature has been higher (0.96 ℃) and there were relatively more snowfalls (Tab. II). In this way the LAN rised only 103 m compared to the average 1961-1990.

4. CONCLUSION

The present work analysed temperature data, snowfall and snowpack life with a thickness of more than 30 cm in a series of stations located to the southern side of the Italian Alps.
The conducted analyses showed a change in the regime of the three parameters considered for the period 1987-1988 and a greater deficit in the period 1991-2000 as compared with the subsequent periods.

The air temperature shows a 0.96 °C increase compared to the reference period 1961-1990, in the period December-April (2009-2018). The increase is most important in MA (March-April) with 1.45 °C in the last 10 years.
In the period 2009-2018 it snowed more than average in the months of DJF but much less in MA.
The duration of the snowpack with thicknesses greater than 30 cm is 8-13 days less than the reference period.
The LAN is increasing in altitude reaching over 1800 m in the period 1991-2000.
Over the past 10 years, the altitude of the snow reliability line (LAN), has increased over 103 m with a seasonal temperature increase of 0.9 °C.

The present study thus confirm that results from the analysis of the snowpack onthe Italian Alps are in line with the findings of other authors that studied the Swiss and Austrian Alps.

5. ACKNOWLEDGMENTS

The present work has been realized thanks to the collaboration of the avalanche offices related to the AINEVA (Snow and Avalanche Interregional Association) which have made the data available. (www.aineva.it, www.meteotrentino.it)

6. REFERENCES

ARPA Piemonte, 2007. Il Piemonte nel cambiamento climatico. Osservazioni passate, impatti presenti e strategie future. ARPA Piemonte - Torino, p. 14.

Auer, I., R., Bohm, L., Buffoni, M., Maugeri, T., Nanni, and W. Schoner, 2001: Regional Temperature variability in the European Alps: 1760-1998 from homogenized instrumental time series. Theor. App. Climatol., 21, 1779-1801.

Barbi, A., A., Cagnati, G., Cola, G., Checchetto, A., Chiaudani, A., Crepaz, I., Delillo, L., Mariani, G., Marigo, P., Meneghin, S., Parsi, F., Rechi, B., Renon, B., and T. Robert-Luciani, 2013: Atlante climatico del Veneto. Precipitazioni – Basi informative per l'analisi delle correlazioni tra cambiamenti climatici e dinamiche forestali nel Veneto. Regione del Veneto, Mestre, pp. 296.

Bai, J., and Perron, 1998: Estimating and testing linear models with multiple structural changes. Econometrica 66, 47–78.

Bellin, A. and D., Zardi, 2004: Analisi climatologica di serie storiche delle precipitazioni e temperature in Trentino. Quaderni di idronomia montana n. 23. Provincia Autonoma di Trento. Trento, pp. 256.

Brown, R. D., and D.A., Robinson, 2011: Northern Hemisphere spring snow cover variability and change over 1922– 2010 including an assessment of uncertainty. The Cryosphere, 5, 219-229 258. doi:10.1007/s00704-009-0105-

Cacciamani, C., M., Lavezzi, A., Selvini, R., Tomozeiu, and A., Zuccherelli, A., 2001: Evidenza di cambiamenti climatici sul Nord Italia. Parte 1: Analisi delle temperature e delle precipitazioni, Quaderno Tecnico ARPA SMR 04/2001, pp. 43.

Chiaudani, A., 2008: Due metodi di analisi di discontinuità a confronto: Piecewise e Strucchange in funzione agroclimatica. Atti del Convegno nazionale AIAM, "Innovazione agrometeorologica per i servizi e per la ricerca". San Michele All'Adige, 10-12 giugno 2008 in Rivista Italiana di Agrometeorologia, anno 13, 1, pp. 88-90.

Di Napoli, G., and L., Mercalli, 2008: Il Clima di Torino. Società Meteorologica Italiana e Società Meteorologia Subalpina. Torino. p. 992.

Di Piazza, A., and E., Eccel, 2012: Analisi di serie giornaliere di temperatura e precipitazione in trentino nel periodo 1958-2010. Provincia Autonoma di Trento e Fondazione Edmunf Munch. Trento, pp. 88.

……

(Please ask the author)