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Analysis of Snow Cover Changes using MODIS and Google Earth Engine. A Tool for Measuring Climatic Change Effects on Snow in Italian Western Alps in the period 2000 - 2023

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Abstract. Climate change (CC) is significantly impacting the snow cover of the European Alps, compromising winter tourism, hydrological cycles and water stock for agricultural and civil supply. This study investigates Snow Cover Changes (SCC) in the Western Italian Alps (Piemonte and Valle d'Aosta regions) from 2000 to 2023, using MODIS satellite data. In particular, MOD10A1 images were processed in Google Earth Engine to derive daily snow cover, integral snow cover area (iSCA), snow persistence (SP), and mean daily snowed area (MDSA). Ground data from 7 snowmeter stations were used to validate the satellite-derived SP. The analysis of SCC was performed by quantifying long-term trends of MDSA at-the-pixel-level. The normalized trend (*nT*) index represents the percentage change rate in snow-covered area per mean snow event, since 2000. It was mapped showing different spatial patterns of SCC in the study area. Results reveal an altitudinal gradient in *nT*, with the higher snow cover reduction occurring in lowland and within main valley areas, reaching -5% below 1000m a.s.l. and -1.8% between 1000-1500 m a.s.l. These findings highlight the vulnerability of snow resources due to CC, impacting water availability, winter sports, and regional economies. This study can support adaptation strategies and sustainable resource management in the Western Alps by mapping critical areas where CC effects on snow must be mitigated.

1 Introduction

Snow plays a crucial role both in environmental and economic sectors of the Alpine region, such as in the areas of Piemonte and Valle d'Aosta Regions. It has implications either in the economy, as a defining feature of the winter landscape, attracting tourists and sports people or for the hydrological cycle (Steiger et al., 2019; Sturm et al., 2017). Snow provides abundant quantities of water stocked during the winter and slowly released in spring and summer, creating an important supply for the Alpine valleys and communities. In the last few years, Climate Change (CC) is reshaping this dynamic: due to the rising

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

temperatures, snowfalls are reducing in lowlands and middle mountains, altering melt patterns (Intergovernmental Panel on Climate Change (IPCC), 2022). The climatic emergency poses significant challenges for water management in the region, where water supplies, both in industrial/agricultural and domestic use, depend heavily on the seasonal snowpack, impacting the environment and the economy.

Since the early 1900s, many climatic series studies demonstrate how the climate is changing in the Alpine Region with regards to Piemonte and Valle d'Aosta and how the precipitation (especially the snow) is changing too. In 1964 the Italian Glaciological Committee (CGI) published a bulletin (Comitato Glaciologico Italiano, 1964) in which a snow cover map (1959-1960) was disseminated in order to represent the day of snow persistence on the ground. This product was very interesting at the time, to study and design the reservoirs that were being built. In Cati (1981) dataset on snow cover were shown for the period 1921-1950 and it was written that prof. Gazzolo and prof. Pinna (Gazzolo, 1973; Gazzolo and Pinna, 1973; Pinna, 1973) analyzed that at that time the mean temperature and the related snowfalls were decreased, compared to the previous years of the late 1800s. In 1971, the Institute of Alpine Geography published a volume (Ogliaro, 1971) on the changes of the snow, in terms of permanence and frequency in the thirty years between 1929 and 1958. They observed that the snow persistence registered a common decrease in all the alpine sectors comparing the second 15 years to the firsts (1944-1958 compared to 1929-1943). The variations of the snow persistence were in terms of 20-35 days lost. Also the days of snow precipitation changed, with values of 7-10 days of precipitation lost by the second 15 years compared to the firsts. In 2013 Arpa Piemonte, regional environmental agency, published a report (Faletto et al., 2013) on the snow changes in Piemonte's Alps for the period 1961-2010. The report underlined how the snow cover and the snow falls were in continuous change. Authors analyzed the snow persistence changes with results of a mean decrease of -0.5 days/season of persistence lost over the entire period of 50 years, with peak values of -1.19 days/season. Regarding the precipitations, the values were comparable: a mean value of -0.1 days/season with peak values of 0.28 days/season. In the last few years, different researches were published about Snow Cover Changes (SCC) in mountains area (Fugazza et al., 2021; Maskey et al., 2011; Melón-Nava, 2024; Riggs et al., 2022; Saavedra et al., 2018) still literature lacks of ground truth validation.

Aim of this paper is to reconstruct the evolution of snow cover, from 2000 to 2023, using remote sensing technologies. In particular paper focuses on assessing the intensity of SCC and their impact, looking for possible trends over the last two decades. Beyond phenological indexes, key point of this research is to summarize trends in SCC impact with a single result.

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

2 Materials and Methods

2.1 Area of interest

Area of Interest (AOI) is the Italian Western Alps within the regions of Piemonte and Valle d'Aosta. The morphological setting of the AOI is quite complex (Fig. 1): most of the territory is mountainous and hilly and the lowlands are closely linked to the dynamics of the higher areas.

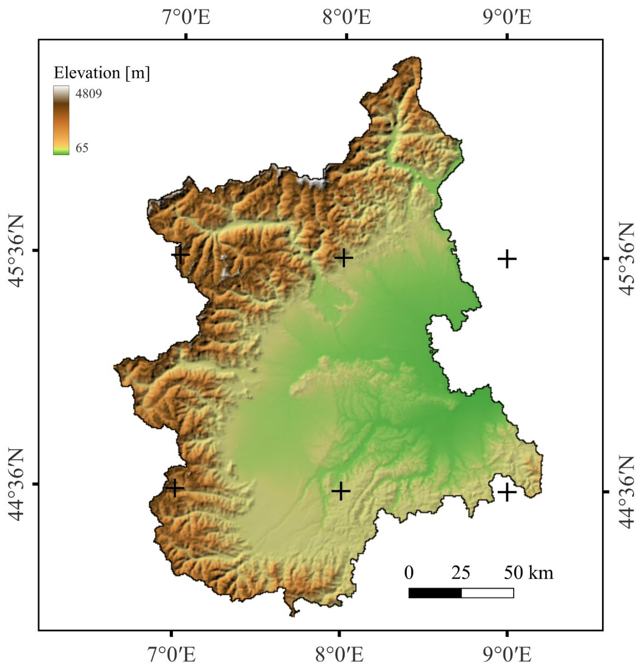

Figure 1: AOI, its morphological complexity and the distribution of the different topographic areas.

Due to the particular morphology of the AOI, the water supply of the lowlands is correlated with the water runoff in mountainous areas. The snow cover offers a natural stock of fresh water during the winter months, its ecosystem service is necessary to the adequate water recharge of canals and aquifers.

2.2 Data collection

2.2.1 MODIS and Elevation data

Moderate-resolution Imaging Spectroradiometer (MODIS) is a satellite mission that provides multispectral imagery with a temporal resolution of 1 day from 2000. In this work, the product MOD10A1.061 Terra was selected and pre-processed in Google Earth Engine (GEE) platform making it possible to monitor the daily evolution of the snow cover at a small scale. In particular, MOD10A1 provides daily snow cover data (in percentage) with a geometric resolution of 500 m (Hall et al., 2002; Liu et al., 2020; Salomonson and Appel, 2004) representing the fraction of the pixel covered by snow. About 8400 images were selected and processed directly in GEE (Gorelick et al., 2017) covering the sensing period between 1st October

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

2000 and 30th September 2023 over AOI. In order to analyze and correct snow cover data in respect to altitude and terrain slope, the Copernicus DEM GLO-30 (Trevisani et al., 2022) was collected and processed in GEE. Copernicus DEM GLO-30 is a raster layer updated in 2015 that maps altitude data with a geometric resolution of 30 m.

2.2.2 Ground data

The necessity for the ground truth emerged because of the fundamental validation process. The AOI is varied: wide lowlands, hilly areas and mountains of variable elevation, up to an altitude of 4805 m a.s.l. (Mont Blanc). We collected data from snowmeter stations inside the networks of stations of Arpa Piemonte and Arpa Valle d'Aosta (Banca dati storica - Arpa Piemonte, 2025; Dataview - Arpa VdA, 2025) covering the entire AOI. The two networks together have more than one hundred stations well distributed throughout the entire territory. To perform this study, it was decided to use 7 stations, well distributed over the AOI both spatially and altimetrically. The dataset was acquired from the websites of each agency, according to the period of analysis: 1st October 2000 to 30th September 2023, obtaining 23 years of daily snow presence on the ground.

2.3 Data processing

2.3.1 Mapping Snow Cover Area, Persistence and daily snowed area

The MOD10A1 V6.1 product was selected in order to map snow cover in AOI. MOD10A1 (Hall and Riggs, 2016) provides daily raster data mapping fractional snow cover (in percentage) with a geometric resolution of 500 m. Using the Quality Bitmask layer provided in MOD10A1 product, a mask for each image was created selecting only 'best' and 'good' quality data and removing pixels having clouds cover, shadows, inland water, visible screen failure, and other sensor failures. A gap-filling procedure was implemented using a linear interpolator involving the nearest available values before and after the missing ones. Subsequently, in order to recover the actual snow cover area (SCA) in a given pixel, the nominal ground sampled area (i.e., 500 m x 500 m) of "NDSI Snow Cover" layer available in MOD16A1 product was normalized by the cosine of the local terrain slope computed from Copernicus DEM. The latter has a native geometric resolution of 30 m and was down sampled using the mean method to the same grid of MOD10A1 data. This procedure was applied to each image in the considered period and the real SCA maps generated. SCA image map for each pixel the real area (in hectares) covered by snow in that observation. Considering the boreal hydrological year (i.e., from 1st October to 30th September), in GEE the cumulative sum of all daily SCA images was calculated and mapped at-the-pixel-level creating 23 new layers called integral snow cover area (iSCA) providing a quantification and a spatial pattern of the yearly snow cover. Starting from MOD10A1 images, new layers were computed by counting the days of snow persistence (SP) within a hydrological year. This count was performed on each MOD10A1 image by creating a binary mask at-the-pixel-level where the snow cover percentage is > 0%. If this condition is satisfied the pixel value for that acquisition was set equal to 1 or 0 if not. The sum of all daily thresholded masks was calculated. A total of 23 SP maps were stacked along a temporal stack providing a quantification and a spatial

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

pattern of the yearly SP. Finally, the ratio between iSCA and SP images was computed for each year of 23 considered. This ratio provided a useful measure of mean daily snowed area (MDSA) for each year and somehow representing the intensity of snow accumulation in a given pixel. Note that dividing iSCA by SP makes MDSA independent from the length of snow period making possible a more robust inter-annual comparison of snow cover.

2.3.2 Snow Persistence Validation

The environmental preservation service, which in the territories of Piemonte and Valle d'Aosta is carried out by the Arpa agencies, made available, free of charge, the nivometric stations datasets with a time series of nivological metrics, starting from the mid-1900s. These data were used as validation of the working method used for this study. In fact, we compared the single pixel of SP product with the corresponding daily snow presence derived by the snowmeter stations. The process was performed on a yearly basis, in order to obtain a continuous validation dataset for the long-term monitoring period. In this way, it was possible to obtain a curve describing, annually, the amount of days of snow presence on the ground from either station data and data obtained from satellite observation. This process led to a temporal comparison of the amount of days of snow persistence on the ground in order to be able to validate the values obtained from the SP product.

2.3.3 Snow Cover Trends Quantification

Once MDSA multiannual stack was downloaded from GEE, a self-develop routine was implemented in the R vs 4.1.1 environment in order to analyze at-the-pixel-level the long-term SCC in AOI. In particular, a linear regression was locally fitted involving 23 MDSA values as the dependent variable and the year as the independent one. The slope (Gain) and intercept (Offset) parameters derived by ordinary least squares method (OLS) were mapped into 2 new layers called $G(x,y)$ and $O(x,y)$ having the 500 m of geometric resolution. $G(x,y)$ maps the local increment or decrement of MDSA along the considered period. This value shows the multi-annual trend of a given area to change the daily snow cover. To assess if this trend is significantly different from 0 (i.e., flat trend or not significant changes), a two-tailed *t*-test (Koch, 1999) on slope parameter from OLS was performed involving 22 degree-of freedoms and a significance level of 95%. All $G(x,y)$ pixels not significant were masked out. Moreover, the determination coefficient of linear regression was also mapped into a new layer called $R^2(x,y)$. The latter represents how the linear trend assumption fits the data. Since some areas in AOI may exhibit a quadratic or (high order polynomial) temporal behavior of MDSA, all pixels having $R^2(x,y) < 0.5$ were masked out. This removal allows to guarantee that remaining local trends show linear-like behavior in the considered period making it possible to easily quantify the SCC and future forecasting.

Finally, $G(x,y)$ was divided by $O(x,y)$ in order to create a new layer called normalized trend - $nT(x,y)$. The latter maps the change rate in respect to the year 2000 assumed as reference. This normalization allows to properly compare areas having different environmental starting conditions (e.g., mountain areas *vs* lowland ones). In fact, $nT(x,y)$ represents changes in snow covered area in a single average snow event. Using the altitude classification according to Kapos (Kapos et al., 2000) the $nT(x,y)$ map was divided in 6 groups according to an altitudinal gradient. The Kolmogorov-Smirnov test (KS) (Pratt and

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

Gibbons, 1981) was adopted for assessing the differences among nT values distributions and exploring how altitude can be a driver of SCC in the considered period.

3 Results

3.1 Snow Persistence Validation

The validation process resulted in a good correlation between ground and satellite datasets (Fig. 2).

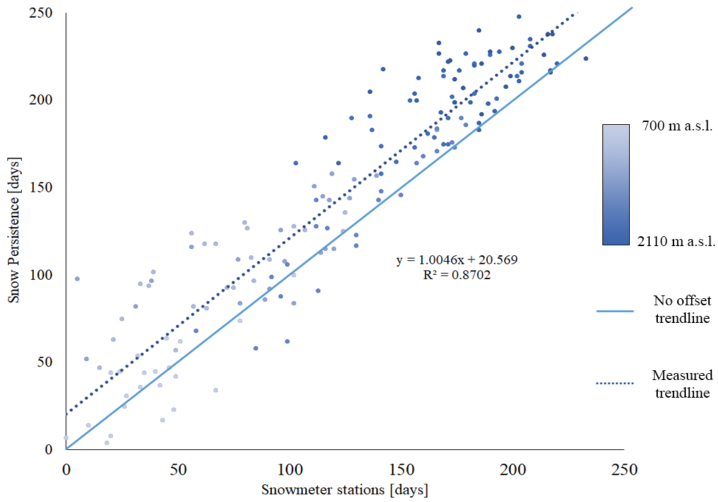

Figure 2: Days of snow persistence calculated by MODIS and ground stations represented in a scatter plot.

In fact, despite the important geometric difference between the two datasets (500 m vs single spot), the annual amount of snow persistence was very close. The presence of a minimal offset (Fig. 2) is caused by the geometric difference of the datasets in question: the punctual dataset compared to a 500 m pixel. In fact, in Fig. 3A we can see how the Antrona station, placed at an elevation of 1500 m a.s.l., presents an almost complete overlap of the curves. While in Fig. 3B in the Entracque - Chiotas station, placed at an altitude of 1970 m a.s.l., we can see how the trend of the satellite curve is flat, precisely because of the location of the weather station (above a dam placed on the threshold of a glacial cirque).

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

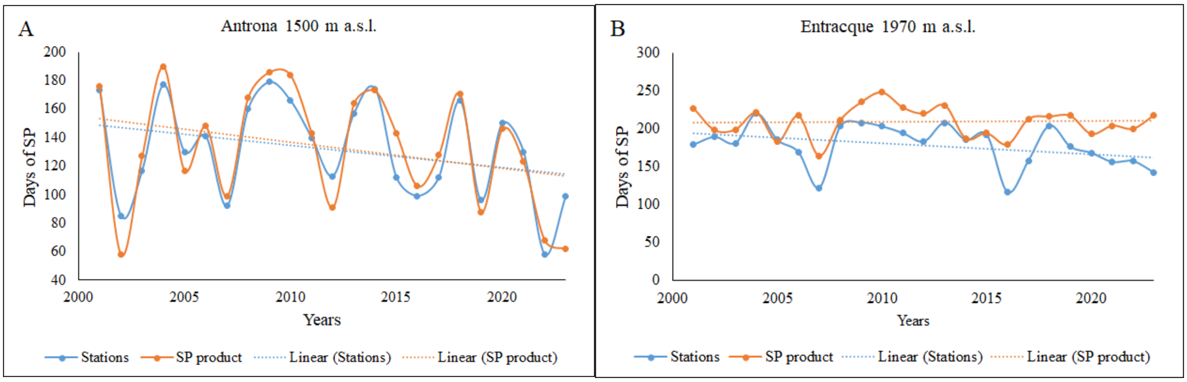

Figure 3: yearly snow persistence comparing SP measure calculated from MODIS (orange) and ground snowmeter station (blue). A) Antrona station B) Entracque - Chiotas station.

3.2 Snow Trends Quantification

As introduced in 2.3.1. and 2.3.3. *nT* represents a spatial product in which it is possible to assess how snow cover changed from 2000 to 2023 at the Italian Western Alps territory level. The *nT* product represents the percentage change yearly rate in snow covered area (at pixel level) for a single mean event in respect to 2000 conditions. In Fig. 4 it is possible to observe the distribution of the changes in AOI.

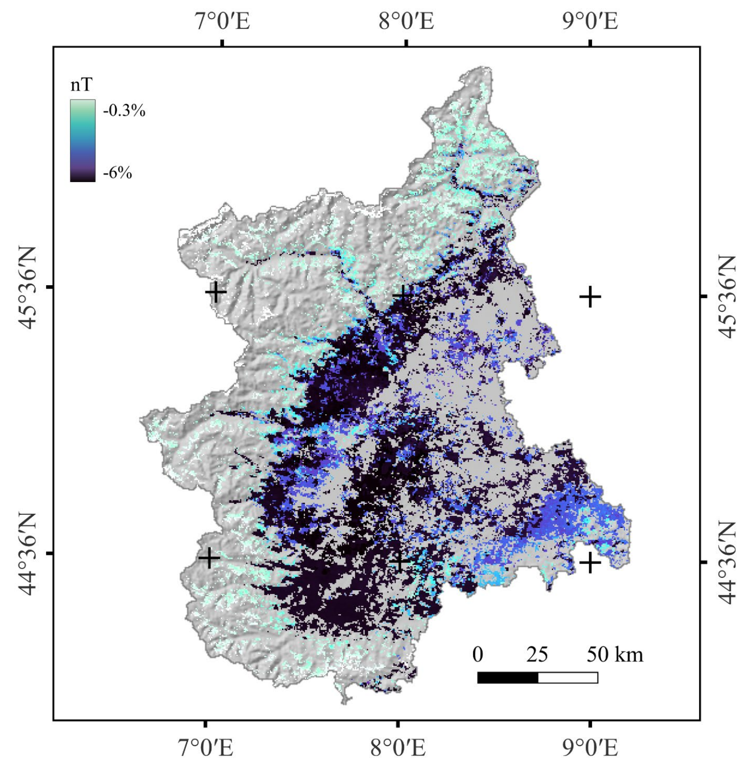

Figure 4: Spatial representation of *nT*, strongly-negative values are related to low altitude areas, instead of less negative values, related to high altitude areas.

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

Figure 4 shows *nT* values in AOI, some areas are not covered because of the masked sectors (as reported in chapter 2.3.3.) that are about 6% of the total pixel for the not significant gain and 58% for the low $R^2(x,y)$ values. Analyzing figure 4, there is a significant trend in the spatial distribution of the obtained values. In fact, the most suffering areas are the ones in the lowlands and main valleys (low altitude sectors in fig. 1) evidenced by the dark blue colors. This impact seems to reduce moving upward in altitude. The altitudinal trend is well represented in figure 5.

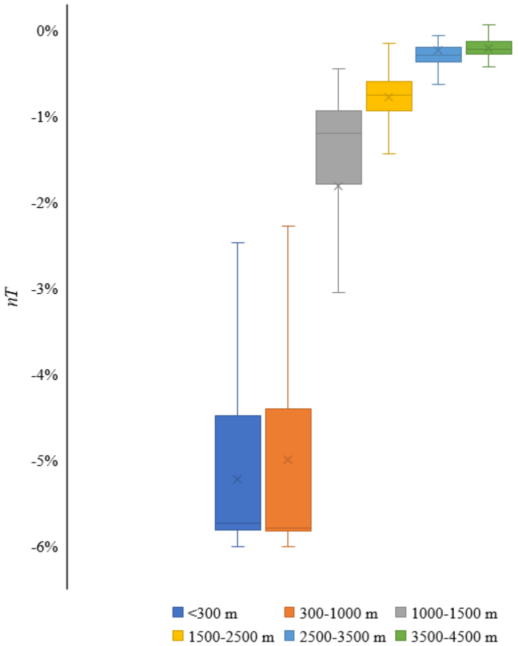

Figure 5: *nT* in relation to the altitude of the AOI. The values of the altitude reported in meters are in m a.s.l.. The altitude classification is taken from (Kapos et al., 2000). The boxes are drawn from 25th to 75th percentile with a horizontal line drawn inside it to denote the median and a cross to represent the mean of the data. The whiskers are drawn from the 5th to the 95th percentile.

Figure 5 shows the *nT* values distributions per altitudinal groups. It is worth noting how pixels with high altitude show in general lower *nT* values. In contrast, pixels on lowland groups show in higher *nT* supporting the hypothesis of an altitudinal gradient of *nT* values with the following interpretative key: lowland areas show in general significant negative trends than high mountain ones. The latter have quite flat trends tending to 0. KS test results (Table 1) support this hypothesis denoting significance differences among altitudinal groups.

Table 1: Signcativity of boxplot in figure 5

p-value\ D	**<300 m**	**300-1000 m**	**1000-1500 m**	**1500-2500 m**	**2500-3500 m**	**3500-4500 m**
<300 m	-	0.18	0.817	0.989	0.999	0.999
300-1000 m	p < 0.001	-	0.718	0.943	0.996	0.998
1000-1500 m	p < 0.001	p < 0.001	-	0.52	0.961	0.996
1500-2500 m	p < 0.001	p < 0.001	p < 0.001	-	0.824	0.944
2500-3500 m	p < 0.001	p < 0.001	p < 0.001	p < 0.001	-	0.31
3500-4500 m	p < 0.001	p < 0.001	p < 0.001	p < 0.001	p < 0.001	-

4 Discussion

Results from this study can be used for highlighting the effects of climate warming within the Italian Western Alps due to SCC in the last two decades. In fact, *nT* synthetizes the percentage variation of snow cover intensity by looking at a single yearly mean snow event. In literature, there are several works that observe phenological changes from satellites: seasonality, persistence, first snowfall (Fugazza et al., 2021; Li et al., 2018; Maskey et al., 2011; Notarnicola, 2020). By introducing the *nT* concept, we observe the intensity and impact of changes affecting snow cover, on a regional scale, beyond the phenological indexes. *nT* value makes it possible to summarize the intensity of SCC and enhances the understanding of its evolutionary trends. From the Earth Observation point of view, *nT* is a good metric to properly compare pixels from different geographic areas. Therefore, it allows to spatialize and describe the effect of the CC in terms of snow cover. *nT* is independent from the changes of seasonality of the snow (i.e., form the length of snow period). It enhances interpretation of environmental changes through the time, summarizing the changing rate (i.e., G(x,y)) and the starting conditions (i.e., O(x,y)).

Application of *nT* within the AOI (Figure 4) shows highlights clear geo-environmental patterns in the spatial distribution of SCC: the most negative values corresponds to the lowlands of Po Plain and to the main valleys, then values increase by altimetric position but not homogeneously. With respect to this, further constrains are latitudinal and geomorphological position (e.g. internal or external position in the mountain belt, proximity to the valleys, exposure, …).

Results of the altitudinal classification within the AOI (Fig. 5) shows the extreme impact of *nT* at low altitudes (below 1000 m a.s.l.) quantified in -5%. In addition, other two areas are strong affected by CC: 1000-1500 m a.s.l. (-1.8%) and 1500-2500 m a.s.l. (-0.7%). As mentioned *nT* shows the changes in snow-whitened areas for a single yearly mean event. This represents that changes are indeed occurring at all elevations, but with greater intensity (in percentage terms, relative to its own mean starting value) at lower elevations. The evolution process, evidenced by *nT* in Figure 5, shows that the areas whitened by a

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

single snow event are decreasing. This result offered by the application of our method is a clear representation of the freezing level is moving upward (in elevation) and the decreasing of snow precipitation. The potential snowfall is becoming almost zero at low altitudes (below 1000 m a.s.l.) and very weak in the mid-mountains (1000-1500 m a.s.l.). As reported by Avanzi (Avanzi, 2024; Avanzi et al., 2024) the drought of the last years affected most, the areas below 1500 m a.s.l. The evidence is underpinned also by *nT*. As shown in Figure 5, the more suffering areas were the ones below 1500 m a.s.l., in which the trend is significantly negative. Same negative trend is reported, at a different observation scale, for whole Alpine Region (Bozzoli et al., 2024; Matiu et al., 2021) . The spatial distribution of SCC, as highlighted by *nT* can be of significant value in terms of territorial and water management policies. Many considerations could be derived within the AOI based on our result, from various point of view: land use, tourism, and water resources.

This study presents some limits, the absence of a quantitative volumetric assessment of the observed changes. This limitation represents a significant future research challenge: quantifying snowpack volume necessitates the exploitation of spatiotemporal Snow Water Equivalent (SWE) data. Furthermore, a portion of the study area currently exhibits non-linear or undefined trends in the observed changes. Consequently, repeated temporal observations will be crucial to accurately discern and characterize the evolving dynamics within these specific sectors.

Nevertheless, the findings of this study offer strategic implications for Alpine communities, underscoring the critical importance of effective water resource management across industrial, agricultural, and public consumption sectors. Moreover, in light of the progressive snow cover reduction documented herein, it is imperative to critically evaluate the long-term sustainability of certain winter sports activities at elevations below 1500 m a.s.l.

5 Conclusion

Snow Cover in the Western Alps is undergoing changes that have significant repercussions on the whole sector. This study revealed, using MODIS satellite data, the effects of the Climate Changes (CC) in the Italian Western Alps, in terms of Snow Cover Changes (SCC) in the period 2000-2023. The herein introduced normalized trend (*nT*) index quantifies these changes by expressing the annual mean change in snow-covered area. Our findings indicate that lowland and main valley areas have undergone the most substantial decrease, with *nT* values decreasing by up to -5% below 1000 m a.s.l. and about -1.8% in areas between 1000-1500 m a.s.l. These findings show the influence of CC on regional snow dynamics, with implications for water resource management, winter tourism, and the long-term sustainability of various economic activities.

Competing interests

The authors declare that they have no conflict of interest.

https://doi.org/10.5194/egusphere-2025-3028
Preprint. Discussion started: 4 July 2025

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