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Laboratory of Alpine Climatology (LabClima): a new research network for climate change research on Monte Rosa, Western Italian Alps

Abstract: Gallarate M., Viani C., Gay A., Marengo A., Baronetti A., Guenzi D., Giardino M., Freppaz M., Motta L., Acquaotta F., *Laboratory of Alpine Climatology (LabClima): a new research network for climate change research on Monte Rosa, Western Italian Alps.* (IT ISSN 0391-9838, 2024). In this work we focus on the Monte Rosa massif, the second highest mountain of the Italian Alps. We investigate the warming rate of this area and how it affected the frontal evolution of its glaciers. Firstly, we analysed the temperature series of two weather stations, located in the Sesia and Lys valleys. Our analysis covers the twenty-year period from 2003 to 2022. From these series we extracted climatic indexes and their time trends. Our results showed an increase in minimum and maximum temperatures, with a significantly decrease in the number of days with extremely low minimum temperatures. We also collected data from the Bulletin of the Italian Glaciological Committee to investigate the oscillations of two glaciers of interest, namely the Lys and Indren Glaciers. We later compared their frontal variation from 1928 to 2017. This analysis showed a net retreat of both glaciers. The most severe retrocessions happened in recent years that also experienced severe droughts. During our work we noted the lack of data relating to elevations above 3000 m a.s.l.. The intention to fill this gap is one of the main motives behind the establishment of the Laboratory of Alpine Climatology. The Laboratory of Alpine Climatology ("Laboratorio di Climatologia Alpina" - LabClima in Italian) is a network of automated weather stations located in the Western Italian Alps. The first fully operational station of LabClima is Passo dei Salati (3030 m a.s.l.). The station has recently reached its first year of activity. In this work we briefly present the data collected so far. The second station, named Garstelet (3455 m a.s.l.), became operational in September 2024. LabClima focuses also on the deployment of innovative sensors in high elevation environments. The sensors intended to study the snow optical properties and the equivalent mass of water contained in the snowpack are presented in the last section of this work.

Key words: climate change, Monte Rosa, Automated Weather Station, glaciers, Snow Water Equivalent.

Riassunto: Gallarate M., Viani C., Gay A., Marengo A., Baronetti A., Guenzi D., Giardino M., Freppaz M., Motta L., Acquaotta F., *Il Laboratorio di Climatologia Alpina (LabClima): un nuovo network di ricerca per l'indagine sul cambiamento climatico sul Monte Rosa, Alpi Occidentali Italiane.* (IT ISSN 0391-9838, 2024). Questo articolo si concentra sul massiccio del Monte Rosa, la seconda vetta più alta delle Alpi italiane. Viene studiato il tasso di riscaldamento di quest'area e il modo in cui ha influenzato l'evoluzione frontale dei suoi ghiacciai. Innanzitutto, abbiamo analizzato le serie di temperature di due stazioni meteorologiche, situate nelle valli del Sesia e del Lys. La nostra analisi copre il ventennio dal 2003 al 2022. Da queste serie abbiamo estrapolato gli indici climatici e i loro trend. I nostri risultati mostrano un aumento delle temperature sia minime che massime, con una diminuzione significativa del numero di giorni con temperature minime estremamente basse. Abbiamo inoltre raccolto i dati del Bollettino del Comitato Glaciologico Italiano per indagare le oscillazioni di due ghiacciai di interesse: i ghiacciai Lys e Indren. Successivamente abbiamo confrontato la loro variazione frontale dal 1928 al 2017. Questa analisi mostra un netto ritiro di entrambi i ghiacciai. Gli arretramenti più ingenti si sono avuti negli ultimi anni, durante i quali si sono verificate anche gravi siccità. Nel corso del nostro lavoro abbiamo notato la mancanza di dati relativi alle altitudini superiori a 3000 m s.l.m. L'intenzione di colmare questa lacuna è uno dei motivi principali alla base della creazione del Laboratorio di Climatologia Alpina. Il Laboratorio di Climatologia Alpina (LabClima) è una rete di stazioni meteorologiche automatizzate situate nelle Alpi dell'Italia occidentale. La prima stazione pienamente operativa di LabClima è Passo dei Salati (3030 m s.l.m.). La stazione ha da poco raggiunto il suo primo anno di attività. In questo lavoro presentiamo brevemente i dati finora raccolti. La seconda stazione, denominata Garstelet (3455 m s.l.m.), è diventata operativa nel settembre 2024. LabClima si concentra anche sull'implementazione di sensori innovativi in territori d'alta quota. Nell'ultima sezione di questo articolo sono presentati i sensori destinati a studiare le proprietà ottiche della neve e la massa equivalente di acqua contenuta nel manto nevoso (SWE).

Termini chiave: cambiamento climatico, Monte Rosa, stazione meteorologica automatizzata, ghiacciai, Snow Water Equivalent.

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INTRODUCTION

The global cryosphere has undergone significant ice mass losses due to climate change and global warming (Zemp *et al.*, 2019). These losses have increased since the beginning of the 21st century (Hugonnet *et al.*, 2021) and percentage melt has been higher for Southern European glaciers compared to other regions (GlaMBIE, 2025). Meteorological and glaciological monitoring in the European Alps began in the late 19th century and saw a significant expansion during the 20th century (Shahgedanova *et al.*, 2021). For this reason, the Alps are the best-known mountain area in terms of weather and climate (Beniston, 2006) retaining many long-term, homogenous ground-based observations (Viviroli *et al.*, 2011). Manual daily observation of weather and snow constitute the core dataset for climatological studies in the Alps (Bozzoli *et al.* 2024). However, the diffusion of automated weather stations since the end of the 20th century increased significantly the spatial coverage and the continuity of the climatological data available (Brugnara and Maugeri, 2019; Pavan *et al.*, 2019). The European Alps are significantly impacted by climate change (Hock *et al.*, 2019) due to rise in air temperatures (Auer *et al.* 2007), changes in precipitation patterns and intensity (Gobiet *et al.*, 2014), and loss of snow cover (Rumpf *et al.*, 2022). The Monte Rosa massif is an area of particular interest for Alpine environment studies focusing on its glacial (Viani *et al.*, 2020; Vione *et al.*, 2021), permafrost (Colombo *et al.* 2019), pedological (Freppaz *et al.*, 2019; Pintaldi *et al.*, 2021) and geomorphological (Tognetto *et al.*, 2021) features. The research carried out so far shows an increase in air temperatures and a reduction in precipitation, both solid (snow) and liquid in the area of interest of the project. For temperatures, the greatest increase was recorded in high elevation locations (Acquaotta *et al.*, 2015). Liquid precipitations show a decrease in localities below 1600 m a.s.l. while, for snowfall, the reduction is observed in localities above 1600 m a.s.l. (Baronetti *et al.*, 2022). From a climatological point of view, the data analysis showed that the considered area has warmed up twice as fast as the surrounding areas, with an increase of 0.5 °C per decade since the 1980s (Zimmermann *et al.*, 2013). Over the last 50 years the extreme maximum temperatures (i.e. the 90th percentile of the maximum daily temperatures series) have increased by 1.5 °C. In the same period, the extreme minimum temperatures (i.e. the 10th percentile of the minimum daily temperatures series) have increased by 2.2°C. Precipitation decreased by an average of 3 mm per year; dry periods experienced an increase (Baronetti *et al.*, 2018; IPCC, 2021). These variations had important effects on the cryosphere such as the retreat of the glaciers (Salvatore *et al.*, 2015; Smiraglia *et al.*, 2015) and the permafrost degradation (Damm and Felderer, 2013; Haberkorn *et al.*, 2021). By the end of the 21st century, a loss ranging from about 63% to 94% of the volume of glaciers has been estimated considering different climate model simulations, thus determining important effects on environmental, social and economic systems (Zekollari *et al.*, 2019).

Monte Rosa is therefore a focal point for the scientific research involving the study of glaciers dynamics and the overall evolution of the Alpine cryosphere. However, this crucial area was subject to a lack of representativeness in the historical meteorological datasets available. In fact, before the start of the Laboratory of Alpine Climatology (LabClima), there were only four automated weather stations located at high elevations on the Sesia and Lys valleys of the Monte Rosa massif. Among those stations, none are in the elevation range between 3000 m a.s.l. and 4000 m a.s.l.. This absence in available data prompted the birth of LabClima to address and fill the existing gap. The Laboratory of Alpine Climatology was born thanks to the contribution of the Cassa di Risparmio di Torino Foundation - CRT, a private non-profit organisation. Part of the instruments installed were acquired thanks to the funding of the Nord Ovest Digitale E Sostenibile (NODES) project that was part of the National Recovery and Resilience Plan funded by the European Union – NextGenerationEU program. LabClima consists in a developing network of automated monitoring stations, managed by the Department of Earth Sciences (DST) of the University of Turin (UNITO) located in western Italy, which are meant to retrieve weather and snow data both for research and educational purposes, addressing the lack of reliable and continuous data for the area at altitudes above 3000 m a.s.l. The long-term sustainability of the project will be granted by internal funding of the DST, along with the partecipation of LabClima in national and international grant calls.

STUDY AREA

LabClima involves a high mountain area of the Monte Rosa massif between the Italian regions of Piedmont and Aosta Valley, within the municipalities of Alagna Valsesia and Gressoney-La-Trinité (fig. 1). The area has a high environmental, cultural, touristic, and scientific value: it is part of the Alta Valsesia Natural Park and of the larger Sesia Val Grande UNESCO Global Geopark. However, the region faces increasing threats from the ongoing climate change, in particular from the associated temperature rise.

The Monte Rosa massif has a relevant touristic role both in winter (due to ski-related activities) and in summer, when it is visited by alpinists, hikers and climbers interested in the panoramic views and naturalistic attractions. Since the late 19th century, Monte Rosa has been an

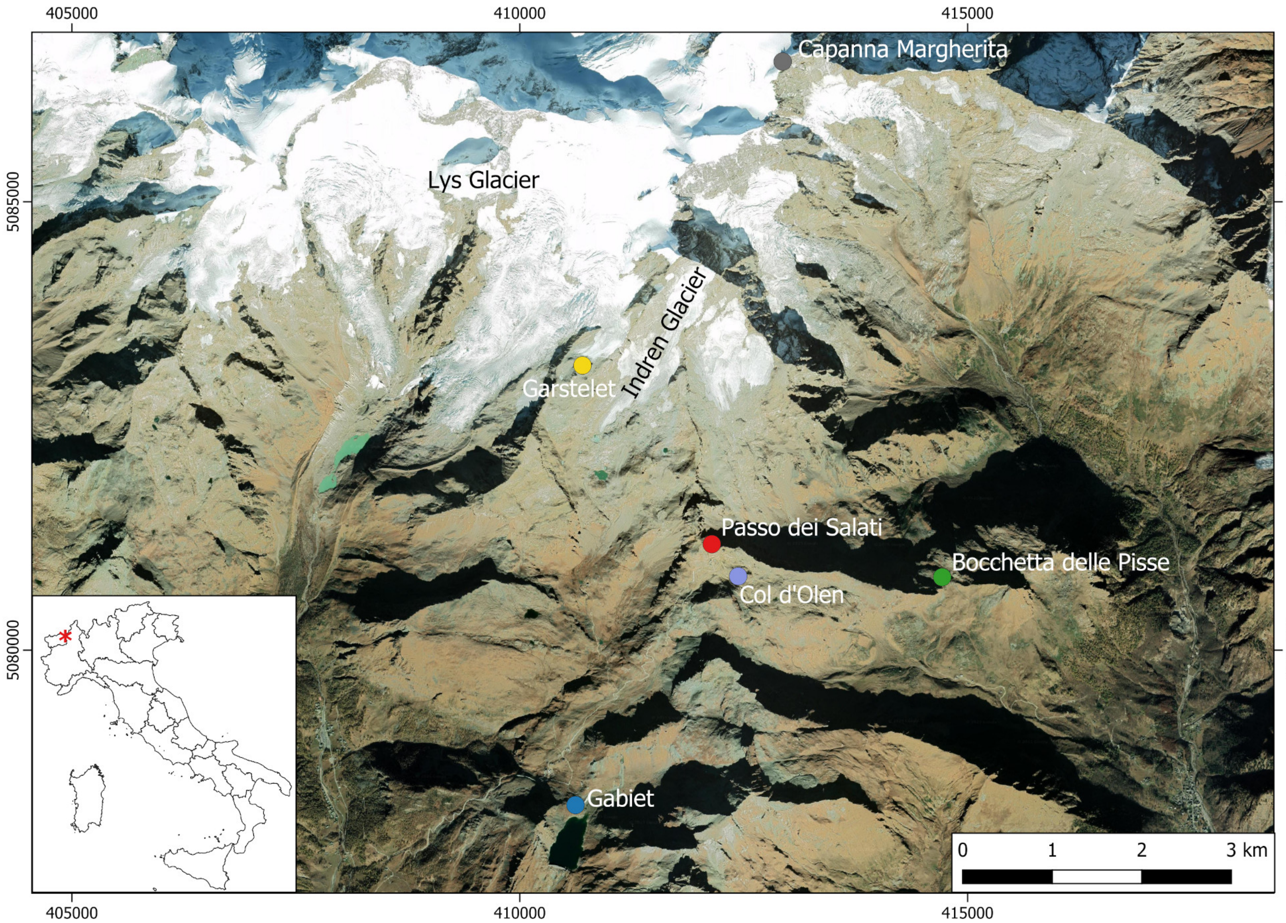

Figure 1 - Satellite view over the study area with the glaciers and location of the automated weather stations (colored dots) mentioned in this paper.

important site for scientific research. In 1893, the Italian Alpine Club built the Capanna Regina Margherita Observatory on Punta Gnifetti (4554 m a.s.l.), which remains active today. It houses a weather station and a laboratory that supports significant international research in physics, glaciology, and meteorology. Another important centre for Alpine research in the Monte Rosa area is the Angelo Mosso Institute, opened in 1907 and located on Col D'Olen (2900 m a.s.l.) and managed by the University of Turin. The Institute is part of the Italian Long-Term Ecosystem Research Network (LTER-IT) which is a component of the European Long-Term Ecosystem Research Network (LTER Europe). At the Mosso Institute and in the surrounding area many research activities are performed by the University of Turin alongside with many other entities that give their contribution to data collection such as the Italian National Research Council (CNR), Alpine Troops Command-Service Meteomont, Monterosa 2000 S.p.A. and Monterosa S.p.A. (Monterosa Ski), Protected areas of Valsesia, Sesia Val Grande Geopark and the Regional Environmental Protection Agencies (ARPAs) of Piedmont and Aosta Valley.

Weather Stations

Prior to the establishment of LabClima, only four automated weather stations operated above 2300 m a.s.l. in the study area: Gabiet, Bocchetta delle Pisse, Col D'Olen and Capanna Margherita.

The Gabiet station (45° 50' 44" N, 7° 50' 52" E, 2373 m a.s.l.) is located in the Gressoney-La-Trinité municipality near the artificial lake Gabiet, on the Aosta Valley side of the massif. The station is managed by the Functional Centre of the Autonomous Aosta Valley Region (CFVdA). The Gabiet automated station had been active since 25/10/2002 and ceased its activity in the month of November 2023, when it was replaced by the Diga Gabiet automated station, which is still located in the proximity of the Gabiet lake, although in a different position. Both the Gabiet station and its successor measure surface air temperature, total and reflected solar radiation, relative humidity, wind speed and direction, precipitation, and snow height. The Gabiet lake has been object of weather observations and measurements since at least the year 1919 when precipitation data began to be collected, in 1928 the measurement of air temperature and snow height started (Mercalli *et al.*, 2003).

The Bocchetta delle Pisse station (45° 52' 32" N, 7° 54' 4" E, 2410 m a.s.l.) is located in the Alagna municipality in the Sesia valley. It is managed by the Regional Environmental Protection Agency of the Piedmont Region (ARPA Piemonte). The station began its activity at the end of October 1987 with measurements of air temperature and wind speed and direction. Since July 1996 precipitation and snow height values are being recorded.

The Col D'Olen automated station (45° 52' 31" N, 7° 52' 18" E, 2900 m a.s.l.) belongs to the Alagna municipality and is located in the proximity of the Angelo Mosso Institute. It is managed by the Italian Army Alpine Troops Command-Service Meteomont and began its activity in 2002 with measurements of air temperature, wind speed and direction, atmospheric pressure, relative humidity, and snow height. In the year 2022, the Col D'Olen station was object of maintenance works and change in the overall data recording process that resulted in substantial gaps in the series and some inhomogeneities in the data before and after the modifications. For this reason, we decided not to employ the data from Col D'Olen to perform our research.

Lastly, the Capanna Margherita automated station (45° 55' 38" N, 7° 52' 37" E, 4554 m a.s.l.) is part of the homonymous observatory located on Punta Gnifetti. The first weather observatory dates back to the year 1899 and recorded weather data, although only relative to the summer period, until 1958. The old building was demolished in 1980, when a new one was built in its place. The current automated station began its activity in 2002 and is managed by ARPA Piemonte. The weather variables measured by the station are air temperature, wind speed and direction, wind gust, atmospheric pressure, and total incoming radiation. Even though the presence of a weather station at such a high elevation constitutes a great asset, the dataset of Capanna Margherita is discontinuous and, therefore, not suitable for climatic analysis.

Glaciers

One of the main features of the Monte Rosa massif is the presence of many glaciers. Just the Italian side of the massif retains 26 glaciers, namely (from west to east): Teodulo Inferiore, Valtournanche, Ventina, Tzére, Grande di Verra, Piccolo di Verra, Castore, Perazzi, Felik, Lys, Garstelet, Indren, Bors, Piode, Sesia-Vigne, Locce Sud, Locce Nord, Pizzo Bianco, Signal, Monte Rosa, Belvedere, Nordend, Piccolo Fillar, Jazzi, Roffel Occidentale (Mercalli *et al.*, 1991; Smiraglia, 2015). Italian glaciers are systematically monitored by glaciological campaigns coordinated by the Italian Glaciological Committee (CGI). Every year, at the end of the ablation summer season, a glaciological survey is carried out during which measures of front variations and elevation and photographs from fixed points, observations of the snow cover and of the front morphology are taken.

We focused on two glaciers of the Monte Rosa massif: Lys and Indren. These two glaciers retain a long series of data collected in the archives of the Italian Glaciological Committee and published in the Bulletin of the CGI and, since 1978, on the journal Geografia Fisica e Dinamica Quaternaria.

The *Lys Glacier* is the largest among the Italian glaciers of Monte Rosa. It was a valley glacier with direct feeding, until the year 2012 when the detachment of its tongue happened transforming it into a mountain glacier. The first accurate descriptions of the Lys Glacier and its history date back to the first years of the Twentieth Century (Dainelli, 1902). Since 1912, thanks to the work of the Aosta Valley native Umberto Monterin and his successors, there are annual records including measurements of the glaciers and many descriptive notes. Along with the first direct scientific measures, Monterin was able to partially reconstruct the evolution of the Lys glacier going back to the year 1812 (Monterin, 1932). Since 2012 the front, that was located at 2355 m a.s.l., has separated from the glacier forming a mass of dead ice. Nevertheless, in the following years the measurements of the glaciological campaigns were continued on this old front, mainly due to the impossibility of reaching the new front (which was located at 2650 m a.s.l.). However, from 2017 the measures on the dead ice mass were discontinued as they are not considered significant anymore. Still, the new active front is unreachable due to high slope and numerous collapses that occurred (Palomba *et al.*, 2018 in Baroni *et al.*, 2018).

The *Indren Glacier* occupies a wide slope delimited by two rocky ridges that form the catchment (Bonardo and Giardino, 2020). In the past this glacier had two branches: eastern and western. Initial measurements were carried out on both branches, but those on the eastern branch were soon ceased due to its pronounced retreat. Since 1927, with the formation of a new ice tongue on the western branch of the glacier, it was possible to distinguish left and right lobes. Measurements were carried out in parallel on both lobes. The right one, being the oldest, stood at an elevation of 2890 m a.s.l., while the more recently formed left lobe reached 3020 m a.s.l. In 1954 the right lobe of the western branch underwent numerous collapses which caused the detachment of the front, which went on to form a mass of dead ice covered with debris (De Gemini *et. al.*, 1956). From 1971 to 1986 no oscillations of the Indren Glacier were recorded, due to the snow preventing operators from performing the usual measurements. Today the annual measurements are carried out on the western branch of the glacier, now free of bifurcations.

Table 1 - Summary of the automated weather stations present on the study area above 2000 m a.s.l.

Name	Elevation (m a.s.l.)	Period analyzed	Number of missing days
Gabiet	2379	01/01/2003 – 31/12/2022	0
Bocchetta delle Pisse	2410	01/01/2003 – 31/12/2022	10
Capanna Margherita	4554	31/08/2002 – 31/12/2022	372
Col D'Olen	2900	20/10/2003 – 31/12/2022	214

METHODOLOGY

Temperatures analysis and climate indices

We collected the daily temperature data belonging to the stations of Bocchetta delle Pisse and Gabiet covering the 20-year period from 2003 to 2022. For each dataset we computed seven values:

– monthly mean temperature;
– maximum value of temperature ever recorded for each month;
– minimum value of temperature ever recorded for each month;
– monthly average of the daily maximum temperatures;
– monthly average of the daily minimum temperatures;
– monthly maximum temperature (i.e. average over the examined period of the maximum temperatures of each month);
– monthly minimum temperature (i.e. average over the examined period of the minimum temperatures of each month).

Subsequently, we used the software package Climpact, developed by the Expert Team on Sector-Specific Climate Indices (ET-SCI) of the World Meteorological Organization (WMO) to retrieve some climatological indices from the two series analyzed. Namely, the indices are (Zhang *et al.*, 2011):

– TN10p: yearly percentage of daily minimum temperature below the 10^{th} percentile of the series;
– TN90p: yearly percentage of daily minimum temperature above the 90^{th} percentile of the series;
– TX10p: yearly percentage of daily maximum temperature below the 10^{th} percentile of the series;
– TX90p: yearly percentage of daily maximum temperature above the 90^{th} percentile of the series;
– TMm: yearly average of the daily mean temperatures;
– TXm: yearly average of the daily maximum temperatures;
– TNm: yearly average of the daily minimum temperatures.

For each of these indices, we computed the linear trend and its relative p-value, obtained with the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975). The significance level was in general fixed at 5% (i.e. $p<0.05$); $p<0.1$ was used in specific cases.

Glaciers

Firstly, we examined the frontal oscillations of the glaciers (e.g. the variation of the front elevation recorded during each campaign) obtaining the cumulative variation of the front altitude. For the Lys Glacier we were able to assess the frontal oscillations and variation for a period longer than a century starting from the year 1913 and ending in 2017 (105 years in total). The period covered by our analysis regarding the Indren Glacier covers from the year 1927 until 2017 (91 years in total). Afterwards, we compared the cumulative variation of the frontal elevation with the Standardized Anomaly Index (SAI) for the FD (i.e. Frost Days) climatic index with the historical temperature series of the Gabiet station that has measures dating back to the year 1928. Given the starting year of the meteorological data at our disposal, this work of comparison covered only the years when both these data and the glaciers frontal variations were available (e.g. from 1928 to 2017, 90 years in total).

The FD index expresses the number of days in a year when the minimum temperature was below the 0 °C threshold. SAI (Katz *et al.*, 1986) is defined as the difference between each (in our case, yearly) index and its mean value over the whole series, divided by its standard deviation. SAI is a good indicator of how a single year deviates from the expected climatology of the studied area and, therefore, can give better insights on events compared to the raw value of an index.

Overall, it is to be expected that strong negative oscillations of the front elevation should be associated with one or multiple negative SAI of FD in the previous years, as they are symptoms of warmer than average years. However, it should be kept in consideration that the Gabiet station is located at lower elevations compared to the glaciers and, therefore, the temperatures it registered had to be higher than the ones actually experienced by the ice masses studied. This constitutes one of the main reasons that led us to the adoption of the SAI, as it is more descriptive of the anomalies leaving partially out the offset derived by the difference in altitude.

RESULTS

Temperatures

During the period analyzed, the temperature extremes in the Gabiet series (fig. 2a) are 24.1 °C (recorded on 05/07/2015) and -26.8 °C (recorded on 27/02/2018). The av-

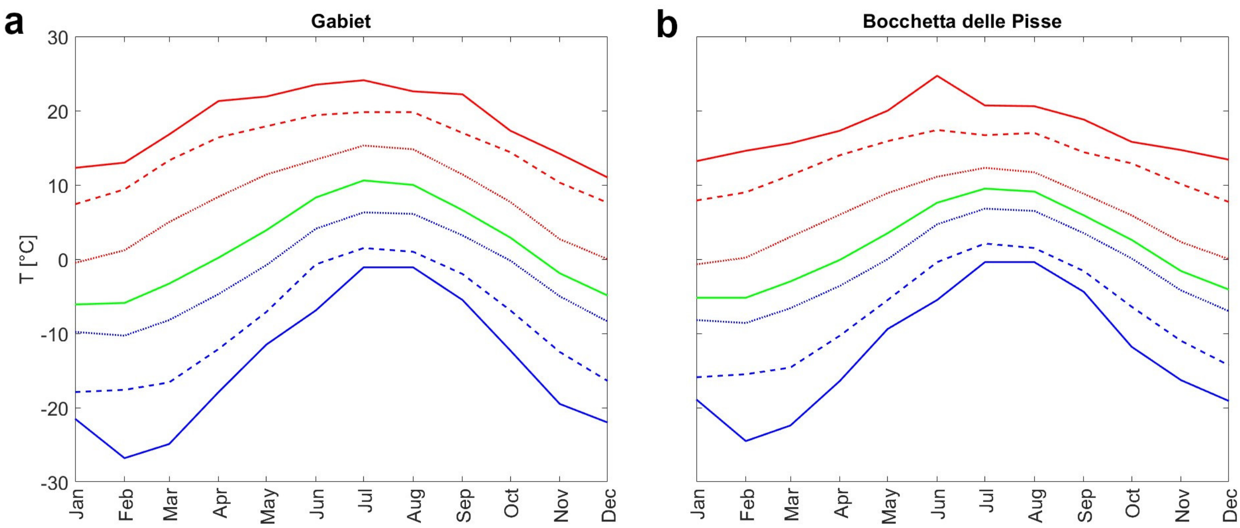

Figure 2 - Multi-annual mean monthly temperature values for the period 2003-2022 of: - highest temperature ever recorded (red solid); - monthly maximum temperature (red dashed); - monthly average of daily maximum temperatures (red dotted); - monthly average temperature (green); - monthly average of daily minimum temperatures (blue dotted); - monthly minimum temperature (blue dashed); -lowest temperature ever recorded (blue solid). Panel a: Gabiet station, 2379 m a.s.l.; Panel b: Bocchetta delle Pisse station, 2410 m a.s.l.

erage temperatures from November to April lay below the freezing point. Considering the monthly average temperatures, January (-6.1 °C) and February (-5.9 °C) are the coldest months; the warmest are July (10.6 °C) and August (10.0 °C).

The temperature extremes of the Bocchetta delle Pisse series (see fig. 2b) are 24.7 °C (on the 27/06/2019) and -24.5 °C (on the 27/02/2018). The average monthly temperatures show the same pattern as Gabiet. In the months from November to April they are below the freezing point. On average the coldest months are January and February (-5.2 °C both) and the warmest are July (9.5 °C) and August (9.1 °C).

Climate Indices

Table 2 shows the linear trend for the computed indices relative to the two analyzed temperature series in the period 2003-2022.

At Gabiet, the statistically significant trends emerged are in TNm, TN10p, and TN90p. They all highlight an increase in minimum temperature. TNm shows an increase of roughly 0.1 °C per year. TN10p (fig. 3) and TN90p have coupled trends that suggest a shift of the extremes of minimum temperatures towards a warmer state.

At Bocchetta delle Pisse, only trends in TN10p, TNm, and TMm are statistically significant. The linear trends of TNm (0.05 °C/year) and TMm (0.06 °C/year) show a rise of the mean and minimum temperatures. The trend of the TN10p index (fig. 3) evidences a decrease of 0.42 % per year. These results, combined with the TX10p trend of -0.47 %/year ($p < 0.1$), underline an ongoing warming process that poses a risk for cryosphere preservation on the Monte Rosa massif.

Glaciers

The *Lys Glacier* had the main positive oscillations between 1914 and 1920 and between 1973 and 1986 (fig. 4). The largest advance was registered in 1917. The others are generally less than 20 m. The most important negative fluctuations (e.g. in the order of 40 m) occurred in 1941-1942, 1947, 1950, 2003 and 2007. The frontal retreats of 2003 and 2007 happened in years affected by severe drought events in the Po River basin with prolonged precipitation deficit (Baronetti *et al.*, 2020). The years 1934, 1965, and 2009 show negative variations exceeding 20 m. In general, for the period covered, the years in which the glacier has been subjected to a decline vastly surpass the years when the front advanced, which are only one fifth of the series. In the period covered by our analysis, front retreats were four times more frequent than advances.

The last front advances occurred between 1973 and 1986. In the same period SAI FD retains mostly positive values. From 1992, the Lys Glacier experienced only retrocessions. In the 21st Century the annual SAI FD has exclusively negative values, often below the -1 threshold (see fig. 5). Between 2003 and 2007 the Lys Glacier front lost 165 m with an average rate of recession of 30 m per year. This result is in accordance with the temperature rise that was discussed in the previous section. An increase in temperatures impacts negatively the number of frost days recorded each year. The lack of frost days in many subsequent years is then reflected in net mass loss for the glacier.

Our data suggest that the *Indren Glacier* experienced few and exiguous advances (fig. 6). Between 1971 and 1986, snow prevented the operators from performing the usual annual measurements. This caused a 16-year gap in

Table 2 - Indices and slopes computed for Bocchetta delle Pisse and Gabiet in the period 2003-2022 (* = 5% significance level, ** = 10% significance level).

Index	TN10p	TN90p	TNm	TX10p	TX90p	TXm	TMm
Bocchetta delle Pisse	-0.42 %/year *	0.24 %/year	0.05 °/year *	-0.47 %/year **	0.46 %/year	0.10 °/year	0.06 °/year *
Gabiet	-0.54 %/year *	0.38 %/year *	0.09 °/year *	-0.01 %/year	-0.2 %/year	-0.03 °/year	0.02 °/year

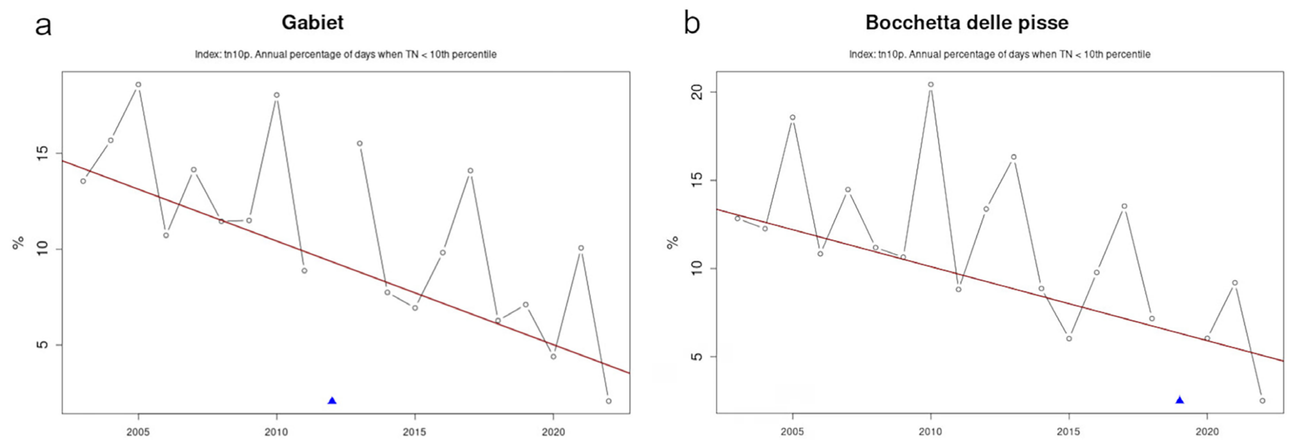

Figure 3 - Time series of the TN10p index (black line and circles) and its linear trend (red line) for the period 2003-2022. Panel a: Gabiet; Panel b: Bocchetta delle Pisse. Blue triangles symbolize missing data.

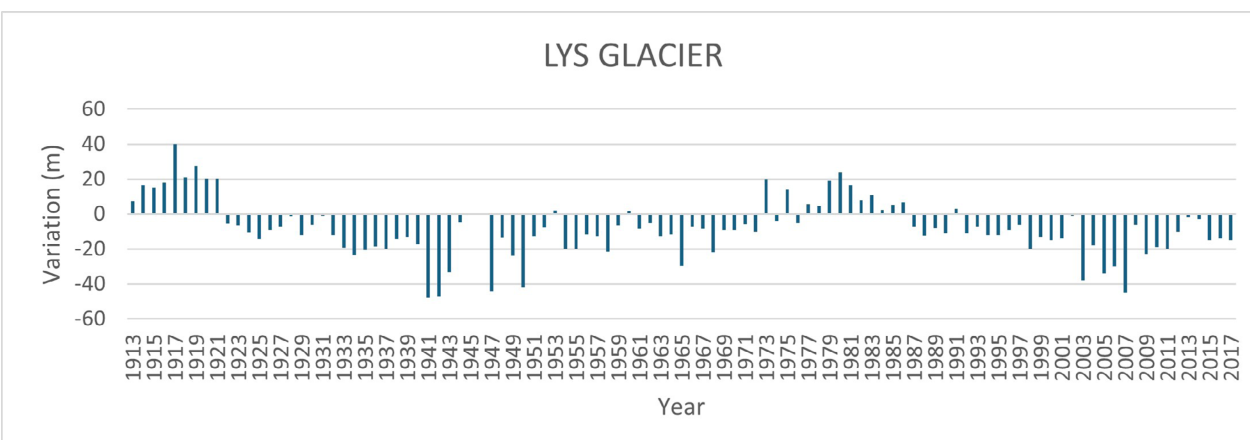

Figure 4 - Annual variation of the Lys glacier front in the 1913-2017 period.

the series that could explain its apparent lack of positive variations. In fact, the same period saw the largest expansion of the Lys Glacier (and of most of the other glaciers in the area). The major negative front oscillations occurred in 1928, 1998, 2006, and 2012. As noted by Baronetti *et al.* (2020), in 1998 and 2012 significant and prolonged drought events occurred in the Western Italian Alps, extending to the Po River basin. From 2019 to 2021 the Indren Glacier has undergone a 24 m recession. The terminal sheet appears to be in disarray; this will most probably result in a dead glacier detachment in the coming years (Palomba *et al.*, 2022 in Baroni *et al.*, 2022).

The SAI FD (fig. 7) for the year 1928 is positive. The same year, the Indren Glacier was subject to a heavy retreat. This discordance is explained by the cause of the 1928 recession: it was due to a detachment from the glacier front during the winter coupled with low snow precipitations in the following spring (Monterin, 1929). The recession of 1998 is associated with slightly negative values of the SAI FD. The largest recession happened in the year 2006. It coincides with the two lowest annual SAI FD values of the Gabiet temperature series. The 2012 recession could not be linked to SAI FD due to the gaps in the Gabiet series. The three most important frontal recession years of the Indren Glacier (i.e. 1998, 2006, and 2012) were observed in the last two decades of the period analyzed. These results are in accordance with the temperature indices analysis performed for the Gabiet and Bocchetta delle Pisse series.

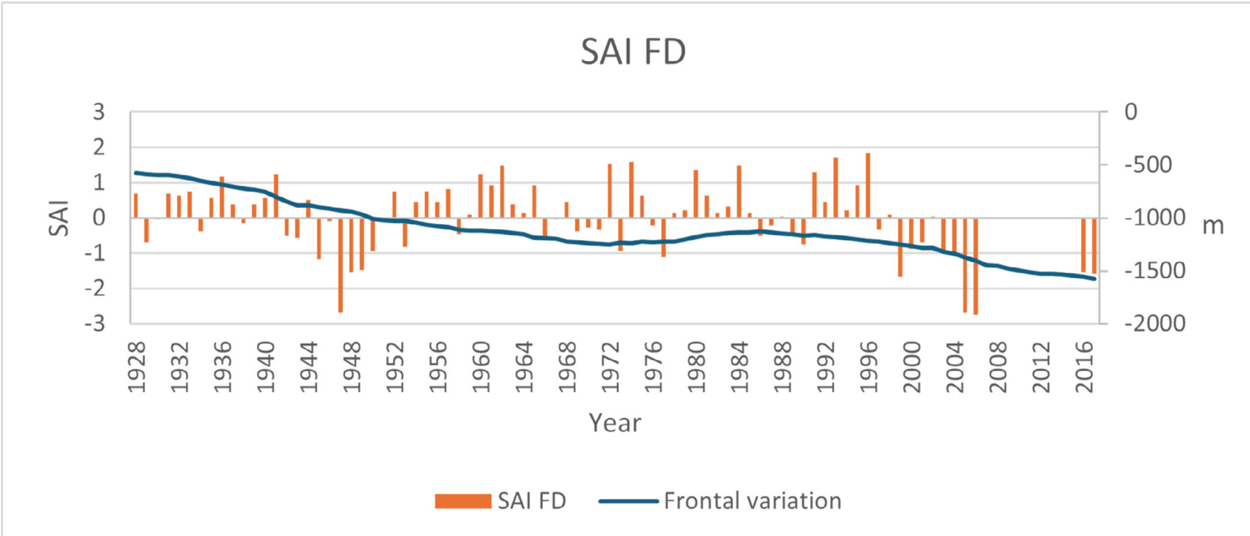

Figure 5 - Yearly SAI of the FD index (SAI FD) for the Gabiet temperature series (orange bars) plotted against the cumulative variation of the Lys glacier front.

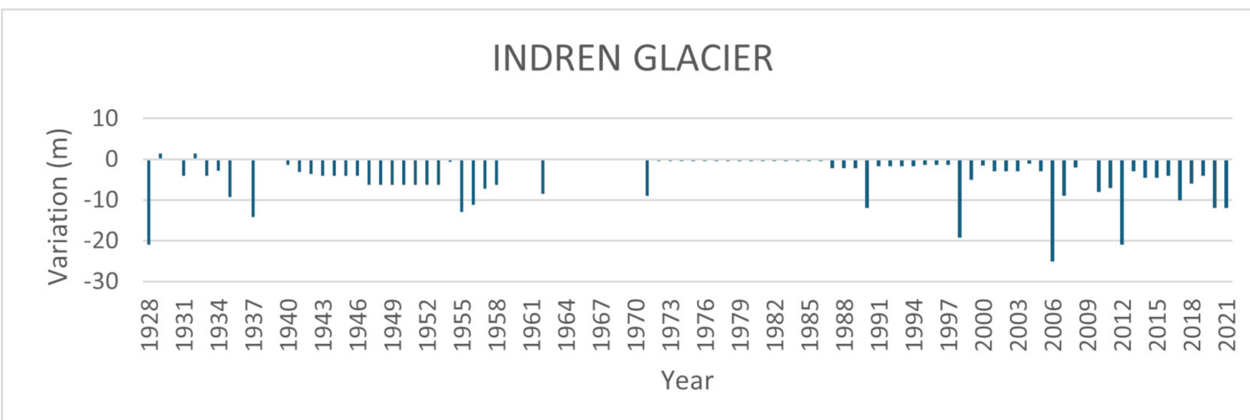

Figure 6 - Annual variation of the Indren Glacier front in the period 1928-2021.

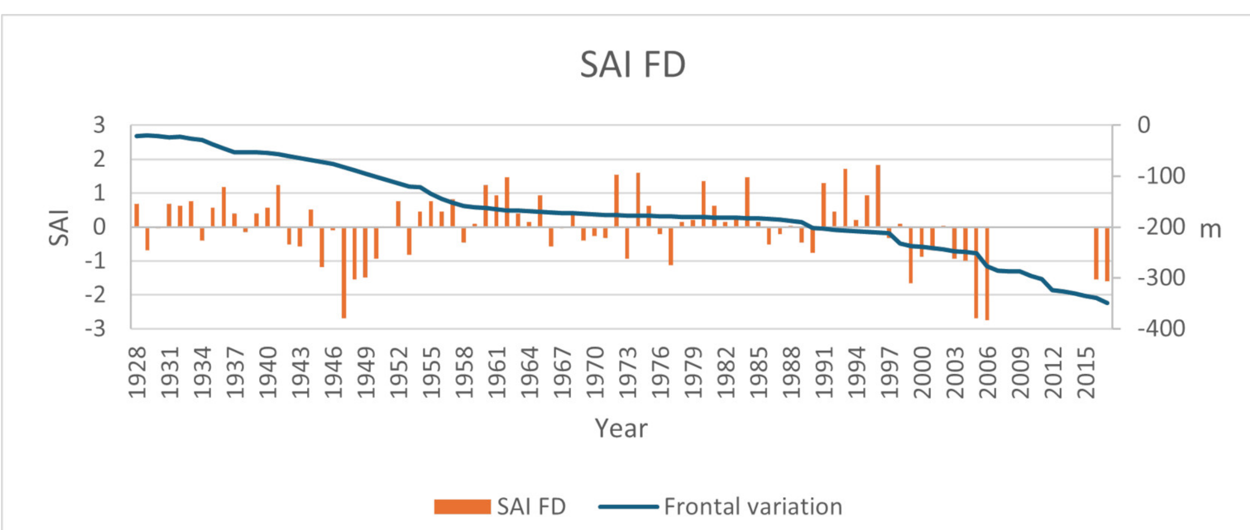

Figure 7 - Yearly SAI of the FD index (SAI FD) for the Gabiet temperature series (orange bars) plotted against the cumulative variation of the Indren glacier front.

The TN10p index trend suggests a general warming of the study area. This phenomenon, combined with the increase in length and frequency of drought events (e.g. Baronetti *et al.*, 2022; Chartier-Rescan *et al.*, 2025), negatively impacts the mass balance of glaciers on the Monte Rosa massif.

THE LABORATORY OF ALPINE CLIMATOLOGY – LABCLIMA

Our study stressed the lack of a network of sensors able to retrieve reliable and continuous weather data above 3000 m a.s.l., a zone characterized both by seasonal snow cover and the overall receding glaciers. We believed that such an asset could be invaluable to better investigate the impact of climate change on the Monte Rosa massif. The filling of this gap in the elevation distribution of data is one of the main reasons that led to the establishment of LabClima.

There are many examples of networks of automated stations in mountainous areas recording meteorological data in remote locations. Among them, the Mount Washington Observatory Regional Mesonet in North America (Fitzgerald *et al.*, 2023), and the SHARE network involving stations from Europe, Asia, Africa, and South America (Vuillermoz *et al.*, 2009). One of the most important and well-established networks of monitoring stations in mountain areas is the Intercantonal Measurement and Information System (IMIS). It was developed in the late 1990s by the Swiss Federal Institute for Snow and Avalanche Research (SLF) (Lehning *et al.*, 1999). IMIS began its activity in the 1996/1997 winter with a network of 20 installations. As of now, 189 IMIS stations located at high elevation (mostly in the range 2000-3000 m a.s.l.), provide weather and snow data to the SLF on a 30-minute basis. These data are used to assess avalanche hazards and other risks for the public, as well as being used as an input for the modelization of the snowpack state in the region through the SNOWPACK model simulations (Pérez-Guillén *et al.*, 2022; Mayer *et al.*, 2024).

The Laboratory of Alpine Climatology aims to reproduce the successes achieved by these international networks. Doing so in an area with a high scientific value and vocation that, prior to LabClima, lacked a similar diffuse structure. One of the most innovative aspects of the LabClima project is that its stations are designed not only to measure the main meteorological parameters (e.g. air temperature, relative humidity, wind speed and direction, precipitations), but to be equipped with state-of-the-art sensors recording some less inquired aspects of the remote Alpine environment.

The first station of the LabClima network was installed at Passo dei Salati, a mountain pass located at 3030 m a.s.l. at the junction of the Sesia and Lys valleys (i.e. the Piedmont and Aosta Valley sides of the lower Monte Rosa massif). The station location (45° 52’ 43” N, 7° 52’ 4” E) coincides with the shared arriving point of the lift facilities operating in Piedmont and Aosta Valley. It is also the base of the lift connecting to the Indren Glacier. Passo dei Salati is therefore easily reachable regardless of the region of departure. This feature, alongside its high elevation, made it an optimal site for the installation of the first station of the network. A second station of the LabClima network has been recently established (45° 53’ 46” N, 7° 50’ 55” E, 3455 m a.s.l.). It is located near the “Città di Mantova” Hut not far from the Lys, Garstelet, and Indren glaciers. The station, named Garstelet after its nearest glacier, became fully operational at the beginning of September 2024. Since then, it continuously records the main weather parameters, snow height, snow water equivalent, type of precipitation, and visibility.

LabClima deploys sensors for direct measurement of the equivalent mass of water of the snowpack (SWE) and the optical properties of snow. This kind of framework was never adopted in such elevated environments. One of the peculiarities of the LabClima is its vocation for transferring, testing and applying new research methodologies to the remote high mountainous environment where it resides. LabClima promotes the exchange of knowledge and collaboration among the working groups dealing with all the aspects of Alpine scientific research. Once validated, the data collected by LabClima would be made available to the public institutions in charge of monitoring and forecasting in the area (e.g. the ARPAs of Piedmont and Aosta Valley). This process should be smooth given the pre-existing research collaboration among the members of LabClima and the ones of the regional agencies operating on Monte Rosa.

LabClima is not only a research laboratory collecting data, but an entity which actively engages with the public aiming to promote a broaden sensibilization on impacts of climate change over the Alpine region, while advocating for a collective effort to tackle the challenges it poses.

Passo dei Salati and Garstelet automated weather stations

The automated weather station of Passo dei Salati (fig. 8) was installed in the summer of 2023. The station has been fully operational since October 2023. Its proximity with the lift facilities allows for some advantages which are not common for such elevations. In fact, thanks to the support of Monterosa2000 (the company managing the nearby skiing facilities) the station is connected to the electricity network of the nearby skiing infrastructure. This allows for a continuous energy supply without the need for batteries nor solar panels. In addition, the 4G networking coverage grants the transmission of the acquired data on near-real time. The available recording channels of the data logger installed at Passo dei Salati exceed the number of sensors currently operating. This feature is intended to allow for easier implementation of new sensors and experimental layouts in future seasons. In case any criticalities arise with the equipped instruments, the station is easily reachable, allowing for fast, safe, and relatively cheap interventions by technicians and researchers. Despite its proximity to the lift facilities, the station is not affected by the presence of skiers and tourists, who could inadvertently damage the sensors installed. This is because the station was intentionally laid on an area outside of any ski trail and accessible only by authorized personnel.

Passo dei Salati measures the main meteorological parameters (e.g. air temperature, relative humidity, wind speed and direction, and precipitation) as well as the height of the snowpack (Table 3). Each datum is registered with a 10-minute frequency, resulting in 144 data per day. For most of the variables collected, the datum represents the point value registered by the sensor at the reference time; the exceptions being: the wind speed and direction, and the precipitation. The former are an average of the values recorded during the 10-minute time span; the latter represents the cumulative values among the period.

The station has two different types of rain gauges: tipping bucket and weighing. This redundancy is intended to compare the performances of the instruments and offers a continuous backup of the precipitation measures in the event of a malfunction affecting one of the rain gauges. Both the gauges are heated, allowing for an estimate of snow precipitations.

Figure 8 - The Passo dei Salati Station. The two rain gauges are visible in the foreground (weighing and, behind it, the tipping bucket); in the background is visible the pole with the anemometer (top of the pole), the snow meter (right branch), the RoX (upper left branch), and the thermo-hygrometer (lower left branch).

Table 3 - Summary of the sensors installed at the Passo dei Salati station (3030 m a.s.l.).

Type of sensor	Variable(s) measured
Thermo-hygrometer	Air Temperature and Relative Humidity
Ultrasonic Anemometer	Wind Speed and Direction
Rain Gauge (Tipping Bucket)	Precipitation
Rain Gauge (Weighing)	Precipitation
Nivometer	Snow Height

The Garstelet station is the most elevated of the LabClima network and the second to become operational. Its data acquisition started in September 2024. Compared to Passo dei Salati, it is not easily accessible during the whole year. The maintenance activities have to be performed during the summer months when the milder weather conditions allow to operate with a helicopter, which is the only viable mean of transport for the necessary equipment. Nevertheless, the Garstelet station has a crucial role in collecting weather parameters and snowpack data in a zone affected by a lack of similar data.

To address the existing lack of reliable data at high elevation, the Garstelet station is equipped with more sensors (Table 4) compared to Passo dei Salati. Garstelet records the same main meteorological parameters as Passo dei Salati, with the addition of air pressure, incoming, reflected, and net solar radiation both Long-Wave and Short-Wave (LW and SW). A present weather optical sensor allows measurements of type, size, and fall speed of precipitation particles. It also gives information on the visibility at the site, estimating the Meteorological Observable Range (MOR). Snow meter measurements are supported by temperature acquired by a thermometric array consisting of five thermometers installed at 50 cm vertical distance from one another. The operating range of this array goes from the ground levele up to 200 cm. Similar to Passo dei Salati, all the sensors at Garstelet record at a 10-minutes frequency, granting an accurate description of the weather and snow state nearly at real time.

Table 4 - summary of the sensors installed at the Garstelet station (3455 m a.s.l.).

Type of sensor	Variable(s) measured
Thermo-hygrometer	Air Temperature and Relative Humidity
Anemometer	Wind Speed and Direction
Rain Gauge (Weighing)	Precipitation
Barometer	Air Pressure
Nivometer	Snow Height
Thermometric Array	Snowpack Temperature
Present Weather Sensor	Precipitation Particles Type, Size and Fall Speed Meteorological Observable Range
Radiometer	Upward and Downward Radiation (Short and Long Wave)

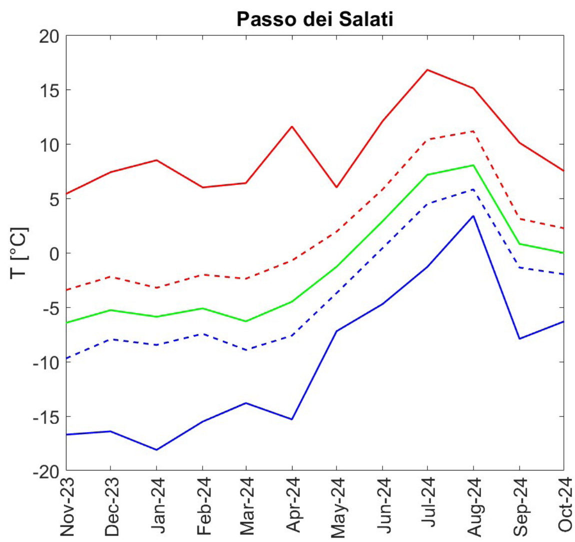

Figure 9 - Graphical representation of the temperature measured at Passo dei Salati during the period 01/11/2023 - 31/10/2024. In order: absolute maximum temperatures for each month (red), monthly average of the daily maximum temperatures (pink), mean monthly temperature (green), monthly average of the daily minimum temperatures (cyan), absolute minimum temperature for each month (blue).

First year overview of Passo dei Salati

Fig. 9 shows the main features of the temperatures measured during the first year of activity of the Passo dei Salati from 01/11/2023 to 31/10/2024. On average, the air temperature was -1.3 °C. The coldest month on average was November (-6.4 °C), followed by January (-6.3 °C). The hottest month was August (8.0 °C), almost a whole degree hotter than the second (July, 7.1 °C). The highest temperature of the series is 16.8 °C, recorded on 30/07/2024 at 14:40 UTC+1. The lowest value is -18.1 °C, recorded on 20/01/2024 at 05:20 UTC+1. Slightly more than a week later, on 29/01/2024 at 12:30 UTC+1, the station recorded 8.5 °C: an increase of more than 25 °C. This unusually warm condition was associated with a foehn (Brinkmann, 1971) event that interested the western Alps during the last days of January 2024. It caused a general rise in temperatures among the region, a common feature of these phenomena (Elvidge and Renfrew, 2015).

From November 2023 to October 2024, of the 52704 theoretically available wind data registered every 10 minutes, 3266 were considered invalid. Those values, occurring almost exclusively in the cold months, are related to snow or ice stuck in the anemometer cavity. Despite these problematic events (which were to be expected during the snowing season at such elevation), the sensor yielded a percentage of valid data equal to 92.8%.

The first year of data suggests that the station is not often subject to strong wind activity (see fig. 10a). The average wind speed is 3.7 m/s with 81.7% of the speeds recorded being equal or lesser than 6 m/s.

The range of directions more frequently observed for the winds at Passo dei Salati is 225° - 270° (i.e. SW to W) with the winds blowing from WSW holding the highest frequency at 20.8%.

Even though the wind speeds equal or higher than 10 m/s account only for the 3.7%, studying their distribution can give more insight about important phenomena for the research area such as foehn winds and wind-related snow ablation. The preferred blowing direction for strong winds (fig. 10b) is in the range 0° - 45° (i.e. N to NW). It accounts for 46.3% of the measurements considered. The peak direction frequency (22.8%) is NNW. The distribution of strong winds at Passo dei Salati retains some characteristics from the general wind rose: the secondary peak is associated to WSW, the major direction for the totality of the winds measured. Further investigation and prolonged data acquisition could permit to assess how the air currents distribution is affected by the jet stream and the passage of fronts over the mountain ridge.

LabClima's developing network could contribute to assessing the wind influence on snow accumulation and transport. Its continuous data encourages further research on the possible coupling the wind regimes and snowpack formation and development on the Monte Rosa massif.

Innovative Sensors for snow-related data

LabClima's data acquisition is not centered only on the main meteorological variables typical of automated weather stations. A special focus is given to the adoption and installation of sensors measuring two aspects of the snowpack: its optical properties and the equivalent water mass it yields (e.g. the snow water equivalent or SWE).

Knowing the optical properties of the snow cover is essential for the assessment of snowpack microphysical properties. It also allows to integrate the remote-sensing multispectral data obtained by satellites (Salzano *et al.*, 2021).

The framework of the Laboratory of Alpine Climatology deploys a set of sensors to collect reflectance and albedo data in multiple spectral wavelengths.

Passo dei Salati is equipped with the RoX, an automatic hyperspectral albedometer produced by JB-Hyperspectral Devices GmbH. It operates in the visible (VIS) and near infrared (NIR) bands (e.g. from 450 nm to 900 nm). The implementation of similar instruments has given successful results in polar areas (Picard *et al.*, 2016, Picard *et al.*, 2020).

The RoX records downward and upward solar radiation, giving an estimate of reflectance and albedo in any band of interest in its working spectrum.

Additional sensors operating in the shortwave infrared (SWIR), namely in the 1300 nm and 1600 nm bands will be deployed at Passo dei Salati.

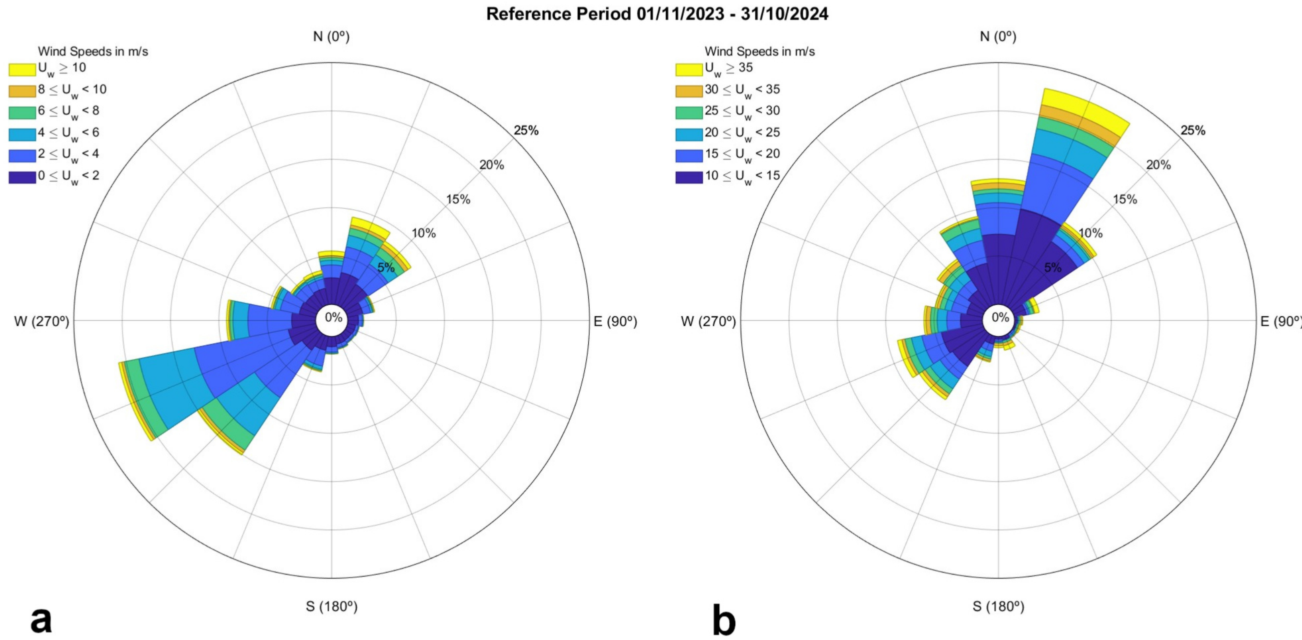

Figure 10 - Windroses representing the distribution of wind speed and direction measured at Passo dei Salati. Panel a: all the valid measures; Panel b: winds with speed above 10 m/s.

The Snow Water Equivalent (SWE) expresses the mass of water that would result from a complete melting of the snowpack. It is an important variable for evaluating the hydrological balance in mountain regions, especially given the potential impact of climate change on high elevation sites (Barnett *et al.*, 2005).

Standard SWE measurements consist of an *in situ* survey performed with a snow pit (Goodinson *et al.*, 1987), an invasive operation that cannot be performed with high temporal frequency at relatively low costs. In alternative, it is common practice to derive SWE from snow height adopting parametrizations and performing numerical simulations (Bartelt and Lehning 2002, Sturm *et al.*, 2010, Pistocchi 2016). However, values of SWE obtained from models inherit errors due to the parameterizations adopted to estimate the snow density.

To get continuous and reliable SWE data, LabClima is testing SWE sensors based on two technologies: Cosmic Ray Neutron Sensing (CRNS) and GNSS signal delay sensors.

CRNS was initially proposed to estimate soil moisture (Zreda *et al.*, 2006). It can be applied to snow covered regions by placing two coupled sensors: one above the snowpack measuring the incoming cosmic rays flux, the other on the ground measuring neutron flux attenuated by the snow layer (Schattan *et al.*, 2017). This kind of sensor is completely automated, giving continuous measures of SWE and having the advantage of allowing for soil moisture measurements when the snow cover is absent.

The Global Navigation Satellite System (GNSS) sensors consist of antennas coupled and placed below and above the snow, with the latter serving as reference (Henkel *et al.*, 2018). This technology has already been applied to Alpine regions yielding promising results with relatively low costs. The same sensor is able to measure SWE, snowpack liquid water content (LW), and snow height (Koch *et al.*, 2019, Capelli *et al.*, 2022). A sensor based on this technology is currently operating at Garstelet alongside a CRNS sensor. The testing of the two technologies at the same site will allow for data comparison and validation through standard-acquired SWE measurements.

CONCLUSIONS

The Monte Rosa massif is a relevant location to understand the impact of climate change on the Alpine cryosphere. Our analysis of the temperature series of Gabiet and Bocchetta delle Pisse confirmed that the area is undergoing a warming process. The climate indices and their trends in the last two decades suggest that both the minimum and maximum temperatures were subject to a stable increase. It is of particular concern the rise in minimum temperatures because it compromises the status of the many glaciers of the massif. Our analysis highlights a decreasing trend in the TN10p index at Bocchetta delle Pisse (-0.42%/year) and Gabiet (-0.54%/year).

The analysis of 90 years of data, from 1928 to 2017, of frontal oscillations of the Lys and Indren Glaciers showed a net retreat for both the ice masses. Intense negative oscillations have become more frequent in recent years. This can be linked to the warming emerging by the temperature analysis. Both glaciers experienced significant retreats during the years characterized by severe and prolonged drought events. In particular, the Lys Glacier experienced the most severe frontal regression between 2003 and 2007, losing 165 m. Our analysis shows that this period coincides with low SAI FD in the Gabiet series. In 2006 the Indren Glacier experienced its most relevant recession over the period analyzed. This event was preceded by the two lowest SAI FD values of the series. In addition, the three most important recessions of the Indren Glacier happened in the last two decades of the period taken into consideration (in 1998, 2006, and 2012) Among those years, 1998 and 2012 were characterized by intense drought events involving the Po River basin.

During our research activity in the Monte Rosa area, we noted a gap in the elevation range represented by the data available. None of the four active weather stations of Monte Rosa were between 3000 m a.s.l. and 4000 m a.s.l.. This existing gap prompted the establishment of the Laboratory of Alpine Climatology – LabClima.

LabClima is a developing network of monitoring stations in the Western Alps. Its first fully operational high elevation station, located at Passo dei Salati on the Monte Rosa massif (Italy), has recently seen its first year of activity. It collects data on the main meteorological variables. A second station, named Garstelet and located at 3455 m a.s.l., was established in September 2024. Addressing the lack of reliable and continuous data at these elevations is of the most importance. It could greatly help assess the impact of climate change in an area with significant environmental, cultural, and economic value. LabClima activities focus also on public engagement, raising the attention given to the fragility of the Alpine region due to global warming.

Innovative sensors are being deployed in the LabClima framework. They focus on measurements of crucial aspects of the seasonal snowpack: its optical properties and the SWE.

Measures of snow cover reflectance on multiple bands, from visible shortwave infrared, will yield important information on the snow properties and could be used to improve satellite data.

The adoption of SWE sensors based on CRNS and GNSS technologies addresses the need for data retaining a high precision and temporal density.

LabClima aims to further develop its network of stations with new installations at different sites. It also intends to deploy new sensors and instruments, prioritizing the transfer, testing and application of methodologies new to the high elevation Alpine environment.

The activities carried out by LabClima aim to improve current knowledge not only in the field of climatology, but also in all areas of research concerning the Alps. For this reason, the laboratory is open to collaboration with institutions, organizations, and working groups that could benefit from the development of its unique network.

AUTHORS CONTRIBUTION

MG and AM performed the analysis on the temperature series. AG and CV performed the analysis on the Lys and Indren Glaciers. MG performed the analysis on the Passo dei Salati dataset. CV realized the map presented in fig. 1. AB analyzed the relation between frontal oscillations and drought events. FA and MA conceived the work. MG wrote the paper with the contribution of all the Authors. FA acquired financial support.

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DATA AVAILABILITY

The data will be made available upon reasonable request to the corresponding author.

REFERENCES

Acquaotta F., Fratianni S., Garzena D., 2015. *Temperature changes in the North-Western Italian Alps from 1961 to 2010*. Theoretical and Applied Climatology, 122 (3-4), 619-6341. https://doi.org/10.1007/s00704-014-1316-7

Auer I., Böhm R., Jurkovic A., Lipa W., Orlik A., Potzmann R., Schöner W., Ungersböck M., Matulla C., Briffa K., Jones P., Efthymiadis D., Brunetti M., Nanni T., Maugeri M., Mercalli L., Mestre O., Moisselin J.M., Begert M., Müller-Westermeier G., Kveton V., Bochnicek O., Stastny P., Lapin M., Szalai S., Szentimrey T., Cegnar T., Dolinar M., Gajic-Capka M., Zaninovic K., Majstorovic Z., Nieplova E., 2007. *HISTALP – historical instrumental climatological surface time series of the Greater Alpine Region*, International Journal of Climatology, 27, 17-46. https://doi.org/10.1002/joc.1377

Baronetti A., Acquaotta F., Fratianni S., 2018. *Rainfall variability from a dense rain gauge network in North-West Italy*, Climate Research, 75 (3), 201-213. https://doi.org/10.3354/cr01517

Baronetti A., González-Hidalgo J.C., Vicente-Serrano S.M., Acquaotta F., Fratianni S., 2020. *A weekly spatio-temporal distribution of drought events over the Po Plain (North Italy) in the last five decades*, International Journal of Climatology, 40, 4463-4476. https://doi.org/10.1002/joc.6467

Baronetti A., Dubreuil V., Provenzale A., Fratianni S., 2022. *Future droughts in northern Italy: high-resolution projections using EURO-CORDEX and MED-CORDEX ensembles*. Climatic Change, 172 (3), 22. https://doi.org/10.1007/s10584-022-03370-7

Baroni C., Bondesan, A., Carturan L., Chiarle, M. (Eds), 2019. *Annual glaciological survey of Italian glaciers (2018) - Campagna glaciologica annuale dei ghiacciai italiani (2018).* Geografia Fisica e Dinamica Quaternaria, 42 (2), 113-202. doi: 10.4461/GFDQ.2019.42.9

Baroni C., Bondesan A., Carturan L., Chiarle M., Scotti R. (Eds), 2022. *Annual glaciological survey of Italian glaciers (2021) - Campagna glaciologica annuale dei ghiacciai italiani (2021).* Geografia Fisica e Dinamica Quaternaria, 45 (1), 69-167. https://doi.org/10.4461/GFDQ.2022.45.5

Brinkmann W.A.R., 1971. *What is a Foehn?,* Weather, 26, 230-240. https://doi.org/10.1002/j.1477-8696.1971.tb04200.x

Barnett T., Adam J., Lettenmaier D., 2005. *Potential impacts of a warming climate on water availability in snow-dominated regions*, Nature, 438, 303-309. https://doi.org/10.1038/nature04141

Bartelt P., Lehning M., 2002. *A physical SNOWPACK model for the Swiss avalanche warning: Part I: numerical model*, Cold Regions Science and Technology, 35, 123-145. https://doi.org/10.1016/S0165-232X(02)00074-5

Beniston M., 2006. *Mountain weather and climate: a general overview and a focus on climatic change in the Alps*, Hydrobiologia, 562, 3-16. https://doi.org/10.1007/s10750-005-1802-0

Bonardo V., Giardino M., 2020. *La carovana dei ghiacciai 2020*. Comitato Glaciologico Italiano, Torino.

Bozzoli M., Crespi A., Matiu M., Majone B., Giovannini L., Zardi D., Brugnara Y., Bozzo A., Cat Berro D., Mercalli L., Bertoldi G., 2024. *Long-term snowfall trends and variability in the Alps*, International Journal of Climatology, 44 (13), 4571-4591. https://doi.org/10.1002/joc.8597

Brugnara Y., Maugeri M., 2019. *Daily precipitation variability in the southern Alps since the late 19th century.* International Journal of Climatology, 39, 3492-3504. https://doi.org/10.1002/joc.6034

Capelli A., Koch F., Henkel P., Lamm M., Appel F., Marty C., Schweizer J., 2022. *GNSS signal-based snow water equivalent determination for different snowpack conditions along a steep elevation gradient*, The Cryosphere, 16, 505-531, https://doi.org/10.5194/tc-16-505-2022

Chartier-Rescan C., Wood R.R., Brunner M.I., 2025. *Snow drought propagation and its impacts on streamflow drought in the Alps*, Environmental Research Letters, 20, 054032. https://doi.org/ 10.1088/1748-9326/adc824

Colombo N., Salerno F., Martin M., Malandrino M., Giardino M., Serra E., Godone D., Said-Pullicino D., Fratianni S., Paro L., Tartari G., Freppaz M., 2019. *Influence of permafrost, rock and ice glaciers on chemistry of high-elevation ponds (NW Italian Alps)*, Science of the Total Environment, 685, 886-901. https://doi.org/10.1016/j.scitotenv.2019.06.233

Dainelli G., 1902. *Alcune osservazioni sui ghiacciai del versante italiano del Monte Rosa*. Bollettino del C.A.I. 68, XXXV, 5-64.

Damm B., Felderer, A., 2013. *Impact of atmospheric warming on permafrost degradation and debris flow initiation: a case study from the eastern European Alps*, E&G Quaternary Science Journal, 62, 136-149. https://doi.org/10.3285/eg.62.2.05

De Gemini F., Valtz L., Monterin W., Gatti G., De Maria D., 1956. *Gruppo del Monte Rosa*. In: *Relazioni delle Campagne Glaciologiche 1955.* Bollettino del Comitato Glaciologico Italiano II, 7, 137-142.

Elvidge A., Renfrew, I., 2015. *The Ccauses of Foehn warming in the Lee of Mountains*, Bulletin of the American Meteorological Society, 97, 455-466. https://doi.org/10.1175/BAMS-D-14-00194.1.

Fitzgerald B.J., Broccolo J., Garrett K., 2023. *The Mount Washington observatory regional mesonet: a technical overview of a mountain-based mesonet*, Journal of Atmospheric and Oceanic Technology, 40, 439-453. https://doi.org/10.1175/JTECH-D-22-0054.1

Freppaz M., Viglietti D., Balestrini R., Lonati M., Colombo N., 2019. *Climatic and pedoclimatic factors driving C and N dynamics in soil and surface water in the alpine tundra (NW-Italian Alps).* Nature Conservation, 34, 67-90. https://doi.org/10.3897/natureconservation.34.30737

Gobiet A., Kotlarski S., Beniston M., Heinrich G., Rajczak J., Stoffel M., 2014, *21st century climate change in the European Alps. A review*, Science of The Total Environment, 493, 1138-1151. https://doi.org/10.1016/j.scitotenv.2013.07.050.

Goodison B.E., Glynn J.E., Harvey K.D., Slater J.E., 1987, *Snow surveying in Canada: a perspective*, Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques, 12 (2), 27-42. https://doi.org/10.4296/cwrj1202027

Haberkorn A., Kenner R., Noetzli J., Phillips M., 2021, *Changes in ground temperature and dynamics in mountain permafrost in the Swiss Alps.* Frontiers in Earth Science, 9-626686. https://doi.org/10.3389/feart.2021.626686

Henkel P., Koch F., Appel F., Bach H., Prasch M., Schmid L., Schweizer J., Mauser W., 2018, *Snow water equivalent of dry snow derived from GNSS Carrier Phases*, IEEE Transactions on Geoscience and Remote Sensing, 1-12. https://doi.org/10.1109/TGRS.2018.2802494.

Hock R., Rasul G., Adler C., Cáceres B., Gruber S., Hirabayashi Y., Jackson M., Kääb A., Kang S., Kutuzov S., Milner A., Molau U., Morin S., Orlove B., Steltzer H., 2019. *High mountain areas*, IPCC special report on the ocean and cryosphere in a changing climate, 131-202. https://doi.org/10.1017/9781009157964.004

Hugonnet R., McNabb R., Berthier E., Menounos B., Nuth C., Girod L., Farinotti D., Huss M., Dussaillant I., Brun F., Kæb A., 2021. *Accelerated global glacier mass loss in the early twenty-first century*, Nature, 592, 726-731. https://doi.org/10.1038/s41586-021-03436-z

IPCC, Masson-Delmotte V., Zhai P., Pirani A., Connors S.L., Péan C., Berger S., Caud N., Chen Y., Goldfarb L., Gomis M.I., Huang M., Leitzell K., Lonnoy E., Matthews J.B.R., Maycock T.K., Waterfield T., Yelekçi O., Yu R., Zhou B. (Eds), 2021. *Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge (UK)-New York (NY), 2391 pp. https://doi.org/10.1017/9781009157896

Katz R.W., Glantz M.H., 1986. *Anatomy of a rainfall index*. Monthly Weather Review, 114, 764-771. https://doi.org/10.1175/1520-0493(1986)114<0764:AOARI>2.0.CO;2

Kendall M.G., 1975. *Rank Correlation Methods*, 4th edition, Charles Griffin, London.

Koch F., Henkel P., Appel F., Schmid L., Bach H., Lamm M., 2019. *Retrieval of snow water equivalent, liquid water content, and snow heightof dry and wet snow by combining GPS signal attenuation and time delay*, Water Resources Research, 55, 4465-4487. https://doi.org/10.1029/2018WR024431

Lehning M., Bartelt P., Brown B., Russi T., Stöckli U., Zimmerli M., 1999. *Snowpack model calculations for avalanche warning based upon a new network of weather and snow stations*, Cold Regions Science and Technology, 30 (1-3), 145-157, https://doi.org/10.1016/S0165-232X(99)00022-1

Mann H.B., 1945. *Non-parametric tests against trend*, Econometrica, 13, 163-171.

Mayer S., Hendrick M., Michel A., Richter B., Schweizer J., Wernli H., van Herwijnen A., 2024. *Impact of climate change on snow avalanche activity in the Swiss Alps*, The Cryosphere, 18, 5495-5517. https://doi.org/10.5194/tc-18-5495-2024, 2024

Mercalli L., Biancotti A., Cerutti A.V., 1991. *La montagna di ghiaccio - Storia dei ghiacciai italiani del Monte Rosa*. Walser Kulturzentrum e Comitato Glaciologico italiano, Gressoney-St-Jean.

Mercalli L., Cat Berro D., Montuschi S., Castellano C., Ratti M., Di Napoli G., Mortara G., Guindani N., 2003. *Atlante climatico della Valle d'Aosta*. SMS, Torino, 416 pp.

Monterin U., 1929. *Gruppo del Monte Rosa*. In: *Relazioni delle Campagne Glaciologiche del 1928*. Bollettino del Comitato Glaciologico Italiano I, 9, 266-269.

Monterin U., 1932. *Le oscillazioni del Ghiacciaio del Lys dal 1789 al 1931*. In: *Le variazioni secolari del clima del Gran San Bernardo: 1818-1931* e *Le oscillazioni del Ghiacciaio del Lys al Monte Rosa: 1789-1931*. Bollettino del Comitato Glaciologico Italiano I, 12, 60-106.

Palomba M., Giuliano M., Freppaz M., Piccini P., Princisvalle T., Viani C., Sergio L., Mortara G., Tamburini A., Versaci S., 2019. *Gruppo del Monte Rosa*. In: Baroni C., Bondesan, A., Carturan L., Chiarle, M. (Eds), *Annual glaciological survey of Italian glaciers (2018) - Campagna glaciologica annuale dei ghiacciai italiani (2018)*. Geografia Fisica e Dinamica Quaternaria, 42 (2), 113-202. doi: 10.4461/GFDQ.2019.42.9

Palomba M., Giuliano M., Piccini P., Princisvalle T., Viani C., Tamburini A., Mortara G., Versaci S., 2022. *Gruppo del Monte Rosa*. In: Baroni C., Bondesan A., Carturan L., Chiarle M., Scotti R. (Eds), A*nnual glaciological survey of Italian glaciers (2021) - Campagna glaciologica annuale dei ghiacciai italiani (2021)*. Geografia Fisica e Dinamica Quaternaria, 45 (1), 69-167. https://doi.org/10.4461/GFDQ.2022.45.5

Pavan V., Antolini G., Barbiero R., Berni N., Brunier F., Cacciamani C., Cagnati A., Cazzuli O., Cicogna A., De Luigi C., Di Carlo E., Francioni M., Maraldo L., Marigo G., Micheletti S., Onorato L., Panettieri E., Pellegrini U., Pelosini R., Piccinini D., Ratto S., Ronchi C., Rusca L., Sofia S., Stelluti M., Tomozeiu R., Torrigiani Malaspina T., 2019. *High resolution climate precipitation analysis for north-central Italy, 1961-2015*, Climate Dynamics, 52, 3435-3453. https://doi.org/10.1007/s00382-018-4337-6

Pérez-Guillén C., Techel F., Hendrick M., Volpi M., van Herwijnen A., Olevski T., Obozinski G., Pérez-Cruz F., Schweizer, J., 2022. *Data-driven automated predictions of the avalanche danger level for dry-snow conditions in Switzerland*, Natural Hazards and Earth System Sciences, 22, 2031-2056. https://doi.org/10.5194/nhess-22-2031-2022

Picard G., Libois Q., Arnaud L., Verin G., Dumont M., 2016. *Development and calibration of an automatic spectral albedometer to estimate near-surface snow SSA time series*, The Cryosphere, 10, 1297-1316. https://doi.org/10.5194/tc-10-1297-2016

Picard G., Dumont M., Lamare M., Tuzet F., Larue F., Pirazzini R., Arnaud L., 2020. *Spectral albedo measurements over snow-covered slopes: theory and slope effect corrections*, The Cryosphere, 14, 1497-1517. https://doi.org/10.5194/tc-14-1497-2020

Pintaldi E., D'Amico M.E., Colombo N., Colombero C., Sambuelli L., De Regibus C., Franco D., Perotti L., Paro L., Freppaz M., 2021. *Hidden soils and their carbon stocks at high-elevation in the European Alps (North-West Italy)*. CATENA, 198. https://doi.org/10.1016/j.catena.2020.104700

Pistocchi A., 2016. *Simple estimation of snow density in an Alpine region*, Journal of Hydrology: Regional Studies, 6, 82-89. https://doi.org/10.1016/j.ejrh.2016.03.004

Rumpf S.B., Gravey M., Brönnimann O., Luoto M., Cianfrani C., Mariethoz G., Guisan A., 2022. *From white to green: Snow cover loss and increased vegetation productivity in the European Alps*, Science, 376 (6597), 1119-1122. https://doi.org/10.1126/science.abn6697

Salvatore M.C., Zanoner T., Baroni C., Carton A., Banchieri F.A., Viani C., Giardino M., Perotti L., 2015. *The state of italian glaciers: a snapshot of the 2006-2007 hydrological period*, Geografia Fisica e Dinamica Quaternaria, 38 (2), 175-198. https://doi.org/10.4461/GFDQ.2015.38.16

Salzano R., Lanconelli C., Esposito G., Giusto M., Montagnoli M., Salvatori R., 2021. *On the Seasonality of the Snow Optical Behaviour at Ny Ålesund (Svalbard Islands, Norway)*, Geosciences, 11, 112. https://doi.org/10.3390/geosciences11030112

Schattan P., Baroni G., Oswald S.E., Schober J., Fey C., Kormann C., Huttenlau M., Achleitner S., 2017. *Continuous monitoring of snowpack dynamics in alpine terrain by aboveground neutron sensing*, Water Resources Research, 53, 3615-3634. https://doi.org/10.1002/2016WR020234

Shahgedanova M., Adler C., Gebrekirstos A., Grau H.R., Huggel C., Marchant R., Pepin N., Vanacker V., Viviroli D., Vuille M., 2021. *Mountain Observatories: Status and Prospects for Enhancing and Connecting a Global Community*, Mountain Research and Development, 41 (2), A1-A15. https://doi.org/10.1659/MRD-JOURNAL-D-20-00054.1

Smiraglia C., Diolaiuti G. (Eds), 2015. *Il nuovo catasto dei ghiacciai italiani*. Ev-K2_CNR Ed., Bergamo, 400 pp.

Sturm M., Taras B., Liston G.E., Derksen C., Jonas T., Lea J., 2010. *Estimating snow water equivalent using snow depth data and climate classes,* Journal of Hydrometeorology, 11, 1380-1394. https://doi.org/10.1175/2010JHM1202.1

The GlaMBIE Team, 2025. *Community estimate of global glacier mass changes from 2000 to 2023*, Nature, 639, 382-388. https://doi.org/10.1038/s41586-024-08545-z

Tognetto F., Perotti L., Viani C., Colombo N., Giardino M., 2021. *Geomorphology and geosystem services of the Indren-Cimalegna area (Monte Rosa massif - Western Italian Alps)*, Journal of Maps, 17 (2), 161–172. https://doi.org/10.1080/17445647.2021.1898484

Viani C., Machguth H., Huggel C., Godio A., Franco D., Perotti L., Giardino, M., 2020. *Potential future lakes from continued glacier shrinkage in the Aosta Valley Region (Western Alps, Italy)*, Geomorphology, 355. https://doi.org/https://doi.org/10.1016/j.geomorph.2020.107068

Vione D., Colombo N., Said-Pullicino D., Bocchiola D., Confortola G., Salerno F., Viviano G., Fratianni S., Martin M., Godone D., Freppaz M., 2021. *Seasonal variations in the optical characteristics of dissolved organic matter in glacial pond water*, Science of The Total Environment, 759. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.143464

Viviroli D., Archer D.R., Buytaert W., Fowler H.J., Greenwood G.B., Hamlet A.F., Huang Y., Koboltschnig G., Litaor M.I., López-Moreno J.I., Lorentz S., Schädler B., Schreier H., Schwaiger K., Vuille M., Woods R., 2011. *Climate change and mountain water resources: overview and recommendations for research, management and policy*, Hydrology and Earth System Sciences, 15, 471-504. https://doi.org/10.5194/hess-15-471-2011

Vuillermoz E., Lami A., Tartari G., Schommer B., Toffolon R., Bonasoni P., 2009. *SHARE - Stations at high altitude for research in the environment. An integrated project for monitoring and environmental research in mountain regions*. In: Nationalpark Hohe Tauern - Conference v. 4, 329.331.

Zekollari H., Huss M., Farinotti D., 2019. *Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble*. The Cryosphere, 13 (4), 1125-1146. https://doi.org/10.5194/tc-13-1125-2019

Zhang X., Alexander L., Hegerl G.C., Jones P., Tank A.K., Peterson T.C., Trewin B., Zwiers F.W., 2011. *Indices for monitoring changes in extremes based on daily temperature and precipitation data*, Wiley Interdisciplinary Reviews: Climate Change, 2, 851-870. http://dx.doi.org/10.1002/wcc.147

Zimmermann N.E., Gebetsroither E., Zuger J., 2013. *Future Climate of the European Alps*. In: Cerbu G. (Ed.), *Management strategies to adapt Alpine space forests to climate change risks*, 27-36. In Tech, Rijeka, Croatia. https://doi.org/10.5772/56278

Zreda M., Desilets D., Ferré T.P.A., Scott R.L., 2008. *Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons*, Geophysical Research Letters, 35, L21402. https://doi.org/10.1029/2008GL035655

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