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RESEARCH ARTICLE

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New insights into the world's longest series of monthly snowfall (Parma, Northern Italy, 1777–2018)

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Abstract

The emergence of decreasing trends in snowfall frequency and snow depth highlights the challenges arising from shifts in snow regimes. In particular, snow-dependent southern Europe regions may be negatively impacted by such changes. Snow regimes strongly influence the water availability in reservoirs and groundwater. This study presents the world's longest series of monthly snowfall (fresh snow depth, snow days per year, days with snow on the ground) for the Parma Observatory, northern Italy (44°48′N and 10°19′E) between 1777 and 2018. These datasets were collected over the centuries using early rain gauges and recently, SIAP tipping bucket models. Sources of inhomogeneity were identified and analysed through the study of metadata and of non-parametric tests on datasets. Homogenized time series were obtained after correcting the observed snowfall data for the instruments response and localization characteristics, for the observing practices with the help of the standard normal homogeneity tests. The Buishand and the Mann–Kendall tests were further applied to check the correction and detect possible monotonic trends. Over the study period, days per year of snow decreased after the change point detected in 1897, in association with a rise in surface air temperature (including a distinct urban warming trend). In this study high numbers of snowy days per year (hereafter referred as snowfall frequency) and snow depth values during the latest phase of the LIA at Parma are consistent with a cycle of minimum solar activity, suggesting that enhanced, solar-induced blocking activity dominated, with the arrival into the Mediterranean of large cold air masses developing over Siberia and northern Europe. Over the last century, snow appears to have resonance-like characteristics as similar trends were observed over the Northern Hemisphere, where the extent of the snow cover has been reported to markedly decline in the transition spring and autumn seasons.

KEYWORDS

historical series, meteorological observations, Parma, rain gauge, snowfall

1 | INTRODUCTION

A quantitative assessment of the long-term and inter-annual variability of seasonal snowfall is important for the identification and detection of signals of climate change, the validation of climate models, and a better understanding of the interactions among atmosphere, hydrosphere and cryosphere (Brown, 2014). By delaying the transfer of precipitation to surface runoff and infiltration, snow storage affects the timing and magnitude of water flows peak as generated by snowmelt (Wang *et al.*, 2016). As well, it influences streamflow recession in watersheds (Yarnell *et al.*, 2010) and the extent of the stream network during summer baseflow (Godsey *et al.*, 2014). Documentary evidence provides an opportunity to study climate over historical periods (Dobrovolný *et al.*, 2009; Glaser and Riemann, 2009), however several challenges exist. The first is related to the quality and quantity of sources that are often unevenly distributed in space and time (Bradley and Jones, 1992; Brázdil *et al.*, 2005; Mann *et al.*, 2009; Adamson, 2015). Ideally a wealth of continuous, high-resolution, quantitative weather-related information is necessary to reveal the climatic extremes occurred in the past, even more useful if it can be compared with similar existing information from near or more distant locations. In the case of snowfall-related variables to identify temporal and spatial changes and trends is difficult due to the limited number of long-term snowfall series reconstruction that poses a major challenge for assessing snowfall spatial pattern variation as well as snowfall past and future climate scenarios. Within a snowfall series reconstruction further challenges are to be referred to sources of inhomogeneity caused by changes in observational methodologies, instruments response and localization characteristics. In such a case, quality-control procedures becomes essential to correct and homogenized the datasets.

Diodato *et al.* (2018) presented the first millennium-long (800–2017 CE) reconstruction of a snowfall severity index with annual resolution for Italy, suggesting that the Atlantic Multidecadal Variability (AMV) may induce the frequency of snowstorm in the central Mediterranean region. In fact, large snowfall events occurred during the Little Ice Age (LIA, ~1,300–1850 CE; Miller *et al.*, 2012), were dominated by a negative mode of the AMV. Detailed monthly or annual analyses of snow records, to support or refute this finding, are however only available from the 20th century. For this period, analyses are available on snow depth and duration, and on the spatial distribution of snowfall events, for different regions of the Northern Hemisphere, where snowfall and snow-cover are overall decreasing (Liu *et al.*, 2012; Faranda, 2019). For snow cover-duration regimes in North America, we refer to Leathers and Robinson (1993), Leathers and Luff (1997) and Frei *et al.* (1999). For the atmospheric control on the Eurasian snow extent we refer to Clark *et al.* (1999) and for the Russian winter snow accumulation, its spatial patterns, decadal variability, and teleconnections with Atlantic sea-surface temperatures to the analysis performed by Ye *et al.* (1998) and Ye (2000). Concerning the analyses dealing with the local scale in Europe, Jackson (1978) studied the occurrence of snow in Great Britain. In Eastern Europe, basic snow-cover characteristics were given by Poland by Paczos (1985), while Dobrovolný (1993) investigated long-term snow conditions in the Czech Republic. Studies on snow variability are available for Switzerland (Scherrer and Appenzeller, 2006; Marty and Blanchet, 2011; Laternser and Schneebeli, 2018; Diodato *et al.*, 2020), France (Durand *et al.*, 2009) and Italy (Fazzini *et al.*, 2004; Valt and Cianfarra, 2010; Enzi *et al.*, 2014; Diodato *et al.*, 2018; Diodato and Bellocchi, 2020). In Finland, trends towards shorter snow seasons and greater snow depth were identified by Hyvärinen (2003). Hantel *et al.* (2000) defined the relationship between temperature and number of days with snow cover for Austrian climate stations. However, considering the short temporal span of the available snowfall records, and the limited knowledge we have about the complex weather and climate interactions occurring at multidecadal time-scales, it is essential to deepen our understanding of snowfall characteristics and their historical evolution. In Europe, the number of days with snowfall occurrence varies with latitude-dependent solar radiation and patterns of atmospheric circulation (Kretschmer *et al.*, 2017; Croce *et al.*, 2018). Polar maritime air masses from over the Atlantic collide here with the polar continental air masses connected with the Asian (Siberian) high (Bednorz, 2004). This is the dominant circulation pattern explaining the occurrence of prominent snowfall events over the 17th to 19th centuries (Luterbacher *et al.*, 2001; Shindell *et al.*, 2004; Pfister, 2005). This period, characterized by very cold and snowy conditions in Europe (e.g., Jones and Mann, 2004), coincides with the occurrence of several large volcanic eruptions (Briffa *et al.*, 1998; Gao *et al.*, 2008) and a reduced solar activity, as recorded with cosmogenic nuclides (Stuiver and Braziunas, 1993; Steinhilber *et al.*, 2012) and the observation of low sunspot numbers (Lean *et al.*, 1995; Steinhilber *et al.*, 2009). These situations favoured blocking conditions (i.e., cases where a large anti-cyclonic cell moves northward from its normal position, interrupting the zonal flow), which in turn favoured cold air advection and snowfall (Palmieri *et al.*, 1982).

The current work presents the first monthly resolved reconstruction of snowfall since 1777 AD for the Parma Observatory, centrally located in the Po River Basin, northern Italy. The Italian naturalist and physician Matteo Bruni (1522–1600) reported the climatic fluctuations of northern Italy and the particularly snowy winters occurred in this area in the central part of the LIA (Turchini, 2003). In his account, he noted that unusually harsh, snowy and iced winters caused damage to fruits and vines between 1,571 and 1,595: “Last November 1594 a great cold and snow suddenly began, and the bad weather then lasted all December, still cold, ice and snow, and continued, beginning on January 1st 1595 for almost the whole of April” (*All'ultimo di novembre 1,594 cominciò all'improvviso un gran freddo e neve, il qual mal tempo durò poi tutto il decembre ancora sempre freddo, ghiaccio e neve, e seguitò, cominciando il primo Genaro 1,595 per sin quasi tutto aprile*). However, it is necessary to arrive at the 18th century to find regular and continuous daily snowfall records. In this regard, the Italian regions hold among the world's longest monthly snowfall time series (Enzi *et al.*, 2014), going back to 1780 at Rome (Mangianti and Beltrano, 1991), 1788 at Turin (Leporati and Mercalli, 1994) and 1884 at Montevergine (Diodato, 1997). Nevertheless, Parma possesses the longest continuous record, as it goes back to 1777, although we know (Camuffo and Bertolin, 2012) that meteorological observers were already active in Parma from 1,654 to 1,660, supported by the Grand Duke of Tuscany Ferdinand II de' Medici (1610–1,670). Section 2 describes the environmental setting and the Parma series with its history, definition of analysed variables, and the expected sources of inhomogeneity. The Section 3: Methods—homogeneity testing and correction and trend analysis, reports the quality-control procedure implemented to study and reconstruct the monthly snowfall series in Parma. Then Section 4: Results and Discussion reports (a) the identified breakpoints, their impact and the most likely physical reasons for these shifts and (b) the observed trends, the applied correction and the observed consistency with air temperature series in literature. Finally, the Conclusions section summarizes the main sources of inhomogeneity, their impact, the characteristics and drivers of observed variability and extremes as well as the coherence of observed variability and trend of long time series with other regions in Europe.

2 | DESCRIPTION OF THE PARMA SNOWFALL TIME SERIES

2.1 | Parma and its environmental setting

Parma Observatory (44°48′N and 10°19′E) is near the centre of the Po River Basin (PRB Figure 1a), in the administrative region Emilia Romagna in Italy, surrounded from the pre-Alps to the north and from the Emiliano Apennine to the south, (Figure 1a). Its climate is continental temperate with hot summer (Cfa, according to Köppen-Geiger classification; Fratianni and Acquaotta, 2017), mainly influenced by the Po Valley, which is embedded between the Alps (north and west) and the Apennine (south) (Figure 1b). The interaction between these morphology and weather characteristics governs the occurrence of snowfall events under different conditions. With a snow mean annual snow accumulation of 0.4 m (black dot, Figure 1c), the Parma Observatory outlines a separation between a great snowy pre-Alps to the north and the Apennines to the south, and the limited accumulations of snow to the east, where the climate is less continental because of the proximity of the Adriatic sea. Even if the coloured bands in Figure 1c are smoothed, considerable sub-regional variations in the areas of the Observatory are due to different slope exposures, and the presence of different altitudes and distances to the sea (Figure 1b), which exert some contrasting effects on snow cover (depth and permanence). In fact, the spatial distribution of snow events in the Po Valley is not easily predictable because mountain ranges create different orographic effects by hindering the movement of air masses (Enzi *et al.*, 2014). The south-eastern sector is less snowy, due to the mitigating influence of the Adriatic Sea and a greater exposure to scirocco hot winds.

During the year, cyclonic Atlantic air masses and areas of anti-cyclonic airflows from Central and Eastern Europe alternate. Fields of variable winds are thus associated with wet masses from southwest, and dry and continental winds from northeast. The distribution of rainfall is characterized by two maxima: one in spring and one in autumn (dotted grey curve in Figure 2). Snowfall increases with elevation until 2000 m a.m.s.l. At Parma OBS (Figure 1b), which can be assumed representative of the Po Valley area, the average number of days with snowfall in a year (i.e., yearly snowfall frequency) is about 10, with snow events mostly distributed between December and March (Figure 2, light blue curve). The most abundant snowfall in the Alps and Apennines occurs precisely when the arrival from the south of warmer air and loads of humidity closes a cold period, mitigating the temperatures that thus rise to values close to zero. If the cold has been sufficiently intense, such as to determine values below zero even in plain areas, snowfalls can reach very low altitudes (Bettini, 2016). This is what happens in the central-western sector of the PRB, when hot and humid air coming from the Mediterranean slips on a cushion of cold air, previously flown, trapped in the low layers of the barrier of the Alps and the Apennines.

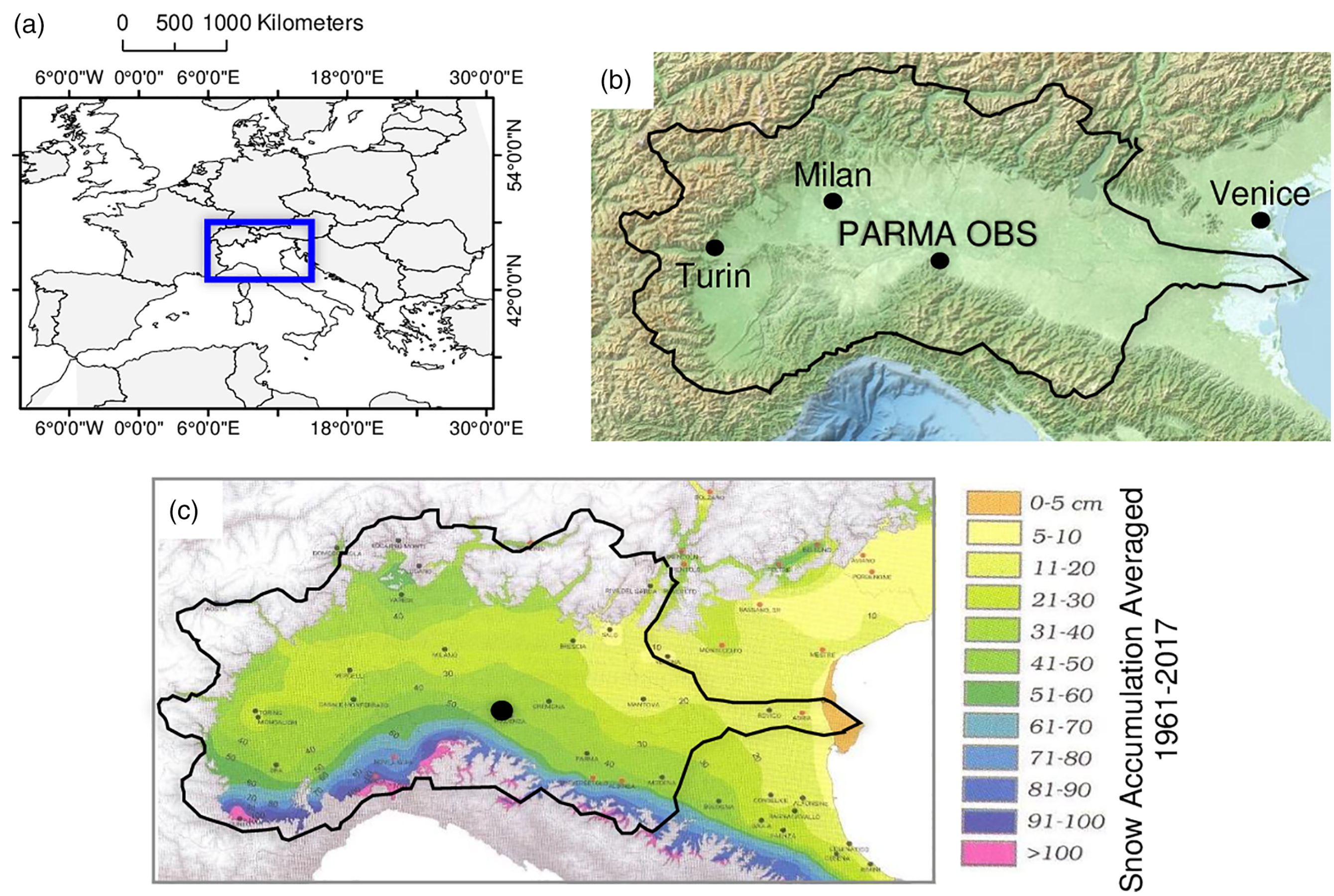

FIGURE 1 Geographical setting (a), North Italy with Po River Basin (blue curve) and main locations and Parma Observatory (b) (arranged from: http://elasticterrain.xyz), and related mean annual snow accumulation averaged upon the 1961–2017 period (c) (arranged from: Pifferetti et al., 2017)

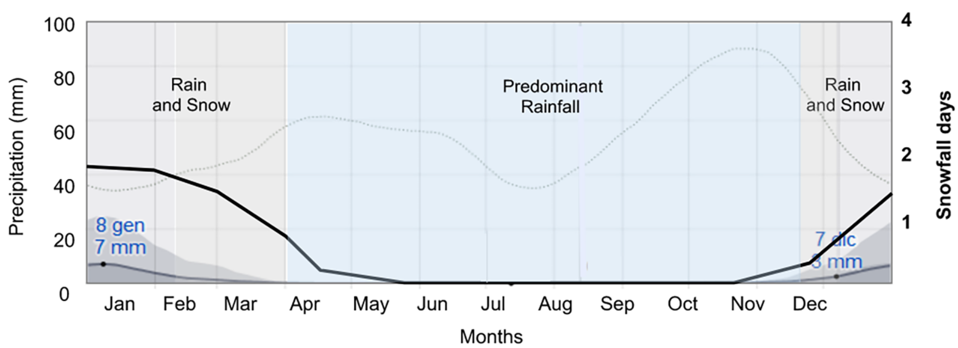

FIGURE 2 Monthly distribution of precipitation amount at Parma OBS with rainfall (dotted grey curve) and equivalent snow water (black curve), related 75th and 90th percentiles (dark grey bands), and monthly snowfall frequency (light blue curve), with snow-free 8 months, from April to November during 1961–2010. The dates in blue indicate that most of the snow fall in the 31 days around January 8, with an average total accumulation equivalent to 7-mm water (arranged from goo.gl/VEPQwt)

It can happen that sometimes it snows despite the arrival of air that is below freezing, as in the case in which streams of very cold air suddenly raise a mass of near-saturation wet air, leading to condensation. This phenomenon, although rare, can be observed in PRB when cold Siberian air penetrates westward into Northern Italy, while very damp air or even a misty blanket stagnates in the plains. In these situations, snowfalls are weak, of short duration and limited to the plains or to the low slopes of the pre-Alps.

2.2 | The snowfall variables observed at the Parma Observatory and their expected sources of inhomogeneity

With King Philip of Spain (1720–1765), the dynasty of the Bourbons succeeded in 1748 the extinct Farnese house, which ruled the Duchy of Parma until 1731, followed by a brief Austrian interregnum. Through the enactment of the “Constitutions for the new royal studies” (1768), the Bourbons gave complete regulations to the whole educational sector in Parma, from primary school to the university. Essential institutions were established for the development of civil society, such as the Palatine Library, the Museum of Antiquity, the Botanical Garden, the Academy of Fine Arts and the related Meteorological Observatory of the Parma University (Figure 3a). The snowfall time series recorded under the aegis of this institution were: (a) snowfall Frequency; (b) snowfall duration with snowfall starting and ending dates; (c) Fresh snow depth; and (d) snow permanence on ground. Short definitions, units, and measurement methods of these variables are summarized in Table 1. Unfortunately, a complete list or logs with metadata descriptions for these variables are missing although some scattered information can be found in contemporary documents (Zanella, 1977) or deduced from data quality analysis. In this work, a framework of metadata has been reconstructed and reported in Figure 4 with five types of possible sources of inhomogeneity in the time series, that is, change in observers, instruments types, sensitivity and location of the instrumentation, and reading time modification.

2.2.1 | The observers

Many scholars are known to have worked at the Meteorological Observatory of Parma University from the second half of the 18th century. A change in the observer, having his own observational methodology, could result in a discontinuity from data analysis. Observers such as Ubaldo Bianchi, Antonio Colla and the directors of the Meteorological Observatory (Pietro Pigorini and Pietro Cardani) collected data and left notes about their observations. Others (referred as Various Observers VV.OO in Figure 4) were unknown. For a more complete overview of the historical evolution of the observational determinations at Parma, the reader is advised to refer to Supporting Materials (SM1).

2.2.2 | The instruments, their sensitivity and location

Similarly, the substitution of a snow gauge, its recalibration or a relocation could have an impact on the observations. The Supplementary Materials (SM1) provides an overview of the instrumentation adopted at the Parma meteorological observatory. For the earlier observations, no information was available about the sensitivity of any early tool, or of graduated dip rod or capacity vessel used to measure the snowfall. This is because from 1777 to 1866 the observers recorded only the frequency, or the starting and ending date of the snowfalls and therefore they did not need a proper snow gauge. Recently the observatory had a tipping bucket SIAP model with the bucket that could have two positions, one during the discharge with the motion determined by the weight imbalance caused by the collected rainwater and the other during rest. Since 1960 the SIAP Gauge was warmed to allow the snow melting. In addition, it has been possible to obtain the sensitivity measures interpreting the last decimal unit of the snow depth records in the registers. These time series started in 1867. For the first ten years the sensitivity was of 1 mm, from 1878 to 1898 it was of ca. 0.5 mm, lower than 0.5 mm in the

(a)


(b)

Mesi	Pioggia	Giorni piovosi	Neve sciolta	Giorni nevic.	Quantità totale dell' acqua racc.
	centim.		centim.		centim.
Gennajo	1, 140	1	1, 060	4	2, 200
Febbrajo	2, 475	6	———	,,	2, 475
Marzo	3, 190	7	4, 235	2	7, 425
Aprile	4, 520	7	0, 555	1	5, 075
Maggio	8, 865	9	———	,,	8, 865
Giugno	1, 165	2	———	,,	1, 165
Luglio	1, 202	1	———	,,	1, 202
Agosto	4, 925	6	———	,,	4, 925
Settembre	6, 955	8	———	,,	6, 955
Ottobre	16, 595	16	———	,,	16, 595
Novembre	24, 290	16	———	,,	24, 290
Dicembre	15, 635	13	———	,,	15, 635
Risultati dell'Anno	90, 957	92	5, 850	7	96, 807
Medie dei 7 Anni precedenti	63, 615	83	6, 984	11	70, 599

FIGURE 3 A view of the city of Parma from the Meteorological Observatory in the 1888 (a) (modified from: https://tinyurl.com/y6jwxb5g), and an excerpt from the table of rain and snow for the year 1838 (b) (from: Colla, 1840)

TABLE 1 Snowfall variables analysed in this work, together with their short definition, unit, and measurement method

Snowfall variable	Short definition	Unit	Measurement method
Snowfall frequency	*N** of snowfall in a month/year	dd	Visual observation
Snowfall duration	Time elapsed between the last and first snowfall within the same snow year (Oct to Apr)	dd	Calculation from visual observations
Snowfall starting date	First snowfall day number counted by October 1st	dd	Visual observation
Snowfall ending date	Last snowfall day number counted by October 1st	dd	Visual observation
(Fresh) snow (depth)	The total depth of snow, on the ground, or collected in a snow gauge, taken once a day at the scheduled time of observation	cm	Reading on a graduated rod/meter immersed perpendicularly on the snow gauge
Snow permanence on ground	Time elapsed with snow permanence on ground	dd	Calculation from visual observations

<table>
<tr><th>Period</th><th>Observator</th><th>Rain/Snow Gauge</th><th>Location</th><th>Reading Time</th><th>Sensitivity</th></tr>
<tr><td>1777-1824</td><td>Bianchi</td><td rowspan="4">Rain Gauge</td><td>1</td><td>-</td><td>-</td></tr>
<tr><td>1825-1831</td><td>Colla</td><td>2</td><td>-</td><td>-</td></tr>
<tr><td>1832-1866</td><td>Colla + VV.OO</td><td rowspan="5">3</td><td>-</td><td>-</td></tr>
<tr><td>1867-1877</td><td>VV.OO</td><td>-</td><td>1</td></tr>
<tr><td>1878-1898</td><td>VV.OO</td><td rowspan="3">Tecnomasio</td><td rowspan="2">9-15-21; (21-21)</td><td>≈ 0.5</td></tr>
<tr><td>1899-1932</td><td>VV.OO</td><td><<0.5</td></tr>
<tr><td>1933-1937</td><td>VV.OO</td><td rowspan="2">8-14-19; (19-19)</td><td rowspan="3">≈ 0.5</td></tr>
<tr><td>1938-1960</td><td>VV.OO</td><td>SIAP Gauge</td><td rowspan="2">4</td></tr>
<tr><td>1960-2018</td><td>VV.OO</td><td>SIAP Gauge*</td><td>Hourly</td></tr>
</table>

FIGURE 4 A scheme of the reconstructed metadata in Parma (Italy) over the period 1777–2018. The scheme reports information on observers, rain/snow gauge, location, reading time and sensitivity and the changing years. Each column may be considered as an inhomogeneity source within the snowfall time series. VV.OO in the observers column refers to: Various observers. Numbers in column location refers to places highlighted in Figure SM2. Numbers in the Reading time columns refers to CET hours

1899–1932 period, and subsequently of ca. 0.5 mm. A change in sensitivity may be the evidence of a change of snow gauge, or graduated rod and vessel.

From 1777 to 1937, the locations of the rain gauges in Parma remained in a homogeneous urban environment within 100 m-radius area). Location 1 (1777–1824) (as reported in SM2) was the Bianchi's house located at about 200 m from the Specola or Parma Observatory (Location 3). Bianchi collected rainfall and snowfall using a rain gauge located on the roof at about 11 m above ground. Location 2 (1825–1831) was Piazza Maggiore (now Piazza Garibaldi) where the observations were conducted with the same instrument as before, placed at 60 Parisian feet (1 Parisian foot = 0.325 m) i.e., ca. 20 m above the square level. Location 3 (1832–1937) was at the top of the Specola (western tower of the University building), at an elevation of 94 Parisian feet that is, ca 30 m as described by Oppici (1873).

Since 1938, the Observatory moved some kilometres out of city center in the Parma's countryside (Location 4 in SM2). Starting from this moment the rain gauge was placed on the grassy ground.

2.2.3 | The reading time and definition of day with snow

Over the 1777–1877 period the readings in the snowfall frequency time series were collected once a day without any interruption and reported in form of note (from 1867–1877 with a snow depth numerical value) on weather and state of the sky in the logs. The definition of day with snow was clarified in 1878 as the 24 hours ranging from 21:00 to 21:00 (Local Solar Time pre 1860 corrected to Central European Time—CET for time homogeneity along the series). This definition changed in

1933 becoming from 19:00 to 19:00. Similarly, the three daily reading times went from the previous time at 09:00, 15:00 and 21:00 to 08:00, 14:00 and 19:00. It was since the 60s of the 20th century that the readings were conducted hourly. As, for the previous metadata information, a modification in the reading time may cause an inhomogeneity in the snowfall datasets.

3 | METHODS

3.1 | Homogeneity tests and correction, and nonparametric sub-periods statistical analysis

Quality-control procedures are essential to detect outliers or changes in the snowfall series (Baronetti *et al*., 2019). In order to study the yearly snowfall regime changes and assess climate anomalies at Parma observatory, the homogeneity of the snowfall time series has been investigated to identify breakpoints and the impact of the corrections. The homogeneity testing has been carried out through the analysis of metadata and all the snowfall time series using a nonparametric statistical approaches commonly used in climatic and hydrological datasets (Mitchell *et al*., 1996; Gonzalez-Rouco *et al*., 2001; Winingaard *et al*., 2003; Štěpánek *et al*., 2009; Vezzoli *et al*., 2012). These tests help in detecting if a sub-set of data follows a given distribution, if data have a time at which a change occurs (i.e., change or break point). Concerning the change-point detection from data, the Buishand range (Buishand, 1982) and the Standard Normal Homogeneity Tests with either Single-Shift or Double Shift (SNHT-SS and SNHT-DS, Alexandersson, 1986) have been applied on the snowfall time series.

Discriminating between the possible sources of inhomogeneities, information retrieved from metadata analysis have been used to discriminate between temporal ranges of homogeneous sub-periods (see Figure 4, column 1) of the snowfall time series. Then, box and whisker diagrams (i.e., box plots in supplementary materials: SM3a, SM4a, SM4c, SM5a) have been used to display variations in the identified data sub-sets without making any preliminary assumption on the underlying statistical distribution. In the box plots, the height of the coloured box corresponds to the mean ± 1 SD, the horizontal black line to the median, and the small square to the mean. The height of the whisker ranges within 1.5 times the distance between the upper and lower quartile that is the interquartile (IQR) indicating the degree of dispersion and skewness in the analysed data sub-sets. The single dots above or below the whiskers highlight the outliers greater/lower than the 1.5 IQR (i.e., exceeding ±2.7 SD). These box plots are particularly useful for comparing different sets of data and have been used also to analyse the results of the SNHT-SS and SNHT-DS test statistics (i.e., box plots in supplementary materials: SM3b, SM4b, SM4d, SM5b) searching for physical reasons for the shifts. The values for the snowfall time series corrections has been identified by the Alexandersson's test statistic (T). This is a value that compares the average of the first k values with that of the remaining (n-k) values (Štěpánek *et al*., 2009; Vezzoli *et al*., 2012) in a time series. The year k is the unknown change point where T_k has a maximum value. The detection of this shift between subsequent sub-periods helps in correcting (i.e., in homogenizing) the original datasets. The null hypothesis of the test is that the time series is homogenous between two given times, to reject it, the test statistic should be greater than a critical value.

Finally, in second analysis, we have applied to the homogenized time series—that is, after the SNHT correction—the Buishand test to verify that no residual breakpoints remained. In this test, the null hypothesis is that a series is homogeneous if the rescaled adjusted partial sum (S_k) is approximately zero. Where S_k is the cumulative deviation from the mean for kth observations of a series. In this test, the significance of a shift can be evaluated by computing the test statistic R_b

$$R_b = \frac{\max S_k - \min S_k}{\sigma} \quad (1)$$

and comparing it with critical values provided by Buishand (1982) to accept or not the null hypothesis.

3.2 | Trend tests

All the snowfall time series were also tested to check the presence of any significant trend. Trend tests help in detecting if a sub-set of data follows a given distribution, that is, if data have a time range with a manifest or significant trend. The nonparametric Mann–Kendall test (Hirsch *et al*., 1982) was applied to detect possible monotonic trends. However, because of its low sensitivity to sudden changes caused by inhomogeneity in the time series (Tabari *et al*., 2011), this test was applied after the correction of all the snowfall datasets, that is, on the homogenized values. The Mann–Kendall null hypothesis is that data originate from a population with independent and identically distributed random variables.

4 | RESULTS AND DISCUSSION

With the help of the statistical analysis and the correction applied to the homogenized snowfall time series after the SNHT, it is possible to summarize the snow variability since 1777, that is, during the late period and the exiting of the LIA, until the modern warming. Changes in snowfall can be visualized and explained by repeated occurrences, depth and duration in monthly and annual records.

TABLE 2 Yearly frequency range mean, *SD*, and outliers as extracted from metadata information and SNHT

	Mean (dd)	*SD* (dd)	Outliers (dd)
Metadata			
1777–1824	13.2	6.1	—
1825–1831	13.7	8.3	—
1832–1866	9.6	6.2	—
1867–1877	9.0	6.2	—
1878–1898	7.9	5.1	23 (1894)
1899–1932	7.6	4.4	21 (1916)
1933–1937	5.4	1.8	—
1938–2018	6.7	3.9	17 (1941,1946)
SNHT-SS			
1777–1858	12.2	6.5	30 (1829)
1859–2018	6.8	4.5	23 (1894)
SNHT-DS			
1777–1845	12.7	6.4	30 (1829)
1846–1947	8.2	5.2	23 (1894)
1948–2018	5.3	3.5	—

4.1 | Homogeneity testing: Identified breakpoints, physical reasons for the shifts and impact of the corrections

4.1.1 | Snowfall frequency and duration (1777–2018)

Figure SM3a highlights the statistic of the yearly snowfall frequency range in the analysed data sub-sets (i.e., from metadata—Figure 4, first column), while Figure SM3b reports the results from the SNHT. Mean, *SD*, and outliers are also reported in Table 2. Similarly, Figures SM4a and SM4c show the statistics of the starting and ending date range by metadata, and Figure SM4b and SM4d by the SNHT. Mean, *SD*, and outliers are reported in Table 3. The physical reasons for the shifts at the breakpoints could be mainly caused by location changes (L1, L2 and L3) as highlighted in Figure SM3a, with a progressive increase in the exposure height of the rain gauge and consequently a decrease in the collected rain/snow over the time. This could be caused by (a) raised

TABLE 3 Starting and ending date (bold) range mean, *SD*, and outliers as extracted from metadata information and SNHT

	Mean (dd)	*SD* (dd)	Outliers (dd)		Mean (dd)	*SD* (dd)	Outliers (dd)
Start date				*End date*			
1777–1824	68.2	22.5	—	1777–1824	**157.3**	**25.3**	—
1825–1831	68.6	24.6	—	1825–1831	**163.0**	**20.1**	—
1832–1866	76.0	26.9	139 (1834, 1850) 164 (1924)	1832–1866	**149.9**	**33.2**	**63 (1862)**
1867–1877	74.8	30.5	—	1867–1877	**155.0**	**34.3**	—
1878–1898	70.9	29.0	—	1878–1898	**141.2**	**32.9**	—
1899–1932	85.6	29.0	—	1899–1932	**146.4**	**31.1**	**46 (1919)**
1933–1937	81.8	16.9	—	1933–1937	**116.4**	**20.5**	—
1938–2018	83.3	25.8	143 (1991) 146 (1943) 154 (1973)	1938–2018	**134.7**	**25.5**	—
SNHT-SS				*SNHT-SS*			
1777–1897	71.4	24.8	164 (1850)	1777–1853	**157.8**	**24.5**	—
1898–2018	84.0	26.2	164 (1924)	1854–2018	**139.0**	**30.2**	**46 (1919)**
SNHT-DS				*SNHT-DS*			
1777–1850	70.7	25.1	164 (1850)	1777–1917	**152.4**	**29.2**	**63 (1862, 1881)** **71 (1883)** **74 (1865)**
1851–2018	80.7	26.2	164 (1924)	1918–1921	**97.5**	**43.6**	—
				1922–2018	**136.1**	**25.7**	—

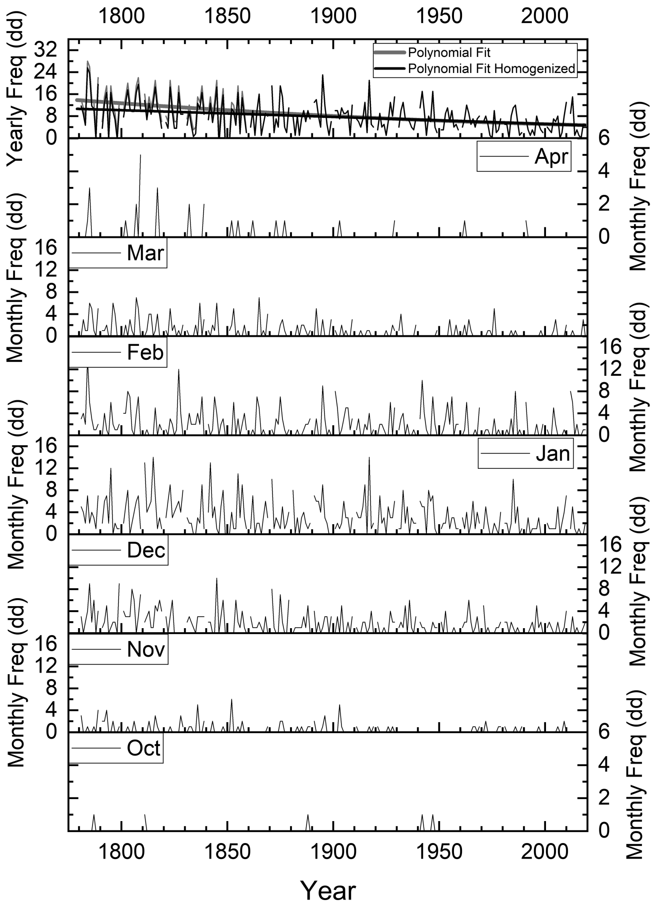

FIGURE 5 Grey line original data; black line corrected homogenized data for the days with snow in Parma over the 1777–2018 period. Thick lines linear fits. Top panel: Original yearly aggregated data of snow frequency in days (grey thick line: Second order polynomial best fit). Corrected homogenized data (black thick line: Second order polynomial best fit). Bottom panels: Monthly snow frequency in days from October to April

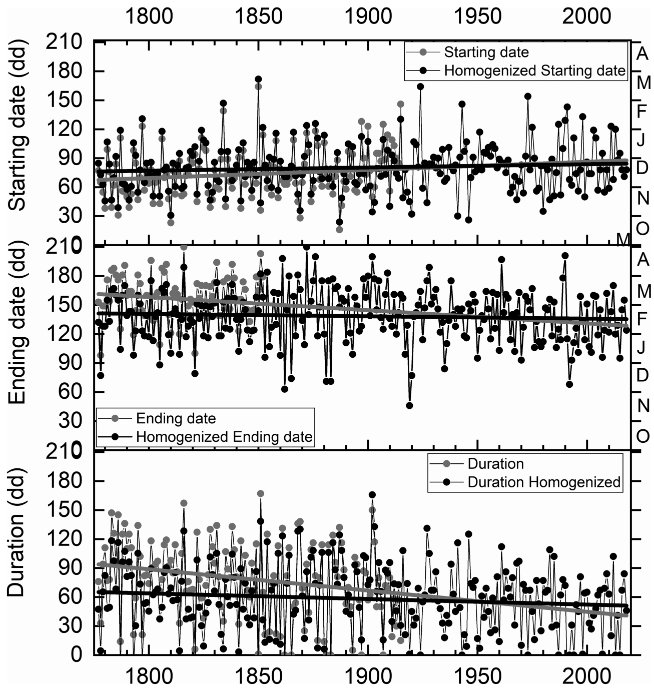

FIGURE 6 Original data (grey dots and line) and homogenized data (black dots and line). For the days with snow in Parma over the 1777–2018 period. Top panel: Starting date of the first snowfall (days) with linear best fits (thick lines). Central panel: Ending date of the last snowfall (days) with second order polynomial best fits (thick lines). Bottom panel: Duration of the snowfall period in days with second order polynomial best fits (thick lines)

wind intensity (Jevons 1862; Symons, 1864); (b) lack of windshield protection for the funnel for reducing the wind influence in case of light snow precipitation or strong wind; (c) a not shielded rain gauge against sunshine with a bias due to evaporation; and (d) water retention or loss when the instrument was emptied (observer influence in case he used capacity measure units). Concerning the impact of the applied corrections, the best fit of the decrease of the yearly frequency of snowy days (black line, Figure 5)—once homogenized for the overall bias caused by the instrumental exposure and observers changes—is reduced to a maximum difference of 2.4 days respect to the original 5.0 days over the 1777–1877 period. Similarly, results from the application of the SNHT (Figure SM3b) show that the change points are around the mid of the 19th century (i.e., in the 1845–1858 period), which are likely not reflecting any kind of climate pattern because they might have been influenced by both locations (L2-L3) and observer's change during and after the direction of the specola by Antonio Colla. The difference between the means of the sub-periods (Table 2) is 5.4 days.

This bias is also corroborated by the statistics in Table 2 and SM3a that report a mean shift of 4.15 ± 1 days at the change between locations L1-L2 and L3.

Analysing the starting/ending day and the duration of the snowfall period. The decrease of snowfall frequency is accompanied by both a contraction of snowfall depth and a shortening of snow duration days, with a delay of Autumn starting date (Figure 6, top panel), and a postponement of the Spring ending date (Figure 6, central panel). Analysing the metadata, the physical reasons explaining the small difference between the original and corrected (homogenized) starting date time series (i.e., from 5.5 days$\pm$26.7 over 121 years up to 15,1 days$\pm$25.7 days of delay over the 241 years) is likely due to the change in location and in the observers, as detected by the whiskers in Figure SM4a and by the SNHT-DS (i.e., shift of 10.0 ± 25.7 days) in Figure SM4b. Later, around the 1897–1898 period, it is the change in sensitivity and in the definition of the snow day that affects the original datasets as detected by Figure SM4a and SM4b SNHT-SS (i.e., shift of 12.6 ± 25.5 days). Finally, the most evident difference between the original and homogenized series of the snowfall ending date occurred during/after the IWW with an earlier ending date registration (Figure SM4d) as highlighted by the SNHT-DS (i.e., shift of 54.9 ± 36.4 days). The output of the Buishand test conducted in second analysis on all the homogenized time series detected a common change point at 1987 with a level of significance of $p = 0.01$. Before the change-point year, snowfall frequency was ca. 8.3 ± 5.5 days (Table 2) per year on average. After the change-point (up to 1987), the average snowfall frequency declined to 4.5 ± 3.6 days per year.

4.1.2 | Fresh snow depth (1868–2018)

Figure SM5a reports the statistics of the data sub-sets obtained by the metadata analysis for the yearly fresh snow range and Figure SM3b the same but obtained by the SNHT. Mean, *SD*, and outliers visualized in Table 4. Snow depth records are available for a shorter period (1868–2018) than snowfall frequency (1777–2018). As for snowfall frequency, snow depth also decreased substantially from the end of the LIA, partially caused by the bias described above. However, this decline has occurred in a more irregular manner, in the months from October to April see monthly time series in Figure 7, and in a more gradual way on annual basis (Figure 7, top panel).

TABLE 4 Yearly fresh snow range mean, *SD*, and outliers in centimetres as extracted from metadata information and SNHT

	Mean (cm)	*SD* (cm)	Outliers (cm)
Metadata			
1867–1877	41.5	49.7	137 (1874)
1878–1898	60.2	52.7	189.5 (1894)
1899–1932	51.8	43.6	179 (1908)
1933–1937	40.6	30.1	—
1938–2018	36.6	31.1	117 (1946)
SNHT-SS			
1867–1964	53.1	43.1	179 (1908) 189.5 (1894)
1965–2018	26.8	24.2	—
SNHT-DS			
1867–1884	41.4	41.7	134.5 (1870) 137 (1874)
1885–1964	55.8	43.2	179 (1908) 189.5 (1894)
1965–2018	26.8	24.2	—

Original (thick grey line second order polynomial fit) and homogenized data (black thick line second order polynomial fit) have a constant bias during the 1868–1937 period mainly caused by the new measuring instrument, that is, the Tecnomasio rain gauge that overestimated the measurements (wider box plot in Figure SM5a). Within that period, the SNHT-DS (Figure SM5b) also detected a change (i.e., 14.4 ± 42.4 cm) due to a higher sensitivity in the readings. In 1938, after the move of the meteorological observatory to the countryside and the new installation of the SIAP rain gauge model, the difference lowers (4.0 ± 30.6 cm—Figure SM5a). In this last period, both the two homogeneity tests (Figure SM5b) detect a change in the year 1964, which was likely caused by the most frequent reading (hourly) and heating of the vessel used to liquefy the fallen snow (shift equals to 26.3 ± 33.7 cm for the SNHT-SS and to 29.0 ± 33.7 cm for the SNHT-DS respectively).

4.1.3 | Snow permanence on the ground (1937–2018)

The time series of snow permanence on the ground reported in days, started in 1937 after the move of the meteorological observatory to the countryside. This series is homogeneous as no specific discontinuities have been highlighted from the analysis of metadata or by the SNHT. The mean value over the 1937–2018 is of about 19 days of snow permanence at ground with a *SD* of 18.5. Outliers resulted during and immediately after the WWII, that is, in 1940 (59 days), 1941 (82 days) and 1946 (92 days) and in 1962 (64 days). With the analysis of the snow permanence at ground, the Parma records are still too limited, the available time-series starting on 1937. In fact, before 1937–1938 only fresh fallen snow was measured but not the days of permanence on the ground, whose registration started in that year. The monthly data going from October to April are reported in Figure 8 together the yearly data in the top panel.

4.2 | Trend testing: Observed trends and consistency with air temperature

4.2.1 | Snowfall frequency and duration (1777–2018)

In the series of snowfall yearly frequency a significant trend was detected. The yearly aggregated snowfall frequency data reported in Figure 5 (top panel) show such decrease tendency on both original and homogenized data (where the significant trend with level of significance

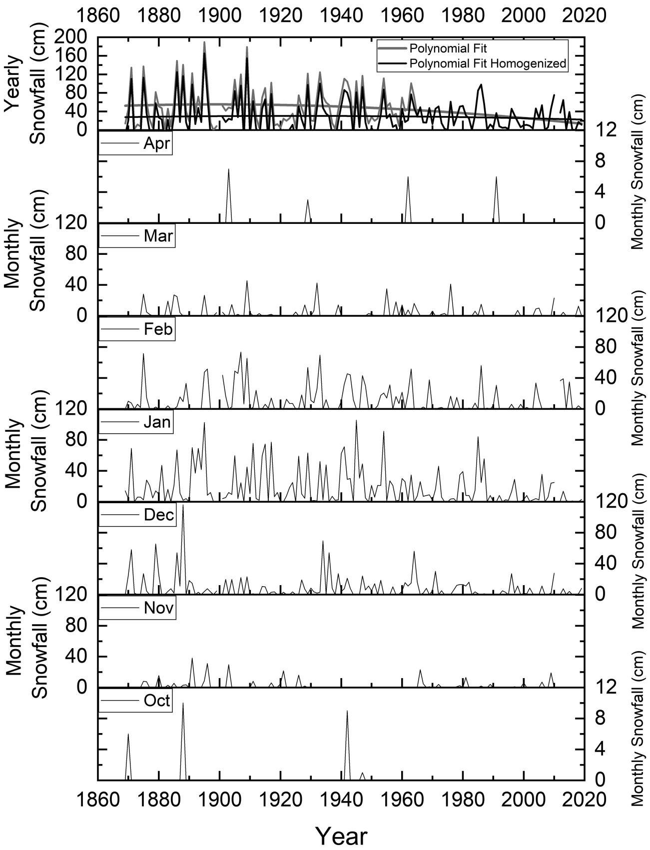

FIGURE 7 Original data (grey line) and homogenized data (black line). Top panel: Snowfall data (in cm) aggregated on yearly basis along the 1867–2018 period in Parma. Grey thick line: Second order best fit on original data and black tick line on homogenized data. Bottom panels: Monthly snowfall in cm from October to April

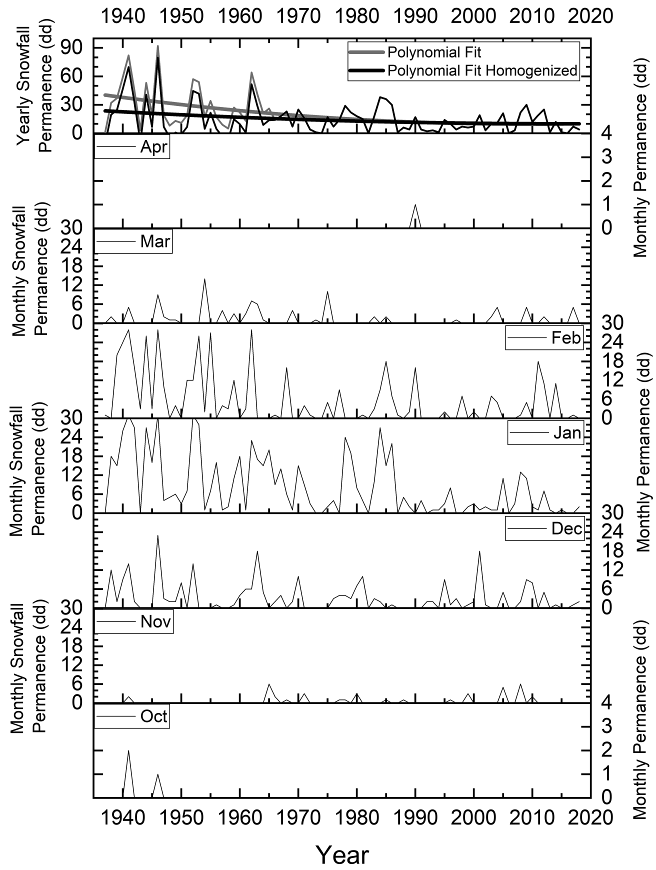

FIGURE 8 Original data (grey line) and homogenized data (black line). Top panel: Permanence of snow on the ground (days) for the aggregation on annual basis along the 1937–2018 period in Parma. Thick lines second order polynomial fit. Bottom panels: Monthly snowfall permanence at ground from October to April in days

[$p < .01$] was detected). The snowfall frequency on a monthly basis (October–April) from the end of 18th century to the beginning of 21th century is also reported. A visible decline on the original series displayed in the first half of the 19th century (grey line) fits with a second order polynomial equation ($R^2 = 0.24$) over the period 1777–1877.

In the best fit over the 1777–1877 period, about 3.0 days in snowfall frequency may be attributable to bias, while ca 2.4 days may be attributable to a change in the pattern of snowfall yearly frequency as detected by the significant decreasing trend with the Mann–Kendall test on the corrected series.

Then, the application of the SNHT-SS test statistic (Table 2) indicates the existence of a change point in the year 1897 for the start and the end of the snowfall season. On average, the length of the snowy season was significantly shortened (Student-*t* test p-value<0.01) to 52 days per year (±35 *SD*) after 1897, from 80 days per year (±41 *SD*) in the previous period, suggesting a climatological explanation. Since the late 19th century, the Atlantic Multidecadal Variability (AMV) has indeed experienced a significant increasing trend (Si et al., 2020), coinciding with the onset of the warming period (Figure 9, orange line). Based on terrestrial records from the northern Atlantic region, the AMV-index reconstruction by Wang et al. (2017) shows considerable variability over time scales of several decades. This multi-decadal climate mode originates dynamically in the North Atlantic Ocean and spreads throughout the Northern Hemisphere through a combination of atmospheric and oceanic processes (Wyatt et al., 2012; Wang et al., 2018). Sutton and Dong (2012) argued that there is a causal link between a positive (warm) AMV phase and drier conditions in the Mediterranean basin. Winter precipitation in northern Italy is also known to be mainly due to large-scale fronts of the North Atlantic and Mediterranean low-pressure synoptic systems, which produce moderate but continuous precipitation (Hawcroft et al., 2012). The variability of this type of precipitation from 1 year to the next and over several decades is mainly modulated by the North Atlantic Oscillation (NAO; e.g., Gómara et al., 2016), which describes the fluctuations in the difference of sea-level atmospheric pressure between

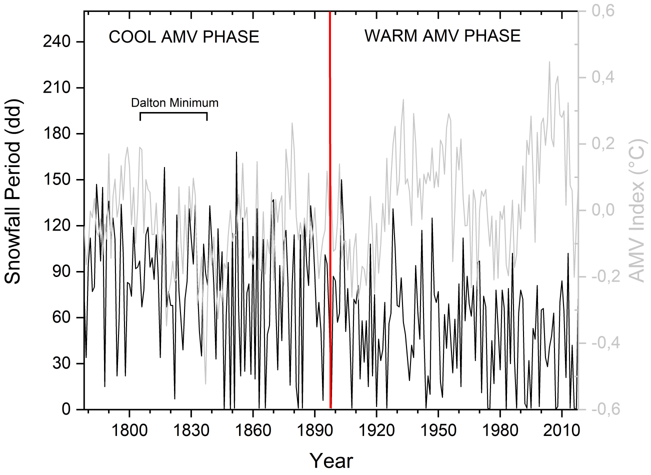

FIGURE 9 Timeline evolution of the homogenized data of yearly snowfall period (range of days from the first to the last date of snowfall) at Parma observatory (blue line) and the Atlantic Multidecadal Variability (AMV) index (orange line). The AMV index is shown as temperature anomaly relative to the 1856–1967 mean. The Dalton minimum period of low solar activity and lower-than-average global temperatures is identified. The vertical bar indicates the change-point year 1897

the Icelandic Low and the Azores High. The cold conditions of the LIA were still dominating after the end of the Dalton minimum of reduced solar activity (~1790–1830; Wagner and Zorita, 2005) until towards the end of the 19th century, but in the process of evolving into an incipient warming that became noticeable later on the 20th century. The decreasing trend of the annual length of the snow season at Parma observatory mirrored this large-scale climate signature (Figure 9, blue line).

4.2.2 | Fresh snow depth (1868–2018)

No significant trends were detected for the fresh snow depth time series. Looking at documentary sources and data in literature, in the last four decades, only during the winters of 1984–1985 and 1985–1986 there was generous snow, but they are far from past memorable winters, such as 1869–1870, 1872–1873, 1884–1885, 1896–1897, 1889–1890, 1893–1894, 1904–1905, 1905–1906, 1916–1917 and 1928–1929, when the mean snowfall was equal to 137 ± 29 cm. The LIA ended with this period of sharp reversal, during which the Alpine glacier fronts undertook their retreat inexorably, towards withdrawing at high altitudes up to disappear in some cases (e.g., Huss *et al.*, 2008; Lüthi, 2014; Goosse *et al.*, 2018).

Southernmost glaciers in Europe, which are a legacy of the central part of the LIA, survive in a warm environment thanks to local topographic and controlling factors, and high levels of accumulation as a result of favourable seasons for snow, but since their maximum during the 19th century they have retreated nowadays, losing 30–100% of their volume (Grunewald and Scheithauer, 2010). For instance, Andrews (1887) noted for the very cold winter of 1881 that it was expected by many that a Frost Fair would once more be held on the Thames (Lockwood *et al.*, 2017). Winters were still severe (and cool summers occurred), compared with the thermal values of the second half of the 20th century (e.g., Brönnimann, 2006; Twardosz and Kossowska-Cezak, 2020). However, only the winters of 1928–1929 and 1955–1956 (especially in February) are nearly comparable to LIA winters. Snow fell over whole Italy on February 1956, while sources document of gondolas stuck in ice along the canals of Venice on February 1929 (Camuffo *et al.*, 2017).

4.2.3 | Snow permanence on the ground (1937–2018)

The trend towards anomalously warm conditions in the last decades (when urban heat islands may also have been a contributing factor, for example, Musco, 2016) indicates that increasing temperatures represent the main factor triggering the decline of snow duration days at ground. With the original and homogenized data aggregated on yearly basis, we see that the best fit value of 29.8 days per year—at beginning of the observation period—for the homogenized series contrast with the value of 40.2 days per year fitted on the original data. This suggests that other factors than rising atmospheric temperature may have caused the decline of snow duration, for example, the snowfall frequency may have played a prominent role. In fact, a strong correlation ($R = 0.84$) exists between snowfall frequency and snow duration in the period 1937–2018. Nevertheless, Brown and Mote (2009) indicated that decreasing snow trends were stronger at lower elevations and in regions with more temperate winter conditions.

We verified further the snow characteristics in March at Parma Observatory by analysing the spring snow extent in the Northern Hemisphere. The departure of snow cover extent from the normal 1981–2010 shows that monthly anomalies are prominent in May 1978, 2008 and 2018. It is evident a contraction of snow cover extent (negative departure in orange colours) in recent decades and a widening of cover extent (positive departure in blue colours) before the most recent warming, across Siberia and North America (SM6).

This trend is confirmed by the decline of spring snow cover extent, as observed in Eurasia (SM6a). Despite both a limited expansion of snow cover in autumn (SMS6b) and an unchanged trend in winter (SMS6c) were observed in Europe and Asia over the last decades, decreasing snow cover extent and increasing variability are documented for the transition seasons, spring and autumn, at the Hemispheric scale since 1920s (Krasting *et al*., 2013). Such snow cover reduction was particularly significant in the Northern Hemisphere mid-latitudes (40°–60°N) between 1922 and 1997 (Brown, 2000).

Accordingly, Serquet *et al*. (2013) discovered a negative trend in the ratio of snowfall to total precipitation days over 1961–2008 across Switzerland in winter and spring, which indicates that a liquid precipitation has become more frequent. In the Alps, the recent surface warming and the associated circulation changes, with a shift towards a predominantly positive phase of the North Atlantic Oscillation (Zampieri *et al*., 2013), have largely concurred to the general reduction of snowfall observed in the past decades (Hantel and Hirtl-Wielke,- 2007; Serquet *et al*., 2011). Accordingly, Déry and Brown (2007), observed monthly mean snow cover extent and air temperature over the Northern Hemisphere are strongly anti-correlated, especially in April–June, when extensive snow cover is accompanied with strong solar activity.

5 | CONCLUSIONS

In this paper, we have attempted to deepen the understanding of snowfall characteristics and historical evolution in the Po plain, Northern Italy. Several conclusions and insights emerge from the results surveyed here with the first, uninterrupted and monthly resolved reconstruction of snowfall in Parma Observatory since 1777 AD (i.e., during the late period of the LIA).

1. The first conclusion, pertains to the metadata and data analysis performed. In case of yearly frequency of snowfall, the main sources of inhomogeneity were identified in changes of instruments locations with progressive increase in the exposure height of the rain gauges in the early periods and in the observers' changes. This caused an overestimation of the yearly snowfall frequency that was reduced, during the series homogenization, to a maximum of 2.4 days. Similar inhomogeneity impact was detected in the analysis of the starting/ending date and duration time series. In such a case, the change in the instrumentation sensitivity, in the definition of snowy day, and in the recording procedure during the IWW were also revealed. Their overall impact resulted in a shortening of the snow period duration over the centuries. Looking at the fresh snow depth time series, the study of metadata and the homogeneity testing detected bias caused mainly by the change of measuring instruments (i.e., the Tecnomasio and the SIAP rain gauges) and by the Urban Heat Island detection with the move of the Parma Observatory from the city center to the countryside in 1938. Concluding, the second analysis test, performed on the homogenized yearly snowfall frequency series, highlighted an impulsive change occurred after 1897, from a mean snowfall frequency of 8.3 ± 5.5 days per year to a decline down to 4.5 ± 3.6. This finding is both statistically supported by comparison with several other coeval multi-centuries snowfall series, which show a slight not-simultaneous occurrence in the whole Italian peninsula due to changes in latitudes and geomorphological conditions.
2. Second, we highlight the causes of recent snowfall decline: an increase in seasonal temperature (Dobrovolný *et al*., 2009; Serquet *et al*., 2013), a contraction of interannual variability of snowfall with a general shortening of 14 days in snow duration due to a delayed starting date in autumn and a postponement ending date in spring, and a glacier recession, mostly due to a decrease in winter precipitation (Vincent *et al*., 2005; Huss *et al*., 2008).
3. Third, our work also highlights a substantial decrease of snow depth from the beginning of major warming. This finding is supported by both instrumental snowfall records over the last four decades in Italy (e.g., Diodato *et al*., 2018) and the analysis of Alpine glacier fronts retreat data (e.g., Huss *et al*., 2008; Lüthi, 2014; Goosse *et al*., 2018).
4. Forth, beyond the climatic changes occurred over time, we document urban heat island (UHI) effects though records of snow permanence at ground only started in 1937. With the caveat of the limited length of the series, we reveal a distinct UHI effect because the location and exposure of instruments did not change since 1937 (Supporting Materials). In Parma, the UHI was calculated by Zanella (1976), which performed a study on heat island measurements for the city having 170,000 inhabitants at that time. From his comparison of urban and a rural (airport) data for the period 1959–1973, he showed an average difference of 1.4°C. Zanella (1976) also reported that the difference varied seasonally, especially in spring and summer. Similarly, Bacci and Maugeri (1992) took measurements in Milan (1,600,000 inhabitants at that time) and found that the temperature difference between the city center and Linate airport was in average close to 1.4°C, with a heating rate of 0.13°C per decade (Santamouris, 2011). The presence of an urban heat island was also identified in the long instrumental

data series (1870–2016) of Turin by Garzena *et al*. (2018), which showed a reduction in the number of occurrences of frost and an increase in the number of tropical-like days and nights. This trend towards anomalously warm conditions in the last decades due to climate change and UHI indicates the decline of snow duration days as caused mainly by the increasing temperatures. Nevertheless, the reported shift around 1897 suggests that other factors than rising temperature may have caused the decline of snow duration as the changes in snowfall frequency, as we found that a strong correlation (R = .84) exists between snowfall frequency and snow duration in the period 1937–2018.

The critical role of snowfall in regulating water distribution and availability of water resources warrants an increased focus on monitoring snow trends. Our results indicate that much progress can be made by considering well-documented snowfall time series.

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CONFLICT OF INTEREST

The authors declare they do not have any conflict of interests.

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