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Unprecedented snow-drought conditions in the Italian Alps during the early 2020s

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Abstract

Snow represents a fundamental water resource for mountain and lowland areas. Changes in the frequency and magnitude of snow droughts can significantly impact societies and ecosystems that rely on snowmelt to satisfy their water demands. Here we documented and quantified the snow drought that affected the Italian Alps during the early 2020s. We used 15 long-term snow-depth series (period 1930–2023, elevation range: 864–2200 m a.s.l.) to simulate the snow water equivalent (SWE), in conjunction with climatic reanalysis data and river discharge observations. We found that the March SWE anomaly in 2022 reached the lowest value in the last century, due to an unprecedented combination of drier- and warmer-than-normal conditions in the period December 2021–March 2022. This event contributed to causing critical hydrological conditions in the Po and Adige rivers which, during summer 2022, experienced the worst hydrological drought ever recorded. Despite its unprecedented magnitude, the snow drought in 2022 is part of a recent pattern of increased intensity and frequency of snow-drought events since the 1990s, due to the combined increasing occurrence of warmer- and drier-than-normal climatic conditions during the snow season. Remarkably, three out of the five most severe snow-drought events occurred in the last five years, with exceptional snow-drought conditions even occurring in the last two consecutive winters, 2022 and 2023. The snow-drought conditions that occurred in the early 2020s in the Italian Alps warn of the pressing need for the implementation of impact mitigation measures to adapt to the fast changing snow and climatic conditions.

1. Introduction

Drought can have dire impacts on human activities and natural ecosystems (e.g. Stephan *et al* 2021). In the last two decades, different areas of Europe have been affected by numerous severe, large-scale drought events (in 2003, 2007, 2011, 2012, 2015, 2017, 2018, 2019, and 2020; Blauhut *et al* 2022). In particular, the Mediterranean area has shown the highest drought frequency and severity since the early 1990s (Spinoni *et al* 2015, Romano *et al* 2022) and droughts are projected to become even more recurrent and intense (Spinoni *et al* 2018, Baronetti *et al* 2022), with profound economic consequences (Naumann *et al* 2021).

Despite a growing concern about drought hazard, snow droughts (i.e. snow water equivalent (SWE) deficit; Pederson *et al* 2011, Harpold *et al* 2017) remain largely unexplored compared to other drought types (Hatchett and McEvoy 2018, Huning and AghaKouchak 2020), such as meteorological/climatological (precipitation deficit), agricultural (soil moisture deficit) and hydrological (deficit in river flow and groundwater, e.g. Van Lanen *et al* 2016) droughts. Drought conditions and record-low snowpacks in the United States in recent decades/years (Mote *et al* 2018, Iglesias *et al* 2022) provided incentive to study this emerging phenomenon (Hatchett and McEvoy 2018).

Although mainly investigated in the United States, recent global research showed that, in the last few decades, the frequency and duration of snow droughts have increased in Europe, which emerged as a hotspot for this kind of drought (Huning and AghaKouchak 2020). This evidence has been corroborated in Italy by the analysis of the long-term variability of simulated SWE across the Italian Alps (Colombo *et al* 2022), with a reported twofold intensification of snow-drought events during the past three decades.

In the last months of 2021 and throughout most of 2022, prolonged drought conditions affected the Mediterranean region and Western Europe (Faranda *et al* 2023). In Northern Italy, the water year 2022 (1 October 2021–30 September 2022) was marked by record-low precipitation and record-high air temperature. This occurrence resulted in a severe hydrological drought; agricultural and energy sectors were deeply affected by the very low discharge of several rivers, which was not sustained by the spring snow melt (Toreti *et al* 2022a, 2022b). In winter 2023, most of southern and western Europe was affected by exceptionally dry and warm meteorological conditions, showing similar patterns with respect to 2022 (Toreti *et al* 2023).

Here we took advantage of a unique dataset of continuous, historical daily snow-depth observations (period 1930–2023) to simulate long-term SWE, in conjunction with climatic reanalysis data and river discharge observations. We then used a stakeholder-oriented approach, based on anomaly indices, to document and quantify the unprecedented snow-drought conditions that affected the Italian Alps in the early 2020s. We used normalised indices which, moving from absolute values to the frequency domain, allow to: (i) compare time series collected from different locations (and possibly affected by local and regional factors), also favouring the comparison between different drivers (Colombo *et al* 2022); (ii) share information (Romano *et al* 2018), crucially supporting decision makers in assessing snow-drought conditions.

2. Data description and methods

2.1. Study region and snow-depth data series

The Italian Alps roughly correspond to the southern European Alps, defined as the mountainous area south of the main Alpine watershed (Brugnara and Maugeri 2019). The Italian Alps play a crucial role in feeding the main river basins of Northern Italy, namely Po, Adige, and Piave (figure 1). According to previous studies (Coppola *et al* 2014, Avanzi *et al* 2023), the snowmelt can contribute to up to 50% of the annual stream flow of the main rivers originating in the Italian Alps. In Northern Italy, economic activities account for more than 40% of the annual Italian gross domestic product and more than 35% of the Italian agricultural production comes from this area (Bozzola and Swanson 2014).

In this study, we used continuous daily measurements of snow depth (HS) retrieved from 15 manual and automatic stations (mostly manual measurements), covering the period between 1930 and 2023, across an elevation range of 864–2200 m a.s.l. (table 1). The stations are mainly located in flat, open areas, on the valley floors or near dams, and are distributed over different elevations and climatic regions in the Italian South Western Alps, North Western Alps, and South Eastern Alps (following ISMSA/SOIUSA, International Standardised Mountain Subdivision of the Alps/Suddivisione Orografica Internazionale Unificata del Sistema Alpino; Marazzi 2005; figure 1).

HS data were compiled by regional and provincial AINEVA avalanche services (Interregional Association for coordination and documentation of snow and avalanche problems), together with regional environmental protection agencies (ARPA Piemonte, ARPA Veneto), Centro Funzionale Regione Valle d'Aosta, Meteotrentino, Italian Meteorological Society (SMI), hydropower companies (CVA S.p.A., Enel S.p.A.), and Ministry of Public Work (hydrological annals). Data quality control, homogeneity assessment, and management of data gaps in the dataset are described in Colombo *et al* (2022), where the dataset was analysed in the time-span 1930–2020. In the present study, we updated the previous historical dataset with the winter seasons 2020/2021, 2021/2022, and 2022/2023. Missing values affected approximately only 1% of the entire dataset, with a maximum value of 3.2% for single series.

2.2. SWE modelling

Since no long-term SWE series exist, SWE has to be modelled (Winkler *et al* 2021, Colombo *et al* 2022). Physically-based models are able to resolve mass and energy exchange, although the amount and quality of required input data significantly limit their

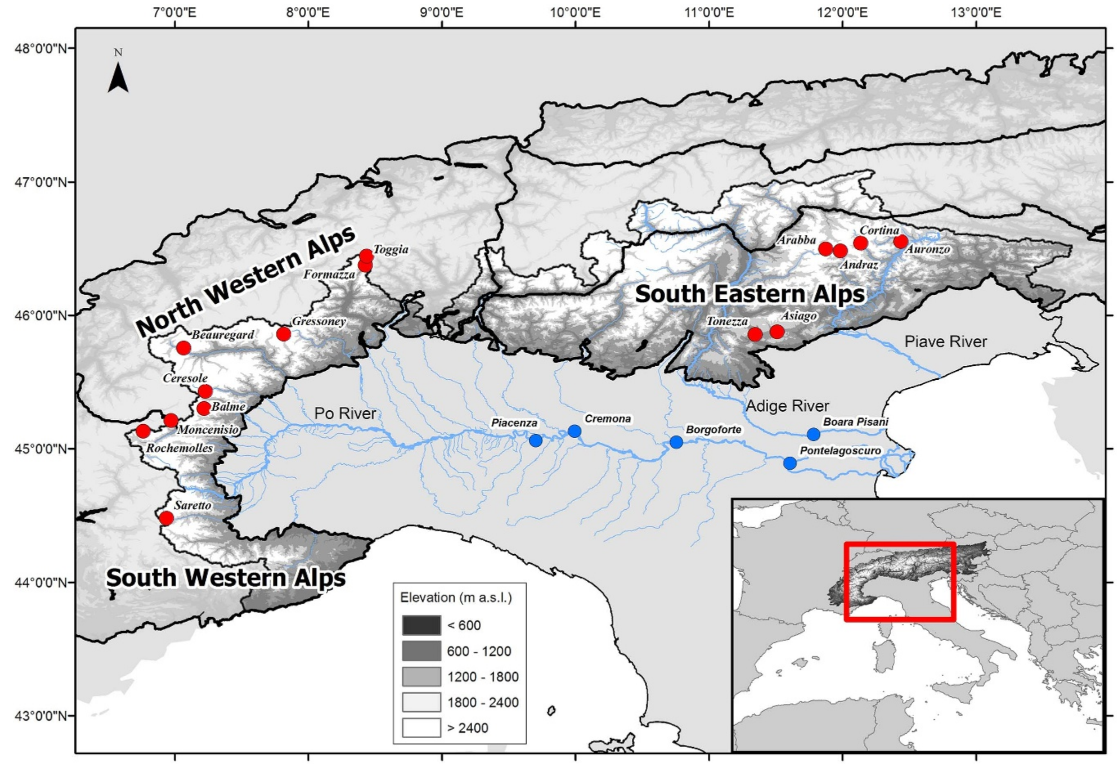

Figure 1. Region of investigation. The thick black line delimits the sectors of the Italian Alps, according to the SOIUSA classification (Marazzi 2005). The red circles identify the locations of the snow-depth (HS) stations. Po, Adige and Piave rivers (and their tributaries) are shown. The blue circles identify the discharge monitoring stations on the Po and Adige rivers. The digital elevation model of the Italian Alpine chain is shown in grey scale within the Italian national border and shaded outside. Adapted from Colombo *et al* (2022), Copyright 2022, with permission from Elsevier.

Table 1. List of the historical HS stations used in this work.

Station name	Elevation (m a.s.l.)	Longitude (WGS84)	Latitude (WGS84)	Time-series length (years)
Auronzo	864	12.44°E	46.55°N	1922–2023*
Tonezza	935	11.34°E	45.86°N	1927–2023*
Asiago	1000	11.51°E	45.88°N	1920–2023*
Cortina	1250	12.14°E	46.54°N	1920–2023*
Formazza	1280	8.42°E	46.38°N	1933–2023*
Andraz	1440	11.98°E	46.48°N	1921–2023*
Balme	1450	7.22°E	45.30°N	1928–2023*
Saretto	1540	6.94°E	44.48°N	1924–2023*
Ceresole	1579	7.23°E	45.43°N	1926–2023*
Arabba	1630	11.87°E	46.50°N	1929–2023*
Beauregard	1772	7.06°E	45.76°N	1924–2022
Gressoney	1850	7.81°E	45.86°N	1939–2023*
Rochemolles	1929	6.76°E	45.13°N	1925–2023*
Moncenisio	2000	6.97°E	45.21°N	1939–2023*
Toggia	2200	46.44°E	46.44°N	1932–2023*

* updated to March 2023.

application in mountainous areas (Egli *et al* 2009), especially considering historical data series (Colombo *et al* 2022). Conversely, empirical regression models (e.g. Jonas *et al* 2009, Pistocchi *et al* 2016, Guyennon *et al* 2019) are too strongly dependent on HS and, although able to adequately model single SWE features (e.g. mean, peak and seasonal SWE), they are not suitable for calculating daily SWE from HS time series (Winkler *et al* 2021).

Thus, in this study, we used a new semiempirical multilayer model for simulating SWE (and bulk density) from a regular time series of HS: the ΔSNOW model (Winkler *et al* 2021). Winkler *et al* (2021) calibrated the model using snow observations recorded during 67 winters at 14 stations, well-distributed over different elevations and climatic regions of the European Alps. Moreover, the authors used data from 71 independent winters from 15 stations for validation. The elevation range of the calibration/validation sites was between 590 and 1780 m a.s.l.

Here, we used the calibration proposed by Winkler *et al* (2021), given the suitability of the parameter setting for modelling SWE from daily HS time series in Alpine areas. Colombo *et al* (2022) validated the ΔSNOW model in the Italian Alps using four stations located between 1250 and 2100 m a.s.l., across the period 1983–2020 (501 observations). Modelled SWE had an overall Pearson correlation (R), mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) of 0.96, 6.3 mm, 39.9 mm, and 56.2 mm, respectively. In this study, we updated the calibration of Colombo *et al* (2022) by adding the measured SWE values from the winter seasons 2020/2021, 2021/2022, and 2022/2023 (36 observations), obtaining updated R, ME, MAE, and RMSE values of 0.96, 7.6 mm, 37.1 mm, and 55.7 mm, respectively. The results indicated a rather good performance in the representation of the SWE, generally in line with the performances of other modelling studies carried out in alpine areas (Colombo *et al* 2022).

2.3. Standardised SWE index

Following Colombo *et al* (2022), we calculated the standardised SWE index (SSWEI) at the monthly scale, choosing the 1961–1990 period as a reference baseline, by fitting a Gamma distribution for each month of the snow season, at each station. We defined the beginning and end of the snow season for each station as the first and last month having a minimum of 50% of monthly mean SWE $>$ 0 over the chosen baseline (Colombo *et al* 2022). All stations had at least 90% of the available months. We calculated a monthly value for all the Italian Alps by averaging all individual, station-based SSWEI values at the 15 stations. Aggregating the anomalies of each single station instead of considering the anomalies of the mean of each SWE series avoided an overrepresentation of those stations with higher SWE values (e.g. stations located at higher elevations). This also allowed to better address the inhomogeneous spatial distribution of the available long-term series (Colombo *et al* 2022). In addition, we explored potential elevational patterns by carrying out the analysis according to the three elevation ranges identified by Colombo *et al* (2022):

- Low elevation (four stations): 864–1250 m a.s.l., snow-cover duration: January–March.
- Medium elevation (eight stations): 1251–1850 m a.s.l., snow-cover duration: December–April.
- High elevation (three stations): 1851–2200 m a.s.l., snow-cover duration: November–May.

We considered the mean SSWEI of March as representative of the SWE accumulation before the melting season, similarly to the widely used 1 April SWE (cf Gottlieb and Mankin 2022), as a good approximation of the snow dynamics across our investigated elevation range (Colombo *et al* 2022). SWE on 1 April is generally considered to most closely approximate the maximum accumulation of snowpack. However, recent work has challenged its usefulness on the basis that snowpacks in different regions (and at different elevations) can peak before or after 1 April (Gottlieb and Mankin 2022). In this study, we considered March SSWEI as more representative of the snow season accumulation than the single 1 April value. This is also in accordance with the findings of a recent study which showed that the peak SWE across the Italian mountains generally occurs in March (Avanzi *et al* 2023).

2.4. Climatic drivers

To investigate the influence of air temperature and precipitation on SSWEI variability, we employed ERA5 (spatial resolution: 0.25° or ∼31 km, temporal resolution: 1 h; Hersbach *et al* 2020, 2023) for the period 1940–2023, selecting all grid points falling into the investigated region delimited by the SOIUSA classification (figure 1). For the previous period 1930–1939, we employed the monthly gridded data LAPrec1901 (Copernicus Climate Change Service (C3S) 2021) for precipitation and HISTALP (www.zamg.ac.at/histalp/dataset/grid/five_min.php) for temperature, after reporting the products to the same climatological means of the corresponding ERA5 records. More details are given in the supplement (text S1).

We calculated the monthly standardised precipitation index ((SPI); McKee *et al* 1993) at each node based on monthly-cumulated precipitation (considering 1-to-6-month accumulation periods), using the 1961–1990 baseline. For each aggregation scale, we considered the spatial mean of March SPIs as the corresponding winter precipitation anomaly index over the Italian Alps, referred as March SPI1 to March SPI6.

We calculated the monthly mean air temperature anomaly over each node by subtraction of associated monthly climatic mean over the 1961–1990 baseline. To obtain monthly air temperature anomaly time series over different aggregation scales (1–6 months), we applied a moving average to the resulting time series. For each aggregation scale, we considered the spatial mean of March monthly mean air temperature anomalies, normalised by the associated standard deviation, as the corresponding winter air temperature anomaly index over the Italian Alps, referred as March AT1* to March AT6*.

2.5. River discharge indices

Hydrological observations can be used as an indicator of the impact of snow drought. Long-term (1930–2023) daily and monthly river discharge measurements (table 2) were supplied by the Regional

Table 2. List of the historical discharge stations used in this study (*updated to March 2023).

Station name	River	Longitude (WGS84)	Latitude (WGS84)	Time-series length (years)*
Boara Pisani	Adige	11.78°E	45.10°N	1928–2023
Piacenza	Po	9.10°E	45.06°N	1924–2023
Cremona	Po	9.99°E	45.13°N	1935–2023
Boretto	Po	10.54°E	44.91°N	1943–2023
Borgoforte	Po	10.75°E	45.05°N	1924–2023
Pontelagoscuro	Po	11.61°E	44.89°N	1923–2023

Agencies for Environmental Protection of the Emilia-Romagna Region and of the Veneto Region for the Po and Adige rivers, respectively, representative of the Italian Alps snow catchment area (figure 1). Similarly to SPI and SSWEI, we calculated a standardised runoff index (SRI) based on the monthly mean discharge at each monitoring station, following Shukla and Wood (2008), using the 1961–1990 baseline.

3. Results and discussion

3.1. Record-low SWE in 2022

The 2022 March SWE, obtained by averaging all station-based values, broke all negative records in the period 1930–2023, reaching a minimum SSWEI value of −3.5 (figure 2(a)). This event surpassed by far any negative anomaly in the analysed time-span, even in the last three decades, which have been already characterised by an intensification of SWE deficits with respect to previous decades, both in the Italian (Colombo *et al* 2022) and European Alps (Marty *et al* 2017a).

In addition to the 2022 event, four other extreme snow-drought events (SSWEI < -2) occurred during the analysed period: 1949 (SSWEI $= -3.0$), 2012 (SSWEI $= -2.3$), 2019 (SSWEI $= -2.3$), and 2023 (SSWEI $= -2.8$). Strikingly, three out of five of these events occurred in the last five years, with exceptional snow-drought conditions even occurring in the last two consecutive winters, 2022 and 2023 (figure 2(a)). Considering only the years with SSWEI < -1.5, 11 out of 15 events occurred in the period 1990–2023. These findings further highlight the striking intensification of snow-drought magnitude and frequency in recent years (Huning and AghaKouchak 2020, Colombo *et al* 2022).

In the last decades, instead of a simple reduction in SWE, peak SWE might just have been moved to an earlier date with respect to March, according to elevation. However, in the Italian Alps, Colombo *et al* (2022) found that the lowest SSWEI values in the period 1930–2020 occurred from the 1990s, irrespective of elevation; more importantly, although they found that highly negative values occurred at the snow season tails (mostly in the spring), all months showed decreasing SSWEI values in the last decades/years. This is also true for 2022 (figure S1). The occurrence of a generally thinner winter snowpack in the last decades, rather than just an earlier occurrence of maximum SWE, is also in agreement with the measured negative SWE (Marty *et al* 2017a) and HS (Matiu *et al* 2021) trends, together with positive snow line elevation trends (Koehler *et al* 2022), in the European Alps.

Considering each elevation range, differently from the recent snow-drought events in 2012, 2019, and 2023, record-low SSWEI values occurred in 2022 across all elevation ranges: High elevation (SSWEI $= -3.9$; figure 2(b)), Medium elevation (SSWEI $= -3.8$; figure 2(c)), and Low elevation (SSWEI $= -2.7$; figure 2(d)). All analysed elevation ranges were deeply impacted, suggesting a combination of meteorological factors as potential cause of this occurrence, namely particularly dry and warm meteorological conditions (details below).

3.2. The role of climate drivers

The amount of SWE is the result of an interplay between precipitation and temperature, and their history throughout the snow season (Marty *et al* 2017a). Therefore, here we tested the relation between March SSWEI and winter precipitation and temperature anomalies, considering aggregation scale from 1 to 6 months for March SPI and March AT*. We performed a multi-linear regression (MLR) without intercept for each aggregation scale, considering four baselines (1930–2023, 1930–1959, 1960–1989, and 1990–2023). We found the best r-squared performance in explaining March SSWEI with a 4 months aggregation scale (i.e. December to March SPI and December to March AT*) for all the considered baselines (table S1). The fact that March SSWEI was best controlled by March SPI4 and March AT4* is in agreement with the findings of Marty *et al* (2017a), who found that measured April SWE was controlled by December–March temperature and precipitation in the European Alps.

The time-span December 2021–March 2022 was characterised by extremely dry conditions (figure 3). Indeed, March SPI4 in 2022 reached the fourth lowest value (−2.5) throughout the analysed period, after the years 1953 (−3.1), 1932 (−2.7), and 1938 (−2.6). For these last three years, March AT4* was always negative, ranging from −0.2 to −1.0. At the same time, in 2022, warm atmospheric conditions occurred, with March AT4* that reached a value of +1.7 (figure 3). The March AT4* value in 2022 was the 10th in the entire series, ranking after very warm winters, which

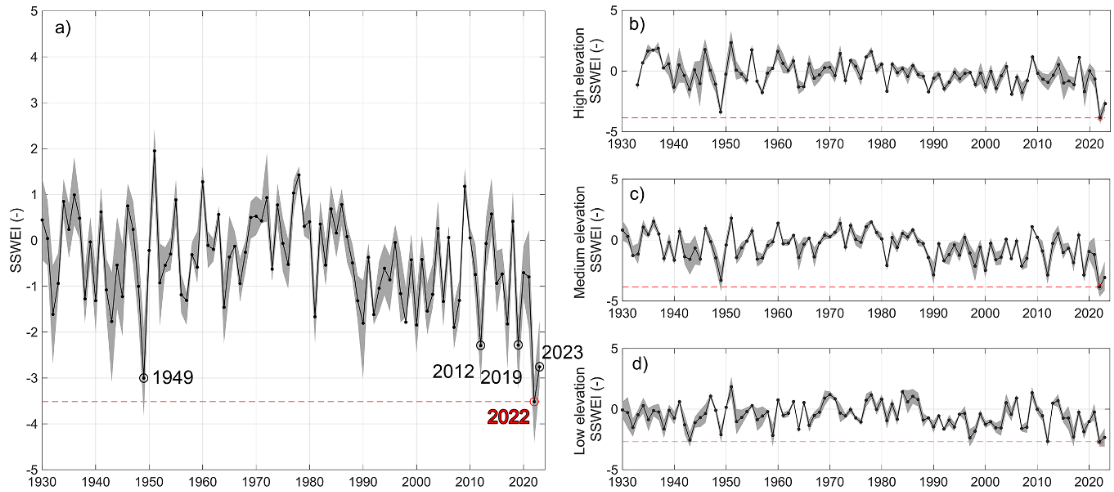

Figure 2. Long-term winter SWE anomalies (March SSWEI), considering all stations (a) and stations located at high (b), medium (c) and low (d) elevations. In all panels, the red dashed lines show the absolute minimum values reached by SSWEI; the grey area in the background shows the interquartile range. Absolute minima for all elevation ranges occurred in 2022; relative minima (SSWEI < -2) occurred in 1949, 2012, 2019, and 2023 are also shown in panel (a).

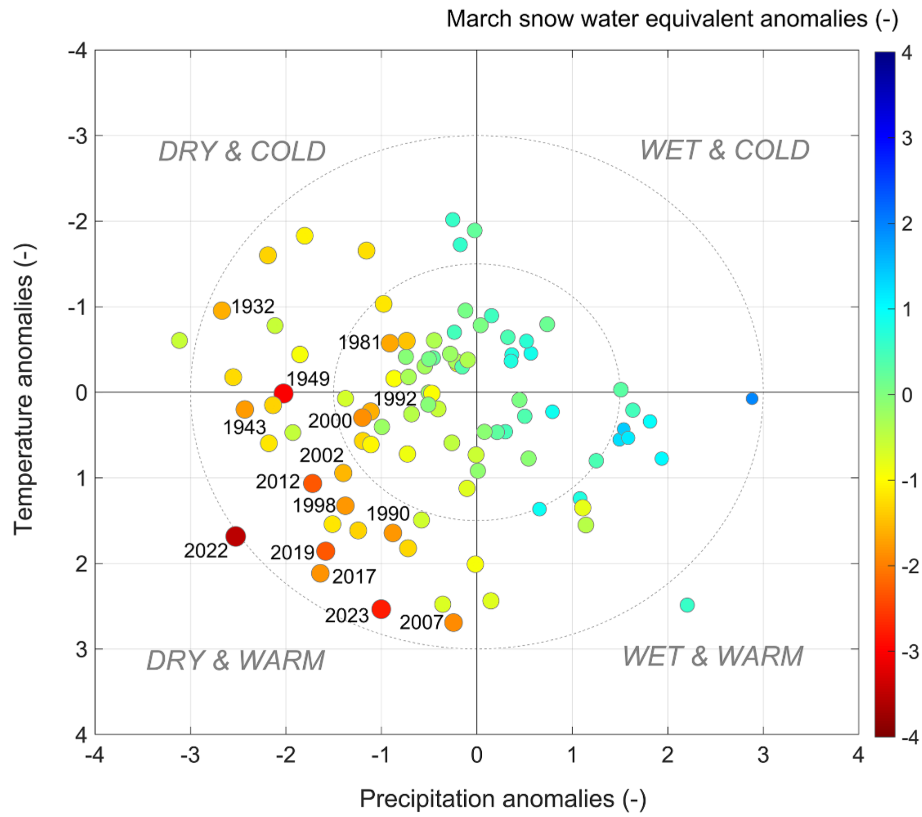

Figure 3. Scatterplot between winter precipitation anomalies (March SPI4) and temperature anomalies (March AT4*). March SWE anomalies (March SSWEI) are shown using a dimension/colour scale, from small/blue (positive, +4) to large/red (negative, −4). Inside and outside circles show 1.5 and 3 isoradial coordinates, respectively. Only the years with SSWEI < -1.5 are labelled.

all occurred after 2000. Although these nine warmer winters (2007, 2008, 2014, 2015, 2016, 2017, 2019, 2020, 2023) had higher temperature anomalies (from +1.8 to +2.7), SSWEI (ranging from −2.8 to 0.6) never reached such a low value as in 2022. This occurrence was likely due to relatively wetter winter conditions (March SPI4 from −1.6 to +2.2) with respect to the 2022 event. Thus, the unprecedented combination of drier- and warmer-than-normal conditions in winter 2021/2022 greatly inhibited seasonal snowpack accumulation, leading to the lowest SSWEI in the past century.

The proposed MLR analysis can also help quantifying the relative contribution of precipitation and

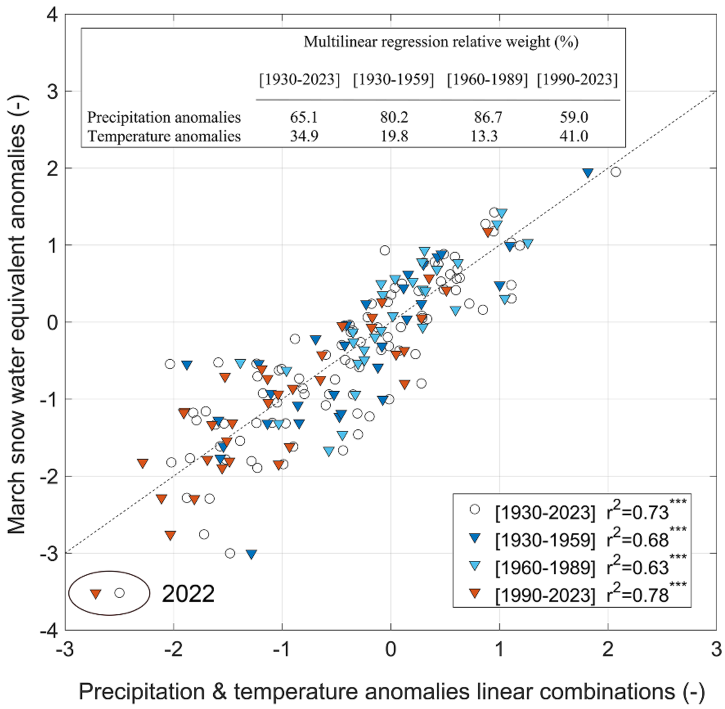

Figure 4. March SSWEI MLR considering March SPI4 (winter precipitation anomalies) and March AT4* (winter temperature anomalies). We considered 1930–2023, 1930–1959, 1960–1989 and 1990–2023 baselines. Intercept is forced to (0,0). Relative regressive weights are reported in the table inset in the top left corner; r2 values are shown in the table inset in the bottom right corner (*** indicates significance at $p < 0.001$).

temperature anomalies in controlling SSWEI, as both predictors follow a normal distribution by construction. We found that, considering the MLR relative weights for the baseline 1930–2023, March SPI4 and March AT4* contributed to 65.1% and 34.9%, respectively (figure 4). Remarkably, the relative weight of March AT4* greatly increased during the past three decades, from 19.8% and 13.3% over the baselines 1930–1959 and 1960–1989, respectively, to 41% over the baseline 1990–2023 (all regression weights and associated 95% confidence intervals are given in table S2). These results indicated the increasing role of temperature in explaining the SWE variability over the last decades, enhancing the effect of precipitation drought events (cf Colombo *et al* 2022). The 2022 event well exemplified the interplay of these conditions.

3.3. Hydrological implications

Warm and dry winter conditions occurring together, as in 2022, generally cause the most severe snow droughts and, consequently, the most severe summer streamflow droughts (Dierauer *et al* 2018). These can result in reduced hydropower production and drinking-irrigation water supply shortages (Dierauer *et al* 2018, 2019). As regards Northern Italy, we analysed historical discharge data collected on the Po and Adige rivers, in the period 1930–2023. In July 2022, the Po River registered the absolute historical minimum in all five analysed stations (Piacenza, Cremona, Boretto, Borgoforte and Pontelagoscuro; figure 5(a1)–(a5)), whereas on the Adige River (Boara Pisani station) a lower discharge was registered only in April 1944 (figure 5(a6)). A direct comparison with the monthly frequency distributions shows an impressive difference in July 2022 with respect to the 5th percentile in the order of $-47.4\% \pm 3\%$ and -45.4% for the Po and Adige rivers, respectively. It is worth noting that the differences of 2022 data with 'ordinary' discharge (when considering both 25th ÷ 75th or 5th ÷ 95th percentile) strongly increased during spring and summer.

Several processes potentially affect the river discharge in spring and summer and some of them are related to human activities, in particular irrigation and hydropower production. Therefore, the July discharge observations also integrate pressures on the water bodies and management options at river scale basis, which in turn can be related to climate factors, adding non-linearity to the processes. A graphical comparison of March SSWEI and July SRI1 (figure 5(b)) clearly shows the unprecedented and contemporary snow and hydrological drought in 2022. The July SRI1 vs March SSWEI Pearson correlation coefficients (figure 5(c)) show that SWE is capable of explaining approximately 50% of the interannual discharge variability. It is worth stressing, however, that part of this correlation can be directly

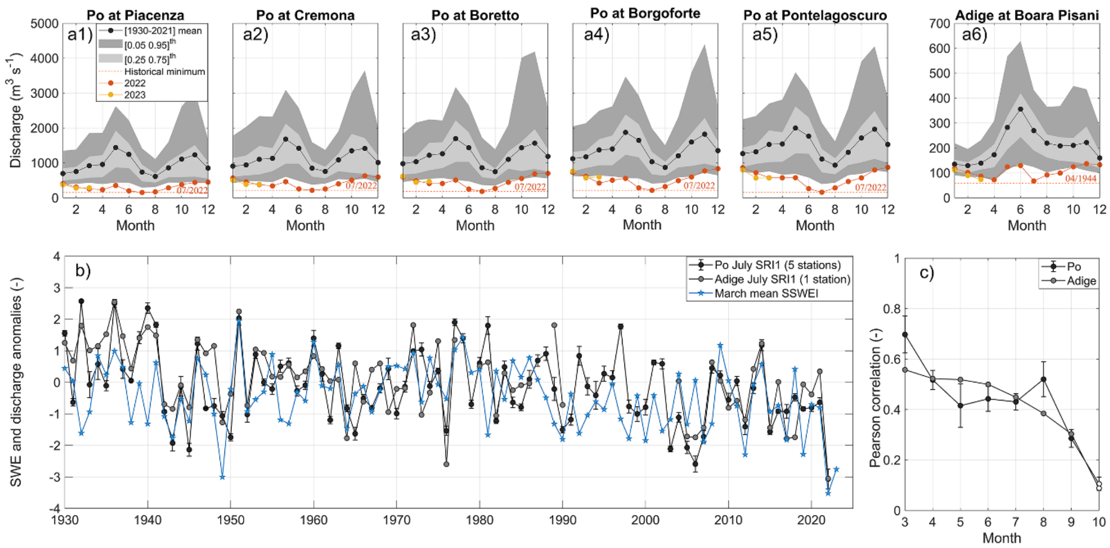

Figure 5. (a1)–(a6) Historical mean and associated 5th, 25th, 75th and 95th percentiles and 2022–2023 mean discharge at the Po and Adige rivers. (b) Historical time series of March SWE and July discharge anomalies (SSWEI and SRI, respectively). (c) Pearson correlation between March SSWEI and July SRI (mean and associated standard deviation are reported for the Po River); solid points indicate significant correlations ($p < 0.05$), hollow points indicate non-significant correlations.

due to the snow-melt process, and part to the increasing withdrawals from the water bodies (both surface and groundwater) due to a lack of resources. Assessing the weight of each process on the July SRI1 in river basins such as the Po and Adige that are so strongly impacted by human activities and in such a complex way is a challenging task beyond the scope of this study.

The critical hydrological conditions in 2022 strongly impacted several sectors, as proven by the drought bulletins issued by the Permanent Observatories for Water Uses of both the Hydrographic District Authorities of Po River (Po River; www.adbpo.it/osservatorio-permanente, accessed 27 April 2023) and Eastern Alps (Adige River; www.alpiorientali.it/osservatorio-permanente.html, accessed 27 April 2023). The 'water severity', that is the ability of the water supply systems to meet the ordinary water needs for all sectors, shifted from 'medium' in April to 'high' from July onwards. The dramatic drought conditions forced both authorities to constantly monitor and re-allocate the very scarce resources available among the different users, with the agricultural sector being particularly affected. Such conditions also strongly impacted the ecosystems; by way of example, the sea water intrusion at the Po delta increased from about 20 km (at Goro monitoring station) at the beginning of June to about 40 km in mid-July (Po river Authority, drought bulletin n.12/2022, July 7th, 2022).

The situation in 2023, until the end of March, appeared rather similar to 2022, not only considering the snow-drought conditions, but also in relation to the hydrological ones (figure 5(a1)–(a6)), which in turn were the historical minima, posing serious concerns for the forthcoming summer, when water needs are expected to strongly increase. For instance, the energy stored in water reservoirs and hydro storage plants accounted for 821 175 MWh, the second worst situation over the period 2015–2023, the worst being 2022 (735 675 MWh) (ENTSO-E Transparency platform, https://transparency.entsoe.eu/dashboard/show, accessed 27 April 2023). Analogously, severe impacts might be expected on the ecosystem services, considering that the sea water intrusion was estimated around 25 km at the end of March 2023 (it was 20 km in April 2022). The occurrence of two consecutive, exceptional snow-drought winters may lead to an unknown scenario, from both hydrological and hydrogeological perspectives, as very little is known about the impacts of persistent snow-drought conditions on groundwater and associated non-linearity (e.g. soil-vegetation-atmosphere interaction, infiltration dynamics, inversion of the vertical river-aquifer gradients).

The unprecedented snow droughts that occurred in the early 2020s offer an analogous perspective for projected future snow conditions in the Italian Alps, and in the European Alps in general. Indeed, in the Alps, future snowfall (Frei *et al* 2018), snow-depth (Marty *et al* 2017b), snow-cover (Matiu and Hanzer 2022) and SWE (Kotlarski *et al* 2022) decreases have been predicted. Such decreases, strongly linked to the expected rise in air temperature (Kotlarski *et al* 2022), might have further large implications on water availability, especially during the warm season (Jenicek *et al* 2018). Northern Italy might be strongly affected by these changes. For instance, in the Po River Basin, nearly 20% and 40% of future irrigation water demands must be met by sources alternative to snowmelt under the +2 °C and +4 °C warming scenarios, respectively (Qin *et al* 2020). Thus, time is running out for anticipating and effectively adapting to the ongoing (future) climatic changes.

4. Conclusions

Here we investigated the exceptional snow-drought conditions that affected the Italian Alps during the early 2020s. During winter 2021/2022, the mean March SWE anomaly, expressed through the SSWEI, reached the lowest value in the last century (time-span 1930–2023). The extreme snow drought impacted all analysed elevation ranges due to an unprecedented combination of drier- and warmer-than-normal conditions in the period December 2021–March 2022. This event contributed to causing critical hydrological conditions, with an extremely severe hydrological drought in the Po and Adige rivers. Summer streamflow was particularly impacted, with an unprecedented hydrological drought that was measured on the Po River in July 2022. Although the snow drought in winter 2021/2022 was the worst ever observed, in the last decades (from 1990s on) there has been an increase in frequency and magnitude of snow-drought events. We found an increasingly relevant role of warming air temperature in driving such events. Thus, considering the predicted air temperature warming, meteorological drought increasing, and SWE decreasing during the next decades, the 2022 snow-drought event could offer an analogous perspective for projected future SWE conditions in the Italian Alps. Remarkably, during winter 2022/2023, the March SWE anomaly reached the third lowest value in the analysed period. The impacts of two consecutive, extreme snow droughts in winters 2022 and 2023 on the hydrological and hydrogeological drought are currently unknown. In the light of our findings, we consider the implementation of risk mitigation measures to be of primary importance, taking into account the 'new normality' of snow conditions in the Italian Alps, and the use of standardised indexes to support effective adaptation practices relying on stakeholders' cooperation.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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