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Characterizing past and current snow seasons through the application of a new multivariate snow index

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ABSTRACT

In recent decades, the snowpack in the Pyrenees has tended to decrease due to a rise in average temperature and precipitation variability. This trend has impacted sectors, such as snow tourism, hydroelectric power generation, and water resources management. To monitor winter snow seasons and detected extreme changes we propose a Multivariate Snow Index (MSI) that characterizes the climatic temporal and spatial variability of the snowpack. MSI is based on high and low quantiles of daily maximum snow depth distributions and can be applied to different regions, spatial scales and both current climate and future projections. The application of the MSI not only reveals a clear spatial pattern across the study region, but also allows the winter snow seasons to be individually characterised at each station. Overall, the Western Pyrenees generally exhibit longer lasting and more intense surplus seasons, while the Eastern Pyrenees show statistically significant downward trends. In the context of climate change, the index provides local information for decision-makers and stakeholders, assisting them in adapting management strategies across various sectors.

1. Introduction

The Pyrenees are a European mountain bioregion that is vulnerable to the effects of climate change, both from an ecological and a socio-economic perspective. At the end of the 21st century, the level of greenhouse gases will play a fundamental role in emission scenarios and temperature increases (IPCC, 2023). The observed increase in temperature in recent decades and the variability in precipitation have shown a trend of decreasing snowpack in this region (OPCC, 2018; 2021a,b; Langsdorf et al., 2022). Rising temperatures in future climate scenarios threaten high mountain regions (e.g. the Himalayas, Andes, Alps), increasing snow scarcity, and reducing snowfall (Pérez-Palazón et al. 2018; Morin et al., 2021). Snow is crucial for water resource and sustaining mountain ecosystems (Beniston, 2003; François et al., 2022). Mountain regions like the Pyrenees it is often the primary economic driver for many communities where snow tourism supports local livelihoods (Pons et al., 2015; Spandre et al., 2019a). The impacts of climate change on high mountain areas are more pronounced, and there are records of daily and monthly temperature exceeding the alert thresholds established in international agreements such as the Paris Agreement (Copernicus, 2023). In the case of precipitation, the variability in time and space, along with limited historical data of regions, makes it challenging to identify a clear trend. Nevertheless, rising temperatures will directly impact the snow precipitation, raise the snow line, and the duration of snow cover (Gobiet et al., 2018). In this sense, precipitation projections accumulate more uncertainty than temperature projections. Therefore, the study of snowpack distribution and evolution is a challenge in the current context. Its distribution can be determined by few or several snowfalls through the indicator Concentration Inex (CI) for example. Recently, Lemus-Canovas et al., 2023 used CI (Martin-Vide, 2004) to quantify snow variability across the main mountain systems of the Iberian Peninsula. In the Pyrenees, snowfall patters vary significantly. Eastern region few snowfalls define the snowpack and in north and western Pyrenees is more evenly distributed during the season (Bonsoms et al., 2021a). Precisely, some studies have identified the relationship between the evolution and variability of the snowpack with the major hemispheric and regional circulation patterns such as the NAO (North Atlantic Oscillation) and the Western Mediterranean Oscillation (WeMO) (Alonso-González et al., 2020; Bonsoms, et al., 2021b; Añel et al., 2014), which are also key drivers of the precipitation patterns

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(Lemus-Canovas and Lopez-Bustins, 2021).

Regional-scale monitoring of the snowpack has become essential to understand this variability. Statistical analysis of imagery series from missions like MODIS, Landsat, and Sentinel, both optical and microwave sensors, has become crucial in understanding the recent evolution and distribution of the snowpack (Gascoin et al., 2015; 2022). Furthermore, physically modelling of the snowpack is possible, which is vital for assessing natural hazards (Nicolet et al., 2018; Richiardi et al., 2023; Faranda, 2020) and understanding hydrological impacts (Fang et al., 2020). This modelling also helps quantify climate change impacts on ski resorts (Gilaberte-Búrdalo et al., 2017; Morin et al., 2021; Pons et al., 2015; Spandre et al., 2019b; Steiger et al., 2019). Overall, remote sensing and climate model provides a broader perspective than observations from nivometeorological stations.

One of the reference frameworks for monitoring climate change are the indicators proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Karl et al., 1999; Peterson et al., 2001). The ETCCDI indices are a set of basic climate indices developed for monitoring climate extremes of temperature and precipitation, but do not consider specific indices for the snow precipitation. Analogous to the ETCCDI, indicators derived from Snow Cover (SC – Snow Cover), in terms of duration and extend, and Snow Depth (SD – Snow Depth) observations have been proposed (Witmer, 1986; Morán-Tejeda et al., 2017). There are numerous indicators with a climate focus such as Snow Water Equivalent (SWE), others the maximum monthly SD, start and end of the continuous SC, the Fresh Snow (FS) accumulated during a season, approximations based on aggregations by specific periods or the exceeding certain thresholds (e.g. SD $>$ 30 cm for operational stations). Additionally, there are indicators focusing on the temporal distribution of snowfall such as the previously mentioned Concentration Index (CI) (Lemus-Canovas et al. 2023), and the Snow Storage Index (SSI) (Hale et al., 2023) which addresses the distribution of snowfall intensity. Indicators that determine the onset of the melt season (Brown and Mote, 2009) and those that quantify the fraction of precipitation falling as snow versus rain (Marty and Blanchet, 2012; Vickers et al., 2022). Recently, a suite of spatially extensive metrics—Snow Cover Frequency (SCF), Snow Disappearance Date (SDD), At-Risk Snow (ARS), and Frequency of a Warm Winter (FWW)—has also been made available to help assess both recent and potential future changes in snow cover (Nolin et al., 2021). However, despite the diversity of indicators concerning snowpack evolution (Abegg et al., 2021; Gobiet et al., 2014; Lejeune et al., 2019) most of them are based on SC and SD. These indicators can be applied to current and climate projections and therefore have results for sectors that require further adaptation to climate change.

The monitoring of these indicators, as well as SD and SC trends have a large variability between regions and altitudes. The main results in the Pyrenees show a statistically significant decrease SD and SC in stations at 2100 m for the period 1980–2016 (López-Moreno et al., 2020). The evolution of the SC shows a non-significant negative trend for the whole Pyrenees in the order of -5% for the period 1982–2020 but a positive trend for durations of SC (Notarnicola, 2022). Currently, there is a gap in indicators to detect climatic extremes while also distributions (regularity/irregularity) and magnitudes during the season, key features for decision making in different sectors. This work proposes a new indicator that combines key aspects of snowpack behaviour during the winter in terms of 1) magnitude (scarcity or surplus) and 2) duration (snow cover days). This multivariate indicator offers a concise and practical way to assess snowpack and can be applied in any mountain region with a snow data.

The objective of this indicator is monitoring SD and providing real-time assessment of whether seasonal snowfall and SD are above or below average. It facilitates detailed and comprehensive comparison with previous seasons, by utilizing historical SD observations series. Additionally, is to improve decision-making support for short- and long-term planning. Key applications include forecasting water resources availability, assessing the viability of snow tourism and understanding the impact on ecological niches. It also supports the development of specific policies for hydrological, environmental and socioeconomic systems, and implementing preventive measures for natural hazards like floods or avalanches, which are critical increasingly exposed populations (García et al., 2009). Following the SMART criteria (Specific, Measurable, Achievable, Relevant, Time-bound). this indicator is derived from the daily snow depth and can be applied at various locations given requirements. Finally, it is transferable to different sectors to support climate adaptation and strategies.

To achieve these objectives, the work begins with an introduction to the study area and a description of the types of data currently available in the region. The second section details the definition and methodology of the new indicator and to calculate trends. The results section presents an analysis of the indicator behaviour across the Pyrenees, complemented by an example from a specific station. Finally, the last section provides conclusions and discussion of the work.

2. Methods

2.1. Study area

The Pyrenees mountain range, located in the northeast of the Iberian Peninsula spans 425 km from the Cantabric Sea in the west to the Mediterranean Sea in the east and covering a total surface area of 19,000 km^2 (Fig. 1). The Pyrenees forms a natural border, both climatically and administratively. Its orientation west-east enhances climatic contrasts between the northern and southern slopes while its complex orography influences the arrival and passage of frontal systems. The Pyrenees feature a high mountain climate, with significant and differentiated rainfall between slopes and temperature distribution closely tied to altitude gradients (Bonsoms, et al., 2021a). Climatically, similar as others European mountain systems, e.g. the Alps (Matiu et al., 2021), the Pyrenees act as climatic boundary between the Atlantic climate in the northeast and the Mediterranean climate in the southeast, with continental features in the central region (Lemus-Canovas et al., 2019). Each climatic region is influenced by distinct atmospheric circulation patterns. Relevant changes in southeast are associated with the interannual variability of the Mediterranean climate while the NAO is responsible for the climatic variability of the North Atlantic (Vicente-Serrano and Heredia-Laclaustra, 2004) where synoptic patterns will determine the direction and intensity of the circulation of depressions and the location of anticyclones.

The precipitation is under the influence of two such distinct water

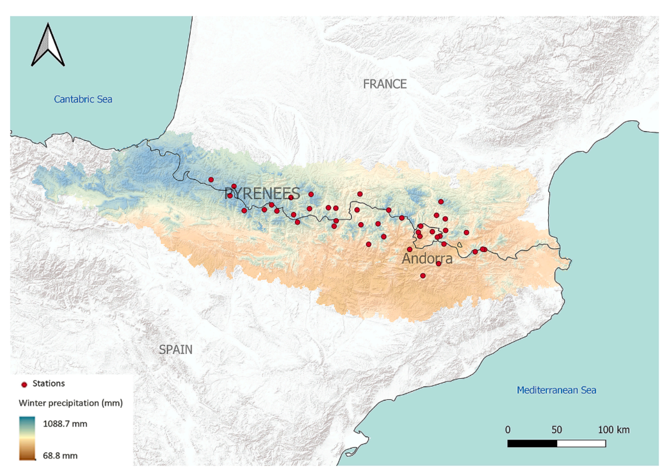

Fig. 1. Study area located in the north-east of the Iberian Peninsula, winter precipitation map (in mm) in the Pyrenees Mountains for the period 1981–2015 (result of the CLIM-PY project) and in red dots are represented all stations used for the present work. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

masses – Mediterranean Sea and the Atlantic Ocean-, as well as by latitude and longitude. The distribution of precipitation decreases from west to east and from south to north (Buisan et al., 2015; 2016). The northern Pyrenees receives more precipitation overall and thus have a large winter snowpack than southern slope (Navarro-Serrano and López-Moreno, 2017) (Fig. 1). This different is due to its greater exposure to cold and humid air masses carried by the prevailing westerly and north-westerly winds from the Atlantic Ocean (Alonso-González et al., 2020; Lemus-Canovas et al., 2019). However, the southern and eastern half of the mountain range, which has a lower snowpack is strongly conditioned by Mediterranean cyclogenesis situations (García-Sellés, 2017) that occur infrequently in winter conditions but pluviometrically contribute greatly to the evolution of the annual snowpack (Esteban et al., 2005). At high mountain above 2000 m low temperatures and the snow precipitation in winter ensure permanent snow cover for much of the year. The orography, both in location and orientation, facilitates a deep and persistent snowpack at higher altitudes of the mountain, while decreases with decreasing elevation.

2.2. Datasets

In the framework of the CLIM-PY project (EFA 081/15) — Characterization of climate evolution and provision of information for adaptation in the Pyrenees— a climatic database of snow depth was developed for the period 1980–2016. This dataset combines snow beacons network, manual observations from ski resorts, meteorological weather stations and refuges, among others, existing in the Pyrenees (Gascoin et al., 2015; Ignacio López-Moreno et al., 2020).To address the gaps in the time series of snow depth the project utilized a methodology that reconstructs missing data by applying the SAFRAN chain (meteorological reanalysis) – CROCUS model (snow cover evolution model) (Durand et al., 1999; Vernay et al., 2022). Combining in situ observations and modelling has improved the quality of the data, giving continuity to the climatic series, especially for ski resorts with manual observations.

High mountain conditions limit the availability of historical climate data, particularly above 2000 m. Most stations are in the altitudinal range between 1500 and 2500 m. Although there are a numerous station above 2000 m, many were installed in 1990 s, with the expansion of snow tourism sector and new ski resorts (Table 1). The CLIMPY project, a database with over 50 measurement points was created, covering most of the Pyrenees. However, data length remains a limitation making it essential for climate studies to analyse spatial patterns and temporal trends.

For this work, to be able to perform the indicator calculations proposed and to have a sufficiently long period for trend analysis, we excluded stations that i) had less of 50 % of days with snow cover; ii) relied on modelled data more than 70 % of observations; and iii) had less than 10 years of operating history. Applying these criteria excluded 15 stations, most of them for not meeting the criterion of snow cover, particularly at lower altitudes. Other, some stations were excluded because the percentage of modelled was too high or the operational period was less 10 years. In total, 44 stations out of the 57 available were selected, with most of them located between 1500 m and 2000 m and between 2000 m and 2500 mm.

For trend analysis, we used a continuous, high-quality dataset covering the period from 1980 to 2016. For the case study, the dataset has been updated with recent data from the National Meteorological Service to evaluate the indicator's performance and demonstrate its applicability across various sectors.

Table 1
Summary of available and used stations by altitude range in the study area. The second column lists the total number of available stations with snow depth measurements. The third column indicates the total number of stations selected and used in the analysis. The last column provides the average length of data (in years) for stations without any modelled data.

Altitude	Number of stations available	Number of stations used	Length of data observed
<1000 *m*	5	0	26 years
1000 m-1500 *m*	12	6	27 years
1500 m-2000 *m*	19	18	27 years
2000 m-2500 *m*	18	18	21 years
>2500 *m*	2	2	15 years

2.3. Multivariate snow index (MSI)

We propose the calculation of a new daily index, Multivariate Snow Index (MSI + Surplus or −Scarcity), which consists of an objective characterization snow depth anomaly. MSI calculation relies from the snow depth), e.g. the maximum daily total Snow Depth *SD*. The index is based on the high/low quantiles of the daily *SD* distributions. The Fig. 2 shows the daily snow depth evolution for a season. The 50th percentile of snow depth (P_{50}) (red line Fig. 2) was calculating using the daily values from all seasons within a reference period. The methodology to compute MSI, first defines two parameters to quantify the surplus seasons from the treatment of *SD*:

a) **Duration** $[SD_d]$: total number of days during the winter season when the maximum daily snow depth *SD* is greater than or equal to respective P_{50} calendar date.

$$SD_d = \sum_{i=1}^{n} 1(SD_i \geq P_{50}) \tag{1}$$

where 1 is the indicator function, which equals 1 if $SD_i \geq P_{50}$ and 0 otherwise, and n is the total number of days in the winter season.

b) **Magnitude** $[SD_m]$: The sum of the positive differences between the daily *SD* and P_{50}, starting from the third consecutive day when *SD* exceeds P_{50}:

$$SD_m = \frac{\sum_{i=k}^{n}(SD_i - P_{50}) \bullet 1(SD_i \geq P_{50})}{n}$$

$$for\ i \geq k \tag{2}$$

In case where $SD_i < P_{50}$, the indicator scarcity SD_{ddry} and SD_{mdry} is obtained. Both the surplus and scarcity values are normalized by total

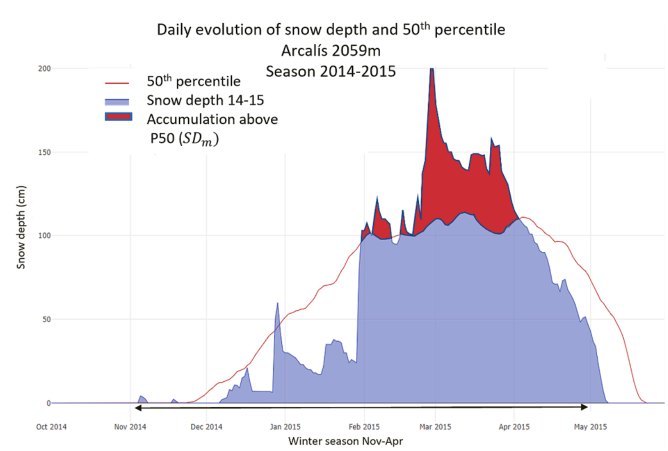

Fig. 2. Daily evolution of snow depth, P_{50} (red line) and SD_m (red area) for a specific station in Andorra (Arcalís station at 2059 m for the 2014–2015 season). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

season length, (181 in this case), to determinate the centimetres lost or gained per day.

It is an index inspired by those used for the climatic characterization of heat waves, where both temporal (frequency, duration) and magnitude (extremes) criteria are defined (Soubeyroux et al., 2015; 2016; ONERC, 2023). The three-day consistency threshold helps identify sustained snow depth changes and differentiate them from isolated anomalies. This consistency configures a relevant situation on a climatic scale. Therefore, if we observe in Fig. 2, the temporal evolution of maximum daily snow depth (blue area) during the 2014–2015 season in Arcalís station (Andorra). The red line represents the calculation of the daily P_{50} for reference period and the duration (SD_d) can be easily inferred. The red area is the accumulated surplus from the third day in which the $SD_i \geq P_{50}$. For example, at the beginning of the season, in January, SD is above P_{50} for two days, insufficient to be considered in the calculation of the surplus (SD_m). Thus, the seasonal concentration or irregularity of snowfalls −or snow accumulation- is quantified through the CI index as proposed in Lemus-Canovas et al. (2023). The CI, introduced by Martin-Vide (2004), is a statistical measure specifically designed to analyse the distribution and concentration of precipitation events within a given time period e.g., winter season. The CI provides a way to quantify the distribution of precipitation events with higher values indicating a more uneven or concentrated distribution, and lower values suggesting a more even distribution of events across the period selected. The equations related to the process of calculation of the CI can be found in detail in Lemus-Canovas et al. (2023).

The availability of data series longer than 10 years enables extract trends and analysis of the MSI + long term evolution. Time trends have been worked from a linear regression with statistically significant when the p-values are ≤ 0.1 for both the duration parameter (SD_d) and the magnitude (SD_m).

To evaluate MSI+ in the results section, the average values has been represented and two contrasting seasons have been also compared. First, a deficit season (2006–2007), with a marked negative precipitation anomaly, which was characterized by low precipitation and was particularly dry in the extreme east of the Pyrenees, where some stations experienced one of the least snowy winters, like Núria at 1971 m (Meteocat, 2007). In contrast, a season with a very marked positive precipitation anomaly (2012–2013) has been selected. This season is taken as an example because it was one of the wettest winters of the last 15 years in a large part of the western Pyrenees, with a record SD total of 410 cm, exceeding the 360 cm of March 2005 at the Bonaigua station at 2266 m (Meteocat, 2013). Finally, the MSI + was explored through a specific case study at weather station.

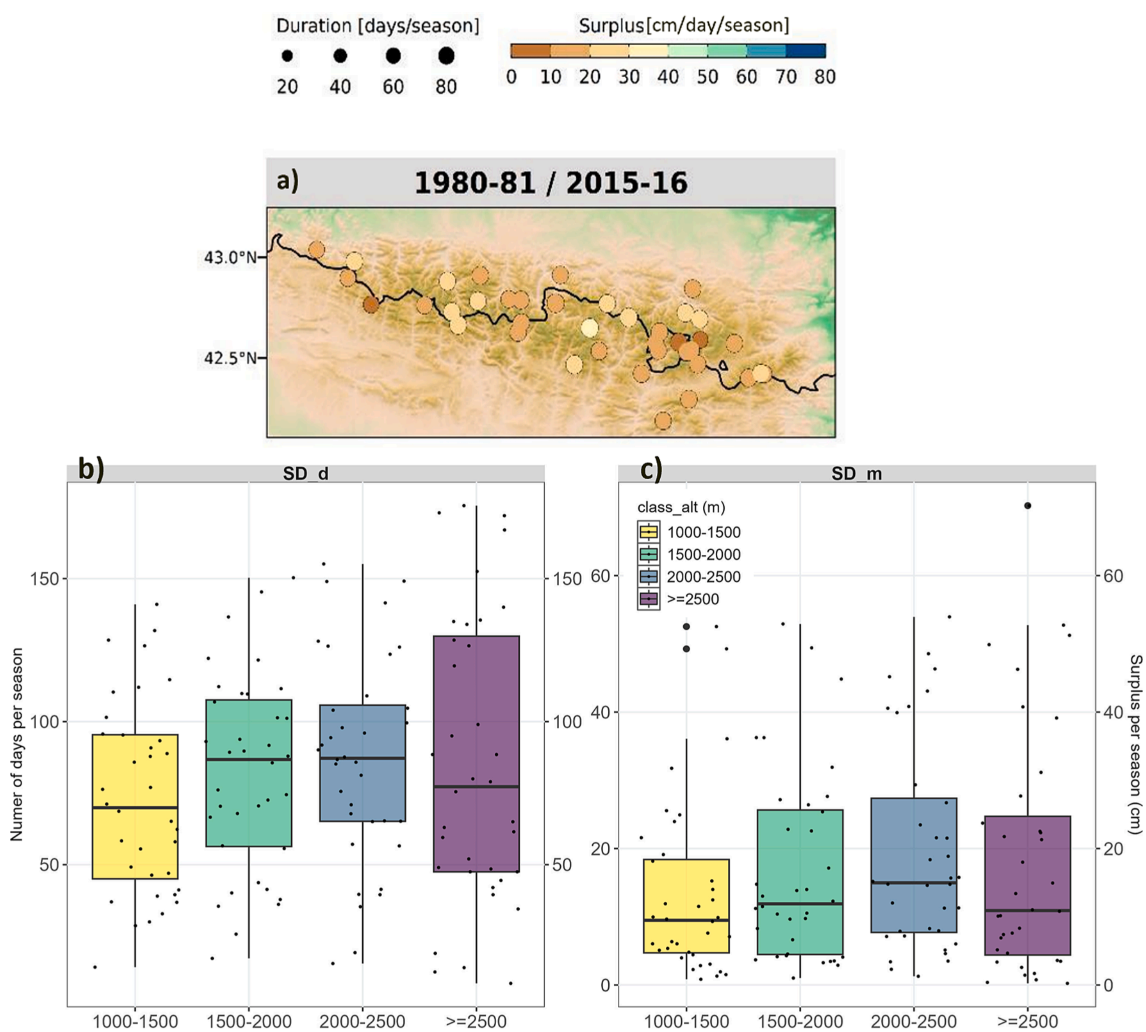

Fig. 3. Spatial distribution of MSI + in the Pyrenean stations a) representing both duration and magnitude (in circles and colour scale, respectively); Boxplots showing the parameters a) SD_d and c) SD_m across different altitude ranges categorized into four altitudinal classes: 1000–1500 m, 1500–2000 m, 2000–2500 m, and ≥ 2500 m.

3. Results

3.1. MSI+

The results of applying the Multivariate Snow Index in Surplus mode (MSI +) across selected observation points are presented below (Fig. 3). These results covered the winter period 1980–2016 (36 years), both the average values for the entire period and detailed analysis of two specific seasons. Fig. 3a shows that, on average, Pyrenean stations accumulate between 10 and 30 cm of snow per day and season above P_{50} (SD_m). The number of days SD_d is very regular along the mountain range and for all the stations, and on average more than 60 days per season. The complementary analysis carried out by calculating the CI index (Fig. S1), as proposed in Lemus-Canovas et al. (2023), provides a way to quantify the distribution of precipitation events during a season. Higher values indicate a more uneven or concentrated distribution, and lower values indicate a more even distribution of events over the selected period. The spatial distribution of the mean CI shows differences in the frequency of snowfall events that contribute to a normal snowpack (P_{50}) along the Pyrenees. Stations located mainly on the northern and western slopes, present many snowfall events distributed over the season (0.45), but stations located further east and on the Mediterranean slopes, snow episodes that contribute to the normality is concentrated in few snowfalls. Despite these differences, the mean distribution of the CI has a low variability, between 0.45 and 0.55, for most stations, except for some in the southeast of the Pyrenees.

Fig. 3b and 3c present the altitudinal distribution of SD_d and SD_m across different ranges defined in Table 1: 1000–1500, 1500–2000, 2000–2500 and ≥ 2500 m. Stations at lower altitudes (1000–1500 m) exhibit shorter mean duration and magnitude. Despite the spread due to the seasonal variations at all altitudes, the SD_d, the number of days with snow depth above P_{50}, increases steadily with altitude up to 2000 m as does the SD_m. However, the two stations at higher altitudes (Espot (2520 m) and Boí (2520 m)) show a scattered distribution and the MSI + parameters are slightly lower compared to nearby areas. The available datasets suggest that in the Pyrenees the 2000–2500 m range experiences longer snow cover periods and accumulates greater snow surpluses during the season.

The 2006–2007 season (Fig. 4a) shows a marked snow deficit across the Pyrenees, with SD_d and SD_m both displaying low values. During the 2006–2007 season SD_d remained below 40 days, with some stations fewer than 20 days. The seasonal magnitude SD_m was similarly low, with most stations not exceeding 10 cm/day. The spatial distribution is relatively homogeneous, with both northern and southern slopes

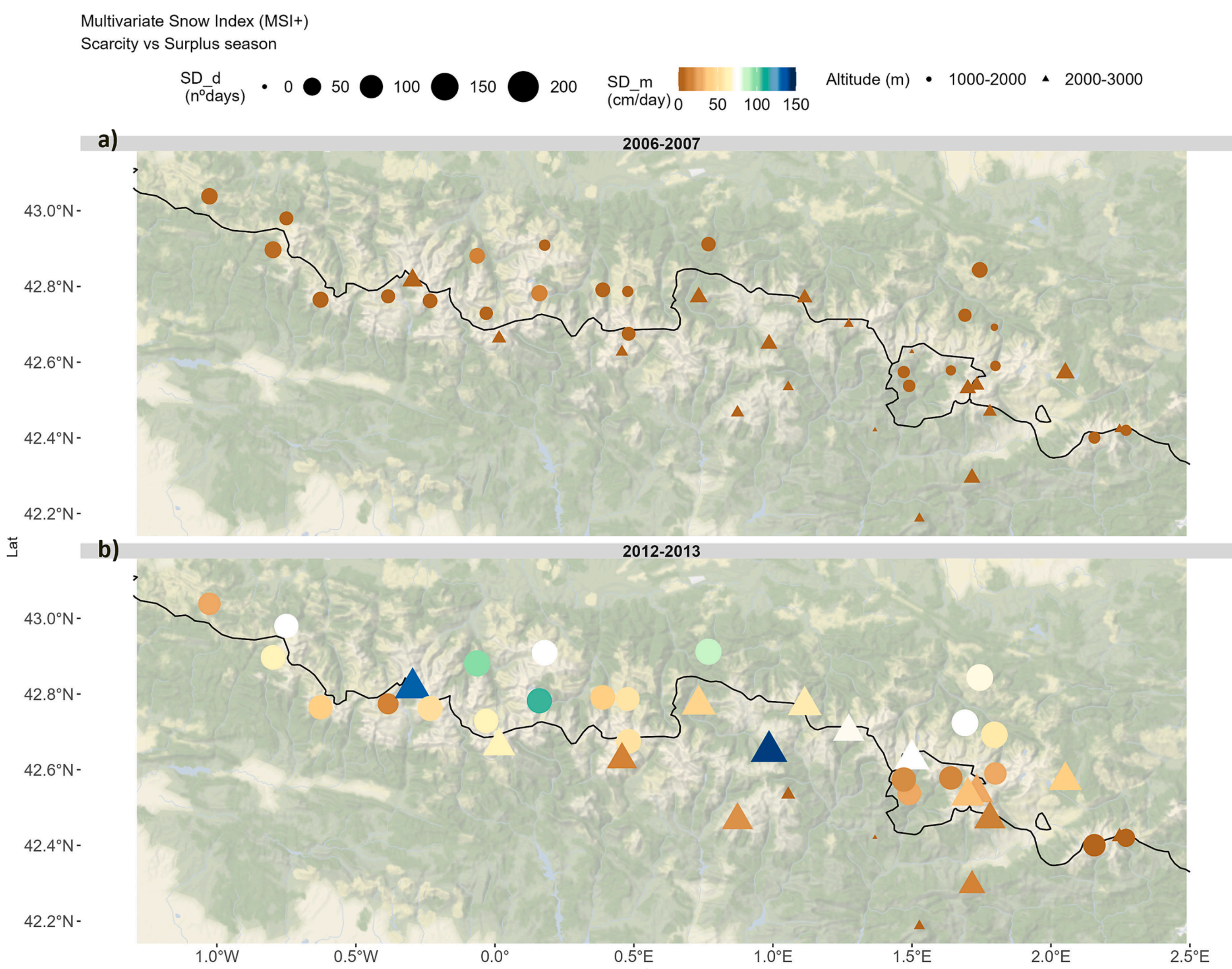

Fig. 4. Spatial distribution and altitudinal behaviour of MSI + for two contrasting seasons: a) 2006–2007 (scarcity season) and b) 2012–2013 (surplus season). Circle and triangle indicate the altitude range of the station (below or above 2000 m, respectively), the symbol size represents SD_d (number of days with snow depth above P_{50}), and colours indicate SD_m (snow surplus magnitude in cm).

experiencing low snow depth. In contrast, the 2012–2013 season (Fig. 4b) reflects a surplus snow year, particularity in the western and northern Pyrenees. the SD_d parameter showed a different pattern with values exceeding more than 80 days in the westernmost stations, and seasonal magnitude surpassing 100 cm per day highlighting an exceptionally wet winter, especially at higher altitudes (>2000 m, triangles) where two stations stand out above the others (Bonaigua 2266 m and Respomuso 2145 m). This pattern was not uniform across the Pyrenees, as stations further east and on the Mediterranean slope recorded lower excesses and, in some cases, very low SD_d values.

The scatter plot represented in Fig. 5, help us to analyse the relationship between altitude and MSI components during the two selected specific seasons (2006–2007 and 2012–2013). During the 2006–2007 season deficit is evident across all altitudes, with very few stations exceeding 50 days. During the surplus snow season (2012–2013), a large variability is observed between stations, showing that MSI components would be more dependent to other geographical factors different than altitude like continentality. As described in the previous figures, for these two specific seasons, the two available stations at high-altitude (≥ 2500 m), also exhibit an anomalous behaviour, and do not allow to identify any altitudinal gradient. This leads to the assumption that the snow cover measurements at both sites are strongly influenced by windblown snow transport or some other local effect. This hypothesis has been confirmed by the regional weather service.

3.2. *Multivariate snow index surplus (MSI +) trends*

The analysis of long-term trends in the MSI + reveals distinct patterns that highlight the spatial variability. For duration (SD_d; Fig. 6a) a slight decline in the number of days with snow depth above P_{50} is observed. Stations located on the southern slope of the Eastern Pyrenees (eastern half) show a statistically significant negative trend of this parameter. On the northern slopes while a decreasing trend in duration is also detected, it is less pronounced and not statistically significant. Regarding magnitude (Fig. 6b), a decrease in the accumulated snow surplus (cm/day/season) is observed, particularly on the eastern region. Stations statistically significant trends are located in the easternmost Pyrenees and altitudes above > 2000 m. In the more Atlantic stations, an increase in this parameter is observed, but no statistically significant trend is detected.

3.3. *MSI + application case at a station*

The MSI + case study focuses on the application of the index at a specific station like Arcalís station, located in the extreme north-west of Andorra at 2059 m. The Fig. 7 shows the climatic characterization of the winter seasons and illustrates the temporal evolution of MSI + from 1980 to 2024. Overall, the seasonal variability is pronounced alternating between very surplus and very scarcity seasons. Before 2000, the duration never exceeded 140 days and magnitude values (SD_m) remained 50 cm/day per season, with a consistency between surplus seasons with more than 100 days SD_d. From 2000 to 2001 season onwards, higher values of SD_d and SD_m are shown. Peak values reveal key insights the highest intensity SD_m of more than 70 cm/day are found in the 2012–2013 season with a maximum snow depth 302 cm. However, the longest duration (SD_d) is found in the 2008–2009 season with 179 days. Overall, there is significant temporal irregularity in snow depth evolution across the entire period, but it is noteworthy that the last 6 years have been dominated by less surplus conditions. This characterisation is very relevant for water resources managers, as snow is the main important water reserve.

4. Discussion

Indexes allow different aspects of our climate to be represented in a simple and easily disseminated way. The MSI was proposed to characterize the climatic variability of snowpack in time and space and offers a flexible approach for monitoring changes at the extremes. This indicator

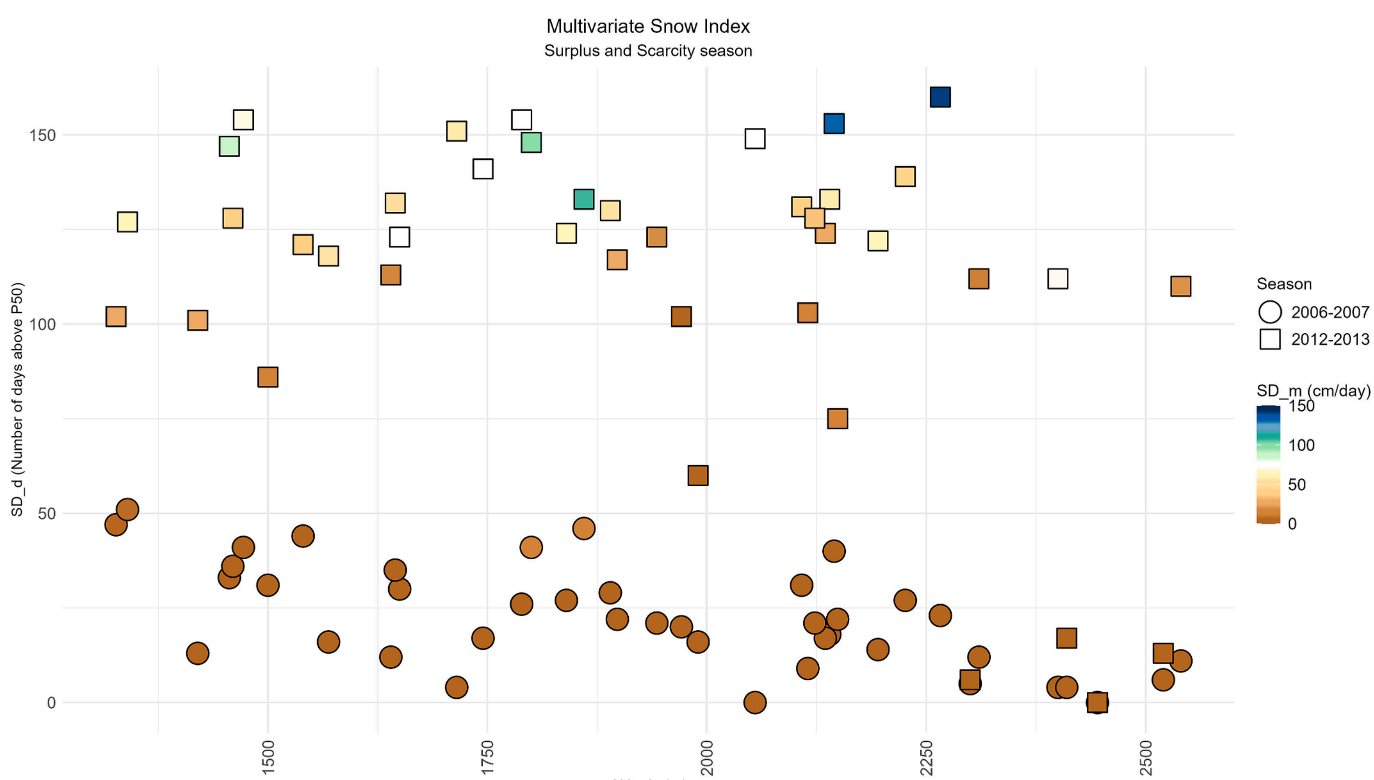

Fig. 5. Scatter plot displays the relationship between station altitude and MSI + components (SD_d and SD_m) for two specifics seasons (2006–2007 and 2012–2013 represented by circles and squares, respectively).

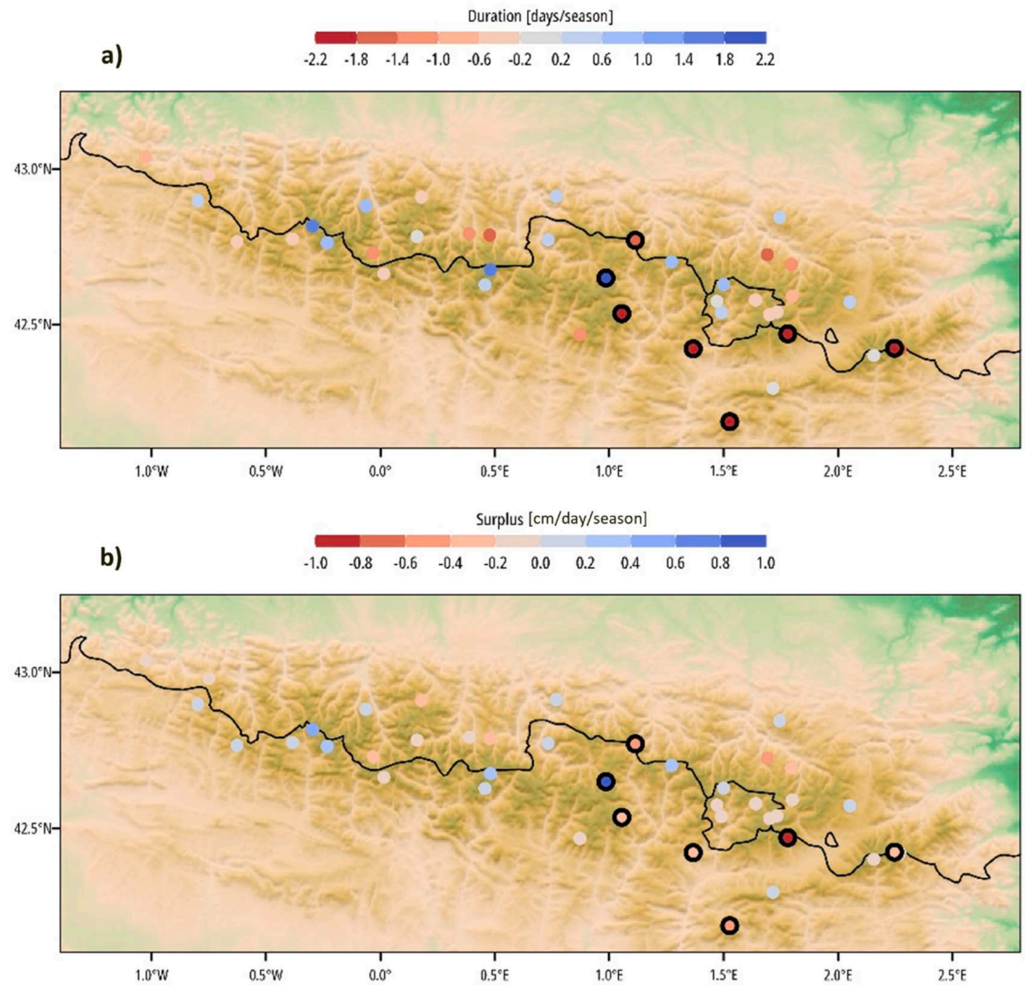

Fig. 6. Spatial distribution in the Pyrenees of the statistical trend of the Multivariate Snow Index Surplus Indicator (MSI +) for the 1980–2016. The upper map displays the trend in duration, i.e. the number of days above the 50th percentile from November to April. The lower map shows, the trend in magnitude, or the exceedance in centimetres per day and season. The black outline of the dots indicates locations where the trend is statistically significant.

is based on percentiles determined by the distribution of the raw data, rather than absolute thresholds. This approach is suitable for regional comparability, improve the detection of climatic extremes and, serves as a tool for analysing snowpack dynamics while ensuring accurate and site-specific analyses.

In the context of climate change, where the increase in global temperature is a fact, the regional impact on the Pyrenees represents a more serious increase in vulnerability. Reduced winter precipitation and rising temperatures play a fundamental role in the evolution of the snow depth and have a direct impact on the calculation of the MSI. Higher temperatures accelerate snow melt and thus reduce the duration and magnitude of MSI+. These effects are amplified by differences in elevation, orientation and the location of the cold season 0 °C isotherm (Le Roux et al., 2021). In addition to the inter-annual variability, it is also of interest to answer questions related to the evolution and availability of the snow resource in the long term. The combined analysis of MSI and other indices, in areas of complex orography with high spatial variability, assists in climatic regionalisation. The use of the MSI assesses the spatio-temporal patterns and the intra- and inter-annual variability of snowpack duration and regularity allowing the differentiation of scarcity and surplus seasons.

A key limitation of indicators calculated at individual observation points is their inability to contextualize information at a territorial scale due to a lack of spatial resolution. Modelling can help to fill this gap, but it remains dependent on observations and there may be discrepancies between observed and modelled results. In particular, SD modelling is challenged by significant spatial variability and the limited length of available series (Vernay et al., 2022). For some stations in the Pyrenees, the proposed indicator may produce unreliable or anomalous results, which may help to identify instrumental changes in snow observations or even areas where the snowpack is strongly influenced by wind or local factors. A transition from manual to automated stations or ensuring the optimal placement of AWS would significantly improve the reliability and applicability of the proposed indicator. Improving measurements would address limitations related to data availability and quality, making it easier to capture the spatio-temporal variability required for accurate calculation of the indicator. Additionally, adding other variables such as temperature, humidity and precipitation improve the definition of indicators more focused on snowmelt, such as SWE, and improving avalanche risk management.

The MSI stands out from existing indicators due to its multivariate approach, integrating both magnitude (scarcity or surplus) and duration (snow cover days). This provides a more comprehensive understanding of snowpack behaviour and offers an advantage for real-time seasonal monitoring, enabling the evaluation and tracking of how whether a season is deficit or surplus compared others. These insights highlight the critical role of location in shaping snowpack behaviour, with timely information that has implications for hydrological process, ecosystems dynamics, water resources, and snow dependent industries such as a tourism. Its flexibility, based on percentiles, makes it adaptable to

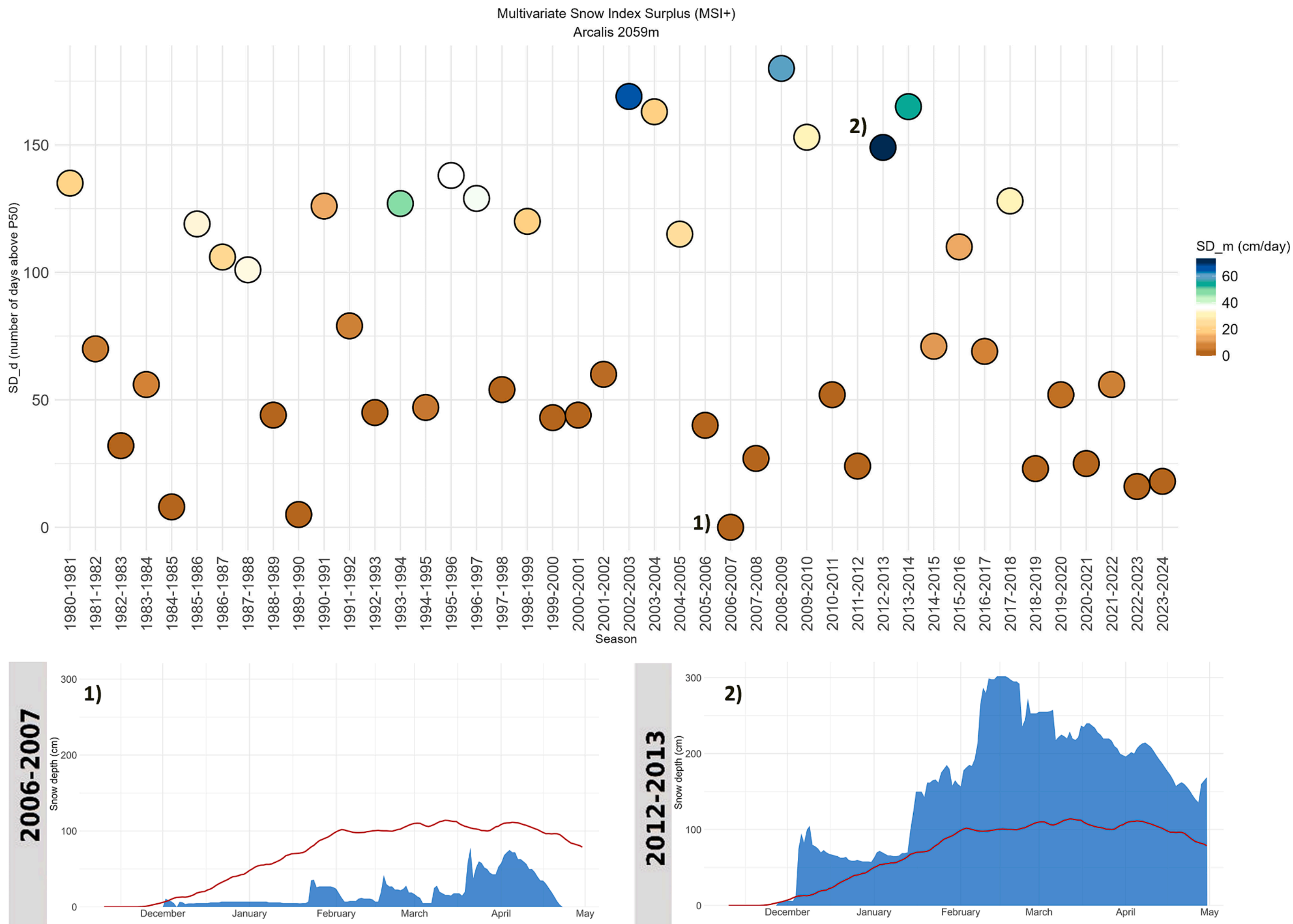

Fig. 7. MSI + application at Arcalís station at 2059 m., displaying the temporal evolution of winter season characteristics from 1980 to 2024. The horizontal axis represents different winter seasons, and the vertical axis shows the duration (SD_d, the number of days when snow depth $\geq P_{50}$). Additional plots, such as evolutions of snow depth for scarcity season 1) and surplus season 2) are also shown to complete the season characterization. The red line illustrates P_{50} and the blue area the snow depth daily evolution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different regions and climates, enabling site-specific analyses while supporting regional comparisons. Furthermore, its user-friendly design and compatibility with both historical and projected climate scenarios make it a practical and forward-looking tool for stakeholders and decision-makers in adapting to climate change. By offering insights into seasonal snow conditions, the MSI facilitates proactive planning and adaptive strategies tailored to the specific challenges of each season.

5. Conclusions

The results derived from MSI+, in surplus mode, over the period 1980–2016 across the Pyrenean massif, reveal that, on average, snow depth remains above P_{50} for 40 and 80 days per season, with an average surplus ranging between 10 and 30 cm/day. Regionally, the Atlantic sectors have the highest values of duration and magnitude, reflecting the dominance of more persistence snowpack conditions. In contrast, the southern and eastern Pyrenees have a similar duration of usual snow conditions, but with notably lower magnitude. This is consistent with the results with higher CI values in this Mediterranean influenced area, where snow accumulation and persistence are often due to a few episodes during the snow season. Thus, the combined analysis of the MSI and CI indices captures the imprint of the Mediterranean climatic variability in certain regions. The application of the new indicator has been exemplified in two contrasting cases: 2006–2007 and 2012–2013. The first is characterised by the lack of snowfall in the Pyrenees, with a very homogeneous spatial distribution of magnitude and duration of the season across all stations. In contrast, the spatial distribution of MSI + explains very well the wet conditions that dominated the northern and western half of the Pyrenees during the 2012–13 season, with more than 80 days of excess conditions, with many stations exceeding 80 cm/day/season. Although the magnitude was not as remarkable in the south-eastern region (< 40 cm/day/season), precipitation remained above normal for more than 60 days. The contrasting behaviour between scarcity and surplus seasons is evident, with 2012–2013 showing significant regional and altitudinal variability compared to the homogenously low conditions in 2006–2007. The MSI + underscores the ability to capture spatial and temporal differences in snowpack behaviour across diverse climatic conditions in the Pyrenees and at different elevations.

Altitude has a significant influence on both the duration and extent of the snow season. Stations at 2000–2500 m have more favourable climatic conditions that tend to result in excess snow cover (>MSI + values). The two stations located around 2500 m exhibit an anomalous MSI + behaviour compared to stations at lower altitudes or nearby areas. This divergence may be influenced by factors such as the specific location of the stations, their orientation, or other local effects that impact snowpack dynamics. These highlight the importance of considering altitude alongside local environmental variables when interpreting MSI. Trends analysis of MSI + identify the areas where the decrease is most relevant and statistically significant, as is the case in the Eastern Pyrenees. Trends in MSI + highlight hydrological sensitivity to climate change, signalling reduced capacity of mountain regions to act as natural water towers capacity and need for sustainable water resource management.

Understanding snow dynamics is essential for improving climate change adaptation in high mountain areas. In this sense, the proposed indicators will complement the traditional snow indicators, helping to provide a better regional characterization into the temporal evolution of snowpack. Finally, MSI also allow a more detailed view of observed and expected changes that can help in decision making for each user and sector. These indicators can be particularly relevant for analysing the vulnerability and reliability in different sectors. Their systematization and continuous monitoring systems through MSI indicator can further refine these insights, enabling joint evaluation of results and enhancing the applicability of the indicators, across regions and sectors.

To facilitate the testing and application of this new index to datasets from other mountain regions, as well as to climate projections of snow cover, and to ensure that all indicators are calculated in a consistent manner, a diagnostic software tool will be developed and made publicly available.

CRediT authorship contribution statement

A. Albalat: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **L. Trapero:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization. **M. Lemus-Canovas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **M. Pons:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2025.133050.

Data availability

The data used in this study are published on the OPCC (PYRENEAN CLIMATE CHANGE OBSERVATORY) geoportal and are the result of the CLIM-PY project. https://opcc-ctp.org/es/geoportal. The code used for calculating the MSI is available in the author’s GitHub repository. https://github.com/AnnaTramun/SnowDepthAnalysis.

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