EXPLORING THE USE OF A MULTIVARIATE SNOW INDEX IN THE PYRENEES TO CHARACTERIZE SNOW SEASONS

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ABSTRACT: In recent decades, snow depth in European mountain regions like the Pyrenees has tended to decrease due to the increase in both temperature and precipitation variability. Several sectors, such as snow tourism and hydroelectric power generation, are affected by these changing snow trends. In order to monitor winter snow seasons, a multivariate snow index (MSI) has been proposed to characterize the climatic variability of the snow depth in time and space. This new index is based on high/low quantiles of daily maximum snow depth (SH) distributions and can be applied to any cold or mountain region, at different spatial scales and for both the present and future climate. The trend analysis on the parameters derived from the MSI (e.g., duration and intensity of snow depth anomalies) can provide a useful tool to identify the vulnerable areas during the snow season.

KEYWORDS: snow depth, multivariate snow index, mountain areas, winter season, snow variability.

1. INTRODUCTION

High mountain areas are a bioregion potentially vulnerable to the effects of climate change. The impacts of climate change in high mountain areas are particularly pronounced, ranging from decreasing biodiversity or shrinking habitats for many species (La Sorte & Jetz, 2010; Freeman et al., 2018) to water availability due to a reduction of snow cover (Morán-Tejeda et al., 2017). Precisely, the observed snow cover reduction is mainly driven by the global and robust increase in temperature, which has already winter tourism impacts as the shortening of the ski season in several mountain ranges (Pons et al., 2015; Spandre et al., 2019; Steiger & Mayer, 2008). The observed role of precipitation in the snowpack is less clear. Its spatial and temporal high variability –especially in mediterranean influenced climates as in the Pyrenees or the Alps-, as well as the lack of long and well distributed time series of precipitation in these environments, make challenging to establish the contribution of precipitation trends to snow cover variability. Although, these changes must be considered for the prevention of natural hazards such as floods and avalanches and improve a proactive management in a increasingly vulnerable population (Beniston et al., 2011; García et al., 2009). Nevertheless, the effects of temperature increases would directly impact the snow variable, the altitude of the snow line, and the duration of snow on the ground (Langsdorf et al., 2022).

Given the relevance of the snowpack for human economical activities, but also for ecosystems water reservoirs and energy production, its monitoring is crucial to anticipate impacts (Hamududu & Killingtveit, 2012). Climate change monitoring through basic climate indices is focused on temperature and precipitation extremes. However, they do not include specific indices for snow variables (Karl & Nicholls, 1999; Peterson et al., 2001; C3S 2024). To address this, various authors have proposed indices derived from Snow Cover presence (SC) and Snow Depth (SD) data, such as maximum monthly snow depth, the start and end of continuous snow cover, and new snow accumulated during a season (Abegg et al., 2021; Bonsoms, Franch, et al., 2021; Ignacio López Moreno et al., 2020.; Morin et al., 2021; Notarnicola, 2022; Vernay et al., 2022).

Although these indicators help to characterize winter conditions under past and future climate scenarios in a simple way, they don't address other relevant intraseasonal aspects (e.g., snow deficits and exceedances during the snow season) and providing a tool for resource management during the season in mountain areas. Most of the climate information generated is focused on regional climate characterisation.

As mentioned, there is a lack of indicators able to: 1) monitor the snowpack changes (eg, duration and magnitude of scarcity/surplus periods along the snow season) at daily scale; 2) Incorporate the temporal variability when analysing the contributions of the snowfalls variability contributing to the winter snowpack, which are particularly key features for decision making in different sectors. Thus, this work proposes an indicator aiming to integrate the above points offering a multivariate

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perspective of the snowpack monitoring being easily applied to any mountain region with daily snow depth data availability.

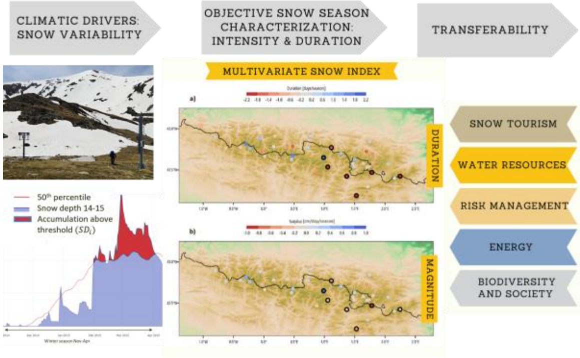

Figure 1: Data collection of the main meteorological variables from observations in high mountain areas. The evolution of the snow depth gives climatic information on daily behaviour. This information is not climatically comparable without an analysis of the duration and magnitude of winters. Offering a multivariate perspective makes it possible to provide answers to other sectors dependent on this variable for their development.

2. METHODS

2.1 *Study area*

The Pyrenees are a mountain range located in the northeast of the Iberian Peninsula, extending from west to east, between the Atlantic Ocean and the Mediterranean Sea, respectively. The south-eastern half of the Pyrenees presents the lowest snow depth across the mountain range (Figure 2). This is partly because winter precipitation is strongly dependent to low frequency mediterranean cyclogenesis, which greatly contributes to the evolution of the annual snow depth in this area (Esteban et al., 2012; García et al., 2009). In contrast, stations located in the westernmost half are more likely to receive more regular and intense snowfalls due to the large-scale atmospheric circulation (Navarro-Serrano & López-Moreno, 2017). Regarding high mountain conditions, from 2000ma.s.l. upwards, low temperatures and regular snow precipitation in winter ensure permanent snow cover for much of the year. Local orographic factors facilitate a deep and persistent snow depth at higher altitudes of the mountain, while decreases as we lose altitude (Bonsoms et al., 2021).

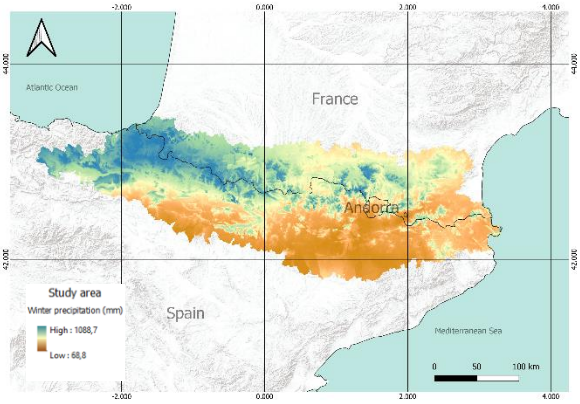

Figure 2: Winter precipitation map (in mm) for the Pyrenees Mountain range -located in the northeast of the Iberian Peninsula- for the period 1981-2015. (Data source: CLIM-PY project).

2.2 *Datasets*

Pyrenean snow depth from in situ observations was directly retrieved from Ignacio López Moreno et al., (2020) 1980-2016 at daily time scale. These data were generated by means of the laser snow depth sensor installed in automatic weather stations or, alternatively, by daily manual observations. To perform the calculations proposed in the following section, we have not considered; i) stations that did not have a minimum of 50% of days with snow on the ground during the season; ii) stations with less than 10 years of available date. Therefore, a final set of 42 stations was used.

2.3 *Multivariate Snow Index (MSI)*

In this work we propose the calculation of a new daily index called Multivariate Snow Index (MSI +Surplus or -Scarcity), which consists in climatic characterization of daily snow depth anomalies. Its calculation is inferred only from SD, i.e. the maximum daily snow depth (SH). The MSI is inspired by those used for the climatic characterization of heat waves, where both temporal (frequency, duration) and intensity –or also refered as magnitude- (extremes) criteria are defined (Lavaysse et al., 2018; Russo et al., 2014; Soubeyroux et al., 2016). The methodology involves four sub-indices: maximum snow depth (SH), fresh snow (the snowfall in 24h, FS, cm), snow day (day with snowfall, 0-1) and presence of snow on the ground (SC, 0-1). To objectively characterize the snow daily evolution throughout the season , the maximum snow depth daily average climate normal and the 50th percentile for the reference period 1981-2010 and for the winter season (November-April) was calculated. We then defined a median snow season by means of the 50th percentile of daily snow depth. The methodology employed to compute the 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 SH is greater than or equal to respective P_{50} calendar date.

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

(1)

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

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

$$SD_i = \frac{\sum_{i=k}^{n}(SH_i - P_{50}) \cdot \mathbb{1}(SH_i \geq P_{50})}{n}$$

$$for\ i \geq k$$

(2)

where k is the index of the third consecutive day that SH exceeds P_{50}. The intensity is divided by the number of days of the season, in this case 181, to determinate the centimeters lost or gained per day.

Therefore, if we observe in figure 1 the temporal evolution of the maximum daily snow depth (SH) (blue area) during the 2014-2015 season in Arcalís station (Andorra), we will see how both SD_d and SD_i are computed. Note that the red line represents the daily P_{50} for the standard reference period, the duration (SD_d) can be easily inferred and then the surplus SD_i parameter as the normalized red area. It is important to highlight, that at the beginning of the season, in January, SH is above P_{50} for two days, insufficient to be considered in the calculation of the surplus SD_i.

On the other hand, for the calculation of the MSI to quantify the scarcity of the season, the methodology should be applied by considering the number of days where SH does not exceed P_{50}. Starting from the third consecutive day below P_{50}, the centimeters lost should be summed. $[SD_{ddry}\ SD_{idry}]$

2.4 <u>CI</u>

Additionally, to MSI there are indicators focusing on the temporal distribution of snowfalls such as the Concentration Index (CI) (Martin-Vide, 2004). The CI was originally designed to analyse the distribution and concentration of precipitation events within a given time period for example, 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. Recently, Lemus-Canovas et al. (2023) introduced its use to derivate the temporal concentration of snowfall in the Iberian Peninsula. In this work, we apply the same approach to the insitu snow depth series available in the Pyrenees. Further details on the statistical calculation of the CI can be found in Martin-Vide et al. (2004).

3. RESULTS

3.1 <u>MSI vs CI</u>

The results of the application of the Multivariate Snow Index in Surplus mode (MSI+) across the Pyrenees are detailed below (Fig. 3). The analyses presented are for the winter period 1980-2016, including results for both the mean values for the whole period (a, b) and for the case of two specific seasons (c, d, e, f). The CI has also been calculated and represented in the same figure to complete and compare the results.

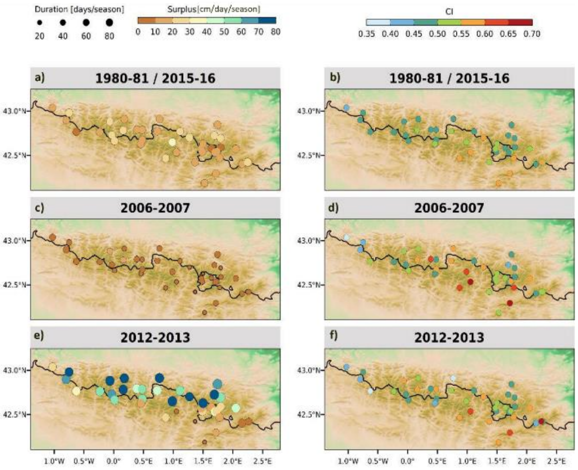

Figure 3: Spatial distribution in the Pyrenean stations of the following indices: a) MSI+ (left column), representing both duration and intensity (in circles and color scale, respectively); b) CI (right column). The first row displays average values for MSI+ and CI from 1980 to 2016 (a and b). The second row presents results for a scarcity season, 2006-2007 (c and d), and the third row for a surplus season, 2012-2013 (e and f).

During the 2006-2007 season (Fig. 3c) SD_d does not exceed 40 days, and in some stations, it is less than 20 days. In terms of seasonal intensity, the SD_i parameter does not reach 10cm/day in most of the stations. CI shows high values, mostly between 0.55 and 0.60, throughout the Pyrenees and with peaks of 0.70 mainly in the stations on the southern slope (Fig. 3d).

In contrast, the analysis of the 2012-2013 season (Fig. 3e), the SD_d parameter shows a duration of more than 80 days in the westernmost stations, with an intensity with values of more than 60cm per day highlighting an exceptionally wet winter. This pattern was not uniform across the Pyrenees, like stations on the easternmost Mediterranean slope where lower intensity values (SD_i) were recorded exceeding the P50 in very few episodes. In some cases, also showing very low SD_d values. The CI values for this season (Fig. 3f), in contrast, showed minimal variation between scarcity and surplus seasons in both absolute values and spatial distribution.

3.2 MSI trends

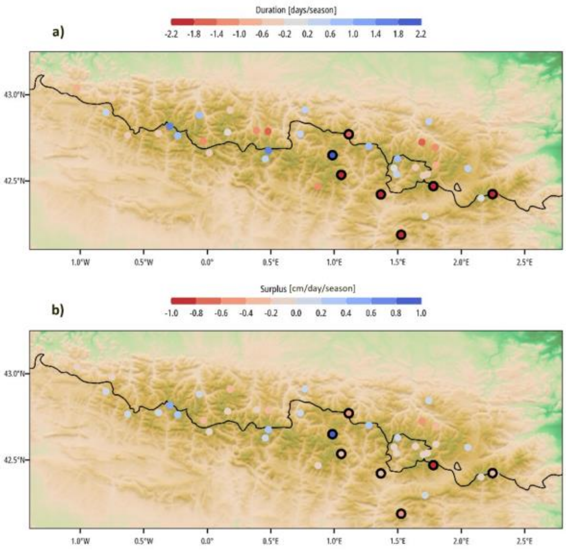

Figure 4: Spatial distribution in the Pyrenees of the statistical trend of the Multivariate Snow Index Surplus (MSI+) for the 1980-2016. The upper map displays the trend in duration, i.e. the number of days above the 50th percentile from November to April. The lower map shows, the trend in intensity, or the exceedance in centimeters per day and season. The black outline of the dots indicates where the trend is statistically significant.

Figure 4 illustrates the temporal and spatial trends in the behavior of MSI+ for the 1980-2016 period. In Figure 4a, the points located in the easternmost Pyrenees and on the Mediterranean slope exhibit a statistically significant decreasing trend in SD_d.

As for the trend in intensity (Fig. 4b), the spatial variation it is not as pronounced as the one presented in duration, but the decrease persists in the same stations in the easternmost Pyrenees.

3.3 MSI application case

The case study of MSI+ application at a specific station is presented below. The station selected for the analysis was the Arcalís station located in the northwest of Andorra at 2059m a.s.l. The Figure 5 illustrates the temporal evolution of MSI+ and CI to all seasons from 1980 to 2024.

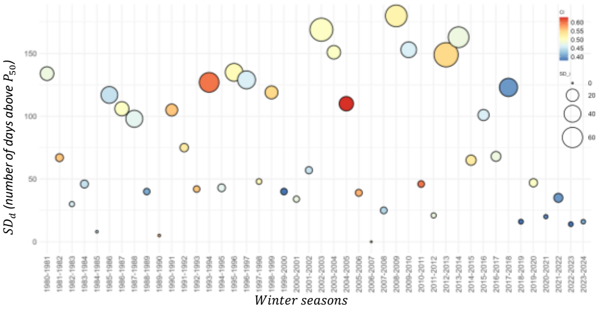

Figure 5: Evolution of MSI+ and CI at Arcalís station at 2059m a.s.l.. Displaying the temporal evolution of winter season characteristics from 1980 to 2024. The horizontal axis represents different winter seasons, and the vertical axis shows the duration SD_d. Additional indicators, such as CI, maximum snow height per season, are also shown to complete the season characterization.

Prior to 2000, it is noteworthy that the duration never exceeded 140 days. The intensity values (SD_i) for the same period do not surpass 50cm/day per season, with a higher regularity between seasons.

After three consecutive scarcity seasons (1999 to 2002), the difference between seasons is more marked, showing a very high interannual variability, alternating between very wet and dry seasons in terms of snow The SH records are found during the 2012-2013 season with 302cm, with an associatedSD_i of more than 70cm/day. However, the maximum duration (SD_d) is found for the 2008-2009 season with 179 days. Regarding to the CI, no large variations are shown between all seasons, except for the 2004-2005 and 1993-1994 seasons when most of the snow depth was accumulated in just a few snowfalls. The last surplus (wet) season was 2017-2018 with more than 100 days of SD_d.

4. CONCLUSIONS AND DISCUSSION

Snow depth is highly variable in both space and time. As we have observed in this study, the interannual variability of snow highlights the difficulty of establishing a climatology for a specific region. In this regard, it is necessary to consolidate a robust and sufficiently long dataset to develop indicators that best characterize this variability.

The main goal of this study has been to define and apply a new indicator so-called Multivariate

Snow Index (MSI) to better characterize the snow seasons and better interpret extreme snow events within a climate change framework. Its application on the dataset available in the Pyrenees massif for the period 1981-2016 has made it possible to establish the climatology and analyse the temporal and spatial trends.

Results show that the Atlantic sectors have the highest values in terms of duration and intensity, where surplus or wet winter seasons are dominant. Whereas the southern slopes and easternmost Pyrenees show a similar duration of the usual snow conditions, but with lower intensities. For the entire Pyrenean massif, on average, the seasons are defined by the persistence of SD_d 40 and 80 days per season, with an excess (intensity SD_i) that varies on average between 20 and 40 cm/day.

In terms of trends, there is no homogeneous behavior throughout the mountain range either, which highlights the climatic variability that is characteristic of the Pyrenees. However, it has been possible to identify the areas where the decrease in duration and intensity is most relevant and statistically significant, as is the case of the Eastern Pyrenees.

The main limitation of the indicators based on observed datasets are their high dependency on the quality of this data. Preliminary work is necessary to establish a reliable database from which indicators can be derived and subsequent conclusions drawn. However, this process is not automatic and requires the expertise to consolidate the data. Once this daily snow depth information is available, the proposed indicator in this work could be applied to any dataset, at any spatial scale, and for any climatic context: past, present and future climate scenarios. One of the next steps will be the application of this approach to different mountain ranges around. In this sense we will be very open to work with other datasets to test our functions and the indicator that has been developed in this work.

DATA AVAILABILITY STATEMENT

The snow depth daily dataset used in this article is available at https://opcc-ctp.org/es/geoportal.

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