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SNOW COVER VARIABILITY IN THE CANTABRIAN MOUNTAINS (SPAIN): A WATERSHED-LEVEL STUDY USING SATELLITE RECORDS (2000–2024)

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ABSTRACT. This study presents an analysis of the main snow cover dynamics in the Cantabrian Mountains (northern Spain) using satellite imagery, examining the snow cover dates of appearance and melting, extent, duration and persistence. The study area comprises 36 hydrographic watersheds. Using Google Earth Engine (GEE), 14,082 satellite images (2000-2024) from MODIS-Terra, Landsat 5-8, and Sentinel-2 were analysed to create daily snow cover classifications. Seasonal series of Snow Cover Fraction (SCF) were extracted by 500-meter elevation intervals in each watershed and analyzed to extract indicators and trends.

Results reveal reductions in snow cover extent. In autumn, it is reduced at ~-2%/decade above 1,500 m. Notable and significant negative trends (~-10% and up to -16%/decade in some basins) were detected in winter, particularly on the southern slopes of the Cantabrian Mountains. In spring, most basins show negligible and homogeneous trends among watersheds, except above 2,000 m, where pronounced reductions in extent (2.5% per decade) are observed. A shortening snow season is detected, caused by earlier occurrences of the Last Ephemeral Snow Day (LESD), occurring 2.7 days by decade earlier vs 0.4 days by decade earlier in case of the First Ephemeral Snow Day (FESD). The duration of the first snow cover of the season decreased noticeably above 1,500 m (9 days/decade). Peak seasonal snow cover extent tends to occur slightly later, and above 2,000 m. These events are markedly shorter due to a delay in the Snow Onset Day (SOD) and earlier Snow Melt Out Day (SMOD). The maximum SCF occurs between January 22nd and February 5th, depending on altitude, and is shifting earlier, especially at lower elevations. The mean snow cover duration is 16.4 days, with notable altitudinal variability (6.6 days at 500–1000 m and 38.5 days above 2,000 m), decreasing by 1 day/decade, with reductions up to 5.8 days/decade above 2,000 m, where the duration of the longest snow cover has decreased 8 days/decade. Snow cover persistence has declined by 1.2%/decade, with sharper reductions (3.4%) above 1,500 m.

Despite biases from prolonged periods of cloud cover, dense canopy cover in some watersheds or the occurrence of rapid snow accumulation and melting events undetected by the satellites, findings ultimately reveal decreases in the duration, extent and persistence of snow cover since the early 21st century, although some of these are not statistically significant. These results highlight shifts in seasonal snow cycles, emphasizing the need for further research with longer time series and alternative observational datasets.

Variabilidad de las cubiertas de nieve en la Cordillera Cantábrica (norte de España): un estudio a nivel de cuencas a partir de registros satelitales (2000-2024)

RESUMEN. Este estudio analiza la dinámica de la cubierta de nieve en la Cordillera Cantábrica (norte de España), mediante imágenes satelitales, evaluando las fechas de aparición y fusión, extensión, duración y permanencia del manto nival. El área de estudio comprende 36 cuencas hidrográficas. Utilizando *Google Earth Engine*, se analizaron 14.082 imágenes satelitales (2000-2024) de MODIS-Terra, Landsat 5-8 y Sentinel-2 para crear clasificaciones diarias de la cubierta de nieve. Se extrajeron series temporales de la Fracción de Cubierta Nival (SCF) en intervalos de 500 metros de altitud en cada cuenca y se analizaron indicadores y tendencias.

Los resultados revelan reducciones en la extensión de la cubierta de nieve. En otoño, la extensión se reduce un 2%/década por encima de los 1.500 m. Se detectaron tendencias negativas notables, de hasta 16%/década en algunas cuencas en invierno, particularmente en la vertiente sur. En primavera, la tendencia es homogénea y estable (con algunas excepciones), aunque por encima de los 2.000 m, la extensión disminuye un 2,5%/década. La temporada de

nieve se acorta por la ocurrencia más temprana de la Fecha de Última Fusión de Nieve Efímera (LESD), que avanza a 2,7 días/década frente al adelanto de 0,4 días/década de la Fecha de Primera Cubierta Nival Efímera (FESD). La duración de la primera cubierta de nieve de la temporada disminuyó por encima de los 1.500 m (9 días/década). El máximo estacional de la extensión de cubiertas de nieve tiende a ocurrir más tarde, y por encima de los 2.000 m es de menor duración debido a un retraso en el día de inicio de la cubierta de nieve más larga (SOD) y a una fusión más temprana de la cubierta de nieve más larga (SMOD). La máxima SCF ocurre entre el 22 de enero y el 5 de febrero, dependiendo de la altitud, y tiende a adelantarse, especialmente en altitudes más bajas. La duración media de las cubiertas de nieve es de 16,4 días, con gran variabilidad altitudinal (6,6 días en 500–1.000 m y 38,5 días por encima de 2.000 m), disminuyendo 1 día/década, con reducciones de hasta 5,8 días/década por encima de los 2.000 m, donde la duración de la cobertura nival más larga ha disminuido 8 días/década. La permanencia de la cubierta de nieve ha disminuido un 1,2%/década (un 3,4% por encima de los 1.500 m).
Aunque existen algunos sesgos, como períodos prolongados de nubosidad, alta cobertura forestal en algunas cuencas o la ocurrencia de eventos rápidos de acumulación y derretimiento de nieve no detectados por los satélites, los resultados revelan disminuciones en la duración, extensión y permanencia de la cubierta de nieve desde principios del s. XXI (aunque algunas no son estadísticamente significativas), particularmente por encima de los 1.500 m. Los cambios en los ciclos estacionales de la nieve en la Cordillera Cantábrica subrayan la necesidad de realizar investigaciones adicionales utilizando series temporales más largas u otros datos observacionales.

Keywords: Snow, Snow Variability, Trend, Cantabrian Mountains, Watershed.

Palabras clave: nieve, variabilidad de la nieve, tendencia, Cordillera Cantábrica, cuencas hidrográficas.

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1. Introduction

Snow cover plays a crucial role in the Earth's energy balance due to its high reflectivity (albedo) (Meng, 2017). It also plays a key role in the hydrological cycle of mountain regions, as it leads to the accumulation of snowpacks that function as natural reservoirs, regulating water availability for human consumption, agriculture, and hydroelectric power generation (Bormann *et al.*, 2018; Gascoin *et al.*, 2015). Snow can also pose significant natural hazards, such as avalanches or landslides (Beato Bergua *et al.*, 2019; García-Hernández and López-Moreno, 2024; Santos González *et al.*, 2010) and rain-on-snow flooding events (Corripio and López-Moreno, 2017; Morán-Tejeda *et al.*, 2019). The study of snow cover variability is essential for understanding climatic patterns and their implications on ecosystems, water resources, and socio-economic activities (Notarnicola, 2020; Zhong *et al.*, 2021).

Snow cover variability refers to the seasonal cycle of snow presence on the surface, including key metrics such as the timing of the first snowfall, duration of snow cover, peak snow accumulation, and the final melt-out date (Zhong *et al.*, 2021). It is influenced by multiple climatic and environmental factors, including temperature fluctuations, precipitation regimes, topographic characteristics, and vegetation cover (Notarnicola, 2020). These effects are particularly relevant in mid-latitude mountain ranges such as the Cantabrian Mountains, where interannual variability in snowfall directly influences water availability, vegetation dynamics, and geomorphological processes (López-Moreno *et al.*, 2020). Changes in snow persistence and seasonality affect plant phenology in alpine ecosystems in the Cantabrian Mountains (Espinosa del Alba *et al.*, 2025; Illa *et al.*, 2022) and impact winter tourism and ski resorts (Pisabarro, 2020). Given the increasing vulnerability of mountain environments to climate change, it is crucial to quantify changes in snow cover trends and their underlying drivers (Notarnicola, 2020; Ye *et al.*, 2015).

The Cantabrian Mountains, located in northern Spain, exhibit a transitional climate between oceanic and Mediterranean influences, leading to high interannual variability in snow cover duration and extent (Ortega Villazán and Morales Rodríguez, 2015). Recent satellite observations indicate significant reductions in snow cover extent and duration (Melón-Nava, 2024). Similar trends have been reported in other European mountain ranges, such as the Pyrenees, where winter snowfall are expected to decrease by up to 29% at lower elevations under Representative Concentration Pathway (RCP) 8.5 scenarios (Bonsoms *et al.*, 2025), and the Alps, where snow cover duration has shortened by 5–7 days per decade since the 1960s (Monteiro and Morin, 2023). On a global scale, satellite records have identified a 5.12% reduction in snow cover (Young, 2023) and decreases of the snow cover extent in all seasons in the Northern Hemisphere since 1975 (Hori *et al.*, 2017). These trends highlight the widespread impact of climate change on mountain cryosphere (Notarnicola, 2024).

Remote sensing is a useful technique in snow cover monitoring, allowing for large-scale analysis with high temporal and spatial resolution. The Normalized Difference Snow Index (NDSI) is widely used to differentiate snow from other land covers (Hall *et al.*, 1995), despite limitations related to cloud cover (Gascoin *et al.*, 2015; Tiede *et al.*, 2021) and forested areas (Gascoin *et al.*, 2024). The MODIS instrument, operational since 2000, provides daily observations with a 500-meter spatial resolution, enabling long-term monitoring of snow variability (Notarnicola, 2024). Additionally, the integration of Landsat and Sentinel-2 imagery has allowed for higher spatial resolution assessments (Zhang and Jiang, 2022). These methodologies have been applied in mountainous regions worldwide such as the Pyrenees (Barrou Dumont *et al.*, 2024; Gascoin *et al.*, 2015) the Alps (Orusa *et al.*, 2023) and the Himalayas (Sasaki *et al.*, 2024).

Cloud-based geospatial analysis platforms, such as GEE, have further enhanced snow studies by facilitating rapid processing of extensive datasets (Gorelick *et al.*, 2017). Several studies have employed Google Earth Engine to analyze snow cover variability across different mountain regions, revealing significant trends in snow variability. Notarnicola (2020) documented hotspots of declining snow persistence in the European Alps, attributing these changes to increasing winter temperatures. In the Himalayas, Sasaki *et al.* (2024) applied machine learning techniques within GEE to map snowline altitudes, observing a general upward shift due to climate warming. Tang *et al.* (2022) assessed snow variability in high mountains in Asia, highlighting regional differences in snow seasonality driven by synoptic weather patterns. Gascoin *et al.* (2015) studied the Pyrenees and confirmed a steady decrease in snow cover extent using MODIS and Landsat imagery. López-Moreno *et al.* (2020) focused on the Iberian Peninsula, where they detected significant reductions in snow duration above 2,000 m. Malnes *et al.* (2016) examined snow season variability in boreal-Arctic transition areas, revealing strong latitudinal gradients in snow persistence. Finally, Ye *et al.* (2015) analyzed interdecadal changes in Eurasia, concluding that atmospheric circulation shifts were a major driver of snow cover trends.

This study is the first to analyse seasonal snow cover dynamics in the Cantabrian Mountains at the scale of hydrographic watersheds. Using MODIS, Landsat 5–8, and Sentinel-2 data (2000–2024), it examines trends in snow cover extent, duration and persistence across 36 hydrographic watersheds, assess variations in key snow variability indicators, and identify differences between elevation bands. By leveraging satellite-based analyses and cloud-computing tools, this research provides a detailed evaluation of snow cover metrics and changes in the Cantabrian Mountains watersheds.

2. Study area

The Cantabrian Mountains are located in the north of Iberian Peninsula, in southwestern Europe (Fig.1). Its highest peak is Torre Cerredo, located in the Picos de Europa National Park, at 2,650 m The range extends longitudinally, with its ridges reaching approximately 2,000 m in the main massifs, which stretch over 300 km, from the Sierra de Ancares (in the provinces of Lugo and León), with Alto de Cuiña (1,992 m) standing out, to the sector of the Sierra de Peña Labra Massif, where Pico Valdecebollas reaches 2,143 m in the province of Palencia, near the border with Cantabria. A few dozen kilometers further east, the Montes de Valnera (1,717 m) is located, straddling Burgos and Cantabria. Although at a lower altitude, this area receives important snowfall and it marks the easternmost extent of the study. The study area covers 16,263 km², divided into 36 hydrographic watersheds, covering four water agencies (C.H. in Spanish): C.H. Cantábrico (northern part of the study area), C.H. Duero (southern part), C.H. Ebro (eastern part), C.H. Miño-Sil (western part).

Snow cover distribution in the Cantabrian Mountains is highly variable, particularly during melting periods, due to the region's transitional climate between oceanic and Mediterranean climate influences, with a continentalized nuance. A distinct contrast exists between the northern and southern slopes (Ortega Villazán and Morales Rodríguez, 2015), where watershed divides act as both a natural barrier and a transitional zone. The northern slopes, under a strong oceanic influence, experience milder annual average temperatures (7.5ºC to 12ºC), consistent precipitation (up to 1,800 mm annually), and frequent cloud cover. In contrast, the southern slopes exhibit greater thermal variability, with larger daily and seasonal temperature oscillations, resulting in colder winters and hotter summers, lower annual precipitation (around 800 mm) and annual average temperatures ranging from 2.5ºC to 10ºC (Aemet, 2018).

Although snowfall events generally bring lower snow levels to the northern slopes, with a decreasing trend toward the east, snow persistence is shaped by multiple factors, including altitude, humidity, temperature, wind-driven accumulation, and solar radiation. The Cantabrian Mountains receive the highest winter precipitation in the Iberian Peninsula, averaging 506 mm (Hidalgo-Hidalgo *et al.*, 2024). Above 1,500 m, winters are harsh throughout the region, with frequent frosts and snowfall, often intensified by strong windstorms. Notably, occasional southerly wind events can cause sudden temperature spikes above 20ºC in northern valleys due to a pronounced Foehn effect.

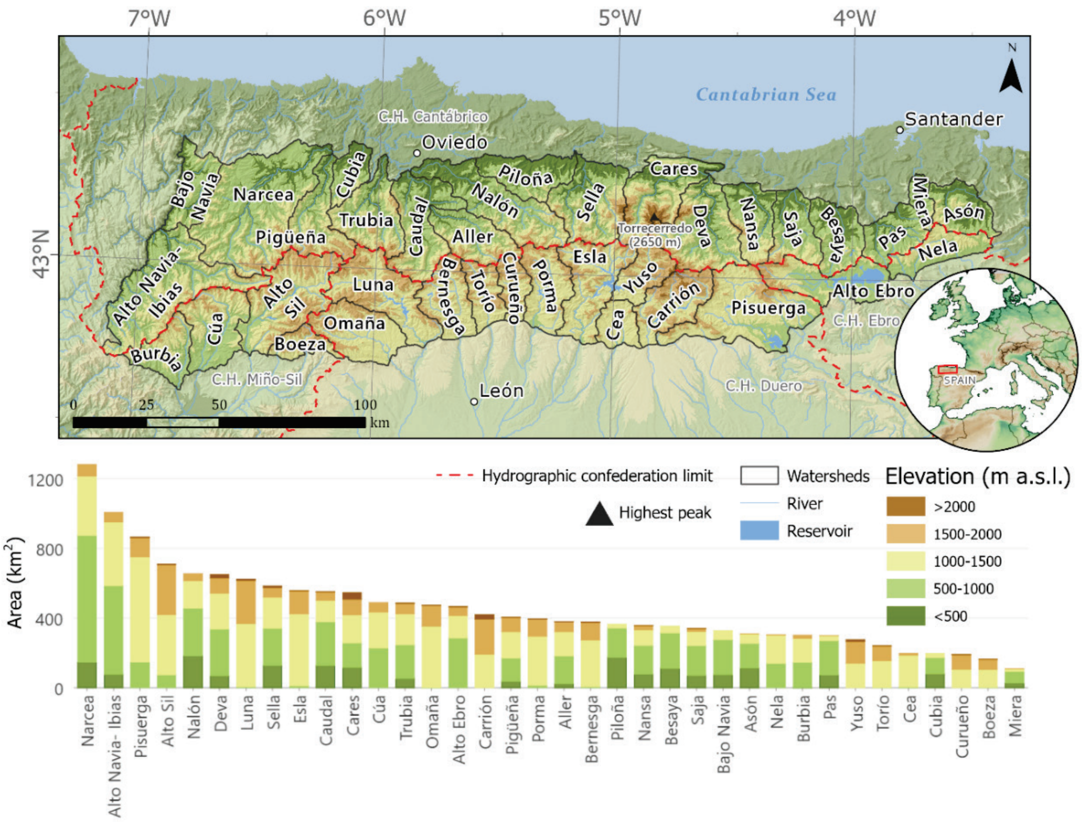

Figure 1. Cantabrian Mountains watersheds map and hypsometric distribution of the 36 watersheds in 500 m interval elevation bands.

3. Data and methodology

3.1. Data

A multi-sensor daily snow cover dataset was generated to analyse snow dynamics in the Cantabrian Mountains. Satellite images from MODIS-Terra, Landsat 5–8, and Sentinel-2 were processed using Google Earth Engine to generate daily time series of snow cover for the period 2000–2024. This was achieved through the methodology detailed in Melón-Nava (2024). MODIS imagery provides continuous daily observations, ensuring baseline temporal coverage throughout the study period. Landsat 5-8 and Sentinel-2 offer higher spatial detail, but with longer revisit intervals. To maximise spatial detail while maintaining temporal continuity, the highest-resolution image available was selected for each day when possible. The Normalized Difference Snow Index (NDSI), $NDSI = \frac{Green\ band - SWIR\ band}{Green\ band + SWIR\ band}$, effectively distinguishes snow from other surfaces like vegetation, soil, and water due to this spectral contrast. It also separates snow from clouds, as clouds exhibit high reflectance in both the visible and SWIR ranges, unlike snow. NDSI values range from -1 to 1, with values greater than 0.4 typically indicating snow, providing a robust threshold for classification according to Hall *et al.* (1995) and Hall and Riggs (2010). For snow-cover classification using MODIS, the 'NDSI_Snow_cover' band was converted to Fractional Snow Cover (FSC) following the approach of Rittger *et al.* (2013) and Salomonson and Appel (2004).

$$FSC = -0.01 + 1.45 \times NDSI$$

Pixels with FSC > 0.15 were classified as snow-covered, representing both partially and fully snow-covered areas, based on the threshold estimations in the Picos de Europa region by Revuelto *et al.* (2021).

The spatial resolution varies depending on the band resolution of each satellite, ranging from 500 m for the MODIS sensor on the Terra satellite, to 30 meters with Landsat, or 20 meters with Sentinel-2. The main limitations include cloud presence, topographic shadows, and underestimation of snow cover in forested areas where snow remains on the ground but not on the top of tree canopies or shrubs. To ensure data quality, the presence of clouds was assessed independently for each satellite image and at the watershed level. For each image and date, the proportion of cloud-covered area was calculated for each watershed based on the available cloud information for each sensor. Watersheds with more than 50% cloud cover on a given date were excluded from the analysis for that date. This procedure ensured that the snow cover time series was based only on valid and reliable observations for each watershed. This approach prevents the total cloud cover filtering of the image, as it was found that, on many occasions, some watersheds were entirely covered by clouds while others had very low cloud cover, allowing for the use of information from the latter. Overestimations of snow cover extent were found in cases where fog coincided with areas not covered by snow, leading to high SCF values. These days have been manually evaluated to determine whether they truly represent the actual snow extent situation. Masking is applied to pixels occupied by clouds, water bodies (rivers and reservoirs) and topographical shadows. In all images, areas corresponding to the main watersheds of the study area, as well as cloud cover and topographic shadows were masked.

The hydrographic watersheds of the Cantabrian Mountains were delineated, resulting in a division into 36 basins. This delineation was based on cartographic data of hydrographic watersheds boundaries. The delineation process was guided by the *Atlas of Spanish Landscapes* (Mata Olmo and Sanz Herráiz, 2003). For the western limit, in the Navia River watershed, the Navia river was used as the boundary, considering only its right side.

An ImageCollection was created in Google Earth Engine to aggregate 24 seasons, from 2000-2001 to 2023-2024. Each season begins on September 1st and ends on August 31st of the following year. This was accomplished using a hierarchical method for each day (Fig.2), prioritising satellite images with the highest spatial resolution (Sentinel-2 > Landsat 5-8 > MODIS).

A total of 14,082 images were used since 2000 September 1st to 2024 August 31st, with 5,193 images from MODIS (daily images from 2000-2024), 520 images from Landsat-5 images (2000-2012), 1,194 images from Landsat-8 images (2013-2024) and 7,175 images from Sentinel-2 (2015-2024). On average, 216 days per year (59.1%) were valid for the study, as they had cloud cover below 80% (Image filtering).

The following stage focuses on filling data gaps at the pixel level, caused by consecutive days of cloud cover obscuring satellite observations. To mitigate this, a temporal gap-filling algorithm is applied, using linear interpolation of snow cover (or absence) between the last valid observation before the cloud period and the first after it. This method, based on Sproles *et al.* (2018) and adapted to the Cantabrian Mountains' conditions, is constrained to a maximum gap of 5 consecutive days, which helps reduce missing values in areas with ephemeral cloud cover. This threshold is consistent with the average cloud persistence in the region (3.3 days on average) (Melón-Nava, 2024). Gap-filling is performed under specific rules: if both pre- and post-cloud observations indicate snow cover or snow-free conditions, the missing days are classified accordingly. For transitions, linear interpolation of NDSI values determines the presence or absence of snow. Therefore, only snow covers recorded during cloud-free periods are analyzed. Rapid snow accumulation and melting events under cloudy conditions are undetected by the satellites, so are not recorded.

The following phase involves creating a daily mosaic that prioritizes the available satellite image for that day with the highest spatial resolution, so Sentinel-2 images are prioritized over Landsat, and both are prioritized over MODIS-Terra. In this way, the snow cover classification with the highest possible resolution is obtained for each day. Following this, the Snow Cover Fraction is calculated, which will serve as the basis for calculating the other snow variability indicators.

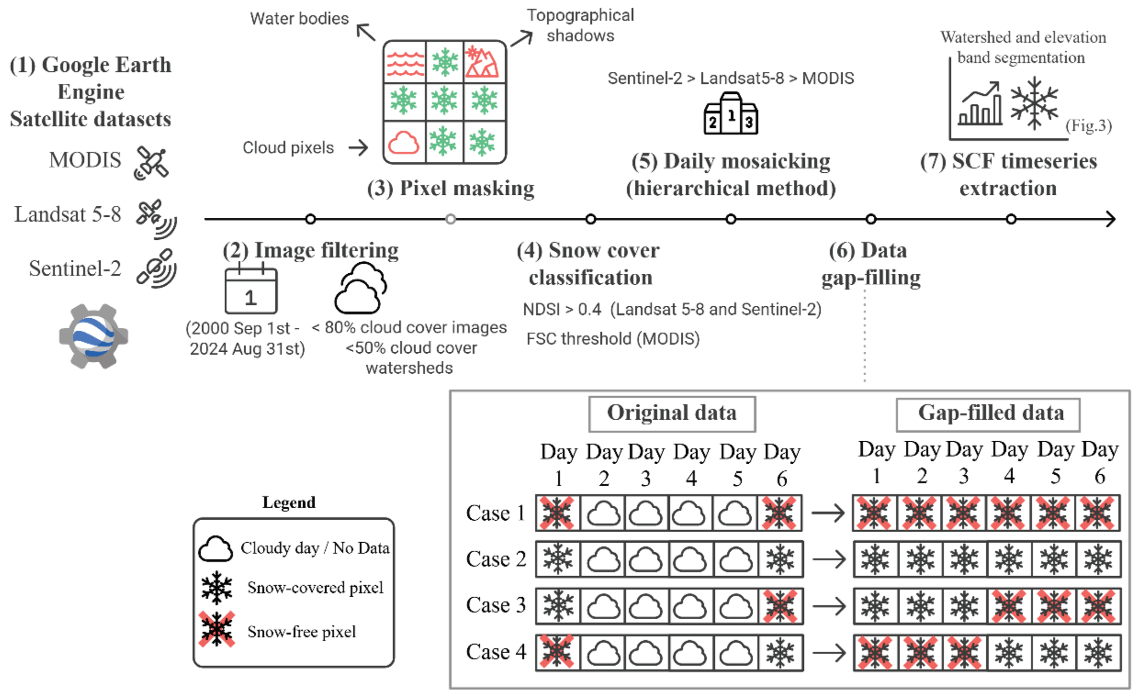

Figure 2. Workflow for obtaining time series of SCF in Google Earth Engine from satellite images. The gap-filling example shows a data gap of 4 days.

3.2. Methodology: Extraction of metrics to assess the seasonal variability of snow cover

Once the daily snow cover image collection is created from the available satellite images, the next step involves generating time series of Snow Cover Fraction (SCF) (Fig. 3), which quantifies the proportion of an area covered by snow in comparison to the total visible area (cloud-free) for a given day. Seasons are defined from September 1st to August 31st across the 36 delineated hydrographic watersheds, segmented into 500-meter elevation bands (<500 m, 500–1000 m, 1000–1500 m, 1500–2000 m, >2000 m). These thresholds were chosen following previous studies in the region (Melón-Nava, 2024) to enable consistent comparisons. SCF is calculated for the whole perimeter of the Cantabrian Mountains, for the watersheds and for all the elevation bands.

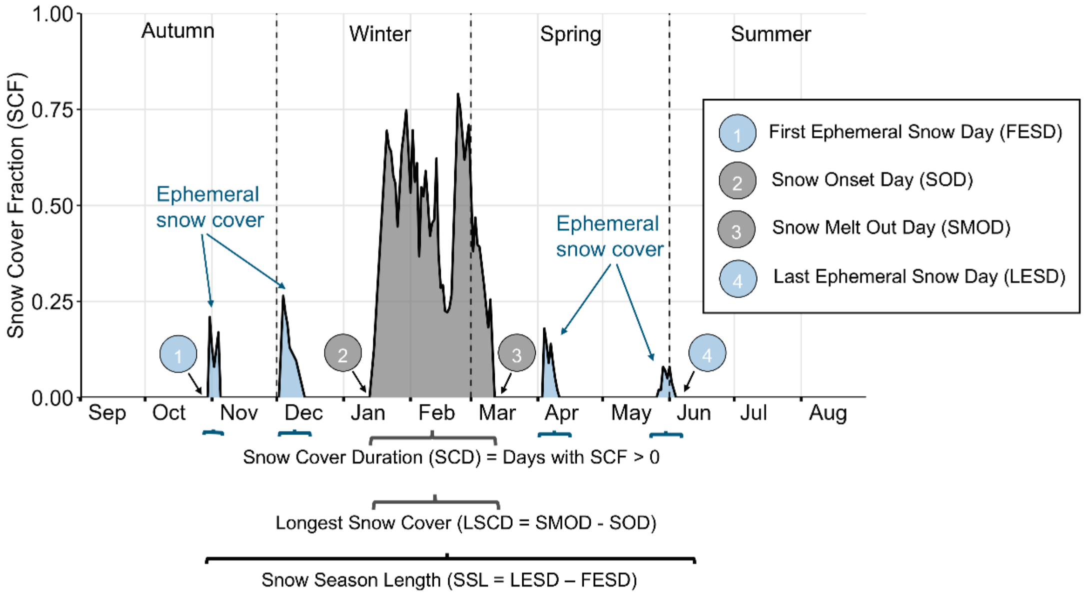

Figure 3. Example of the calculation of snow cover variability metrics for a fictional SCF season.

This process theoretically yields 4,320 time series (24 years × 36 basins × 5 altitudinal ranges), representing the maximum number of possible combinations if all basins included all five altitudinal ranges. However, not all basins cover every altitudinal range due to the watersheds' topographical characteristics. Thus, a total of 3,432 time series have been analysed (24 years × 143 unique altitudinal ranges across the 36 basins). These allow for comparisons between basins, altitudes, and seasons, as well as the extraction of trends using the Sen's slope over the 24-year satellite image record. To assess the statistical significance of these trends, we also applied the Mann-Kendall test. Trends with p-values below 0.05 were considered statistically significant. All analyses were conducted independently for each combination of watershed and altitudinal range.

The analysis was structured into four groups of variables, based on their typology. Firstly, the extent of snow cover was calculated by season of the year: autumn (September-October-November, or S-O-N), winter (December-January-February, or D-J-F) and spring (March-April-May, or M-A-M). Subsequently, an analysis was conducted on the dates of the first (FESD) and last ephemeral snow cover (LESD), as well as the duration of the first snow cover throughout the seasons (Mean FESD Duration). These variables represent the temporal extremes of each season and help define the potential snow cover period in each area. (Table 1).

Then, variables related to the longest-lasting snow cover of each season were examined. This includes measuring the date when the longest snow cover appears (SOD) and melts (SMOD), as well as the date of the most extensive snow cover (Max SCF Day). These variables provide an indication of the most stable and notable snow covers occurring each season in each location.

Table 1. Description of the variables extracted from SCF time series to define the variability of each snow cover season.

ACRONYM	SNOW METRIC	DESCRIPTION
SCF	Snow Cover Fraction	Fraction of the study area covered by snow: 1 represents total snow cover, and 0 means no snow cover.
SCD	Snow Cover Duration	Sum of the days with snow cover greater than 0.05*. Indicates snow frequency throughout the season.
FESD	First Ephemeral Snow Day	First day of the water year (starting from September 1) with detected snow cover (SCF > 0.05*). Calculated by pixel.
LESD	Last Ephemeral Snow Day	Last day of the year (starting from September 1) with detected snow cover (SCF > 0.05*) before total melting. Calculated by pixel.
MEAN FESD DURATION	Mean FESD duration	Duration (in days) of the first ephemeral snow cover detected in the season.
SSL	Snow Season Length	Number of days between the first ephemeral snow day (FESD) and the last ephemeral snow day (LESD). Indicates the absolute dates of the season's first and last snowfall, even if minimal.
SOD	Snow Onset Day	First day (starting from September 1) of the season's Longest Snow Cover Duration (LSCD).
SMOD	Snow Melt Out Day	First snow-free day following the end of the Longest Snow Cover Duration (LSCD) period, starting from September 1.
LSCD	Longest Snow Cover Duration	Longest duration of snow cover during the season. It is calculated as the difference between SMOD and SOD.
RDL (ZHONG *ET AL.*, 2021)	Ratio Duration - Length	Measures the intra-seasonal persistence of snow cover. It is calculated as the ratio of Snow Cover Duration (SCD) to Snow Season Length (SSL). Values close to 1 indicate continuous snow cover during the snow season, whereas lower values indicate intermittent or variable snow cover.
MAX SCF DAY	Day with maximum SCF	Day when the maximum SCF value occurs. If multiple equal maximum values occur (for example, several days with SCF = 1), the average date is taken.

*For the study of snow presence in the SCF time series, values greater than 0.05 were used as the error threshold to prevent a single misclassified pixel as snow from producing an erroneous result. Thus, at least 5% of the area (e.g., a watershed elevation band) must be covered by snow to be considered a snow-covered day.

Finally, the last group of variables refers to the duration and persistence of snow cover. This includes measuring the maximum duration of the most persistent snow cover each season (LSCD), calculated from the previously mentioned SOD and SMOD variables. The mean duration of snow covers was also measured, considering each cover as the period of snow presence between two complete melt events. Additionally, the RDL factor (unitless) was calculated as the ratio between Duration and Length, providing an indication of snow cover stability in each location.

4. Results

4.1. Extent of Snow Cover

The mean SCF values show an uneven distribution throughout the season (Fig. 4). During autumn, snowfall can occur over extensive areas, but snow cover usually persists for only a few days. The mean snow cover extent in autumn is only notable in some years above 1500 m, and even then, the mean snow cover extent in autumn rarely exceeds 25% of the area above 2000 m (Fig. 4). During winter, there is marked interannual variability above 1500 m, with some seasons reaching SCF values close to 1, while others, such as the 2023–2024 season, show mean values near 0.25. In spring, differences between altitudes above 1500 m and lower elevation bands stand out, with a marked altitudinal gradient. The Yuso (0.17) and Carrión (0.15) watersheds exhibit the highest mean SCF throughout the season, in contrast to the low mean values recorded in the Piloña (0.02) and Cubia (0.02). Moreover, substantial differences are observed across the seasons, with the highest mean SCF values occurring in winter, reaching 0.34 for the Yuso watershed. Noticeable variations are also found between altitudinal bands, with the highest mean SCF values occurring at the uppermost elevations. The >2,000 m bands show consistent values across all watersheds, ranging from 0.08 to 0.15 in autumn, 0.73 to 0.82 in winter, and 0.39 to 0.66 in spring. In spring, larger differences between watersheds emerge, with higher values recorded in the Sella watershed (0.66) (see Appendix 1).

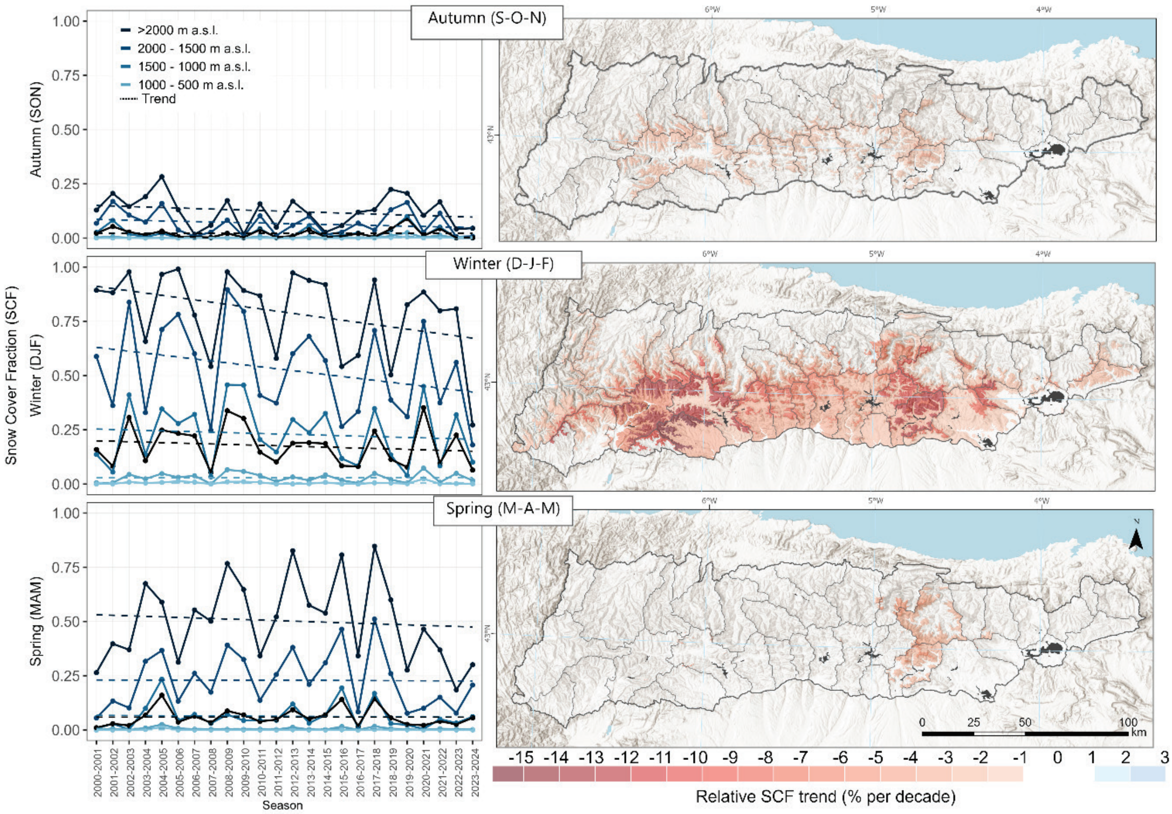

Figure 4. Timeseries of Snow Cover Fraction evolution (2000-2024) and relative SCF trend map (by watersheds) by season of the year (Autumn, Winter and Spring). Black lines in timeseries represent the whole study area values and trendline.

The trend of the SCF in autumn (Table 2) is homogeneous at elevations above 1,500 m, with a decrease of around 2% per decade. However, it is during winter, the period of maximum snow accumulation, that the most marked (and statistically significant) reductions in snow cover extent have occurred during the 2000–2024 period. For the entire Cantabrian Mountains, the decrease is 2.08% per decade, but the most substantial declines are observed in areas with higher snow accumulation (>1500 m). These include an 8.95% per decade reduction in the 1500–2000 m range and a 10.4% per decade decrease above 2,000 m. In the 1000–1500 m range, the decline is more moderated at 2% per decade (Table 2). Due to the asymmetry in altitudes between the northern and southern slopes of the range, declines are more pronounced on the southern slope, which has a higher mean elevation. Above 1,500 m, two key areas stand out (Fig. 4): the southwestern region of the study area, particularly Omaña (-16%/decade), Alto Sil (-13.3%/decade) and Luna (-12.6%/decade) watersheds and the eastern massifs, as the Carrión (-12%/decade), Deva (-10.3%/decade) and Saja (-12.3%/decade) watersheds. In spring, the overall trend for the Cantabrian Mountains remains stable (Table 2), with some exceptions in the Carrión, Deva and Cares watersheds (around -1% to -2% per decade). In areas above 2,000 m, losses exceed 2.4% per decade. In this elevational band, some areas record greater losses, as in the case of Nansa watershed (-7.9% per decade).

Table 2. SCF mean results and trends by season of the year and elevation bands.

	Autumn (S-O-N)		**Winter (D-J-F)**		**Spring (M-A-M)**	
	Mean SCF	**Relative trend (%/decade)**	**Mean SCF**	**Relative trend (%/decade)**	**Mean SCF**	**Relative trend (%/decade)**
Cantabrian Mountains (all altitude ranges)	0.02	0.03	0.18	-2.08*	0.06	-0.01
>2000 m	0.12	-2.32*	0.79	-10.40*	0.50	-2.45
2000 - 1500 m	0.07	-1.63*	0.53	-8.95*	0.23	-0.18
1500 - 1000 m	0.02	0.09	0.23	-2.04*	0.06	-0.37
1000 - 500 m	0.00	-	0.03	0.08	0.01	-0.07

* Trends statistically significant at the 95% confidence level ($p < 0.05$).

4.2. Snow cover temporal patterns

The temporal pattern of snow cover varies each year depending on when the first snow cover is detected, its duration, the date of final snowmelt and when the longest-lasting snow cover occurs each season. These factors have been measured using several parameters, as detailed in Table 1.

Regarding the temporal extremes of snow seasons, the FESD indicates the timing of the first snow cover each season, as long as it is subsequently detected by satellites. In some years, the FESD date is nearly identical or the same across most elevation bands, particularly if the first snowfall event results in widespread snow across all altitudes. In general, FESD occurs earlier in the western part of the Cantabrian Mountains compared to the eastern region (Fig. 5). Above 1,500 m, FESD tends to occur during the first half of November (November 3rd above 2,000 m and November 10th between 2,000 and 1,500 m). In these higher elevation bands, the first snow cover has occasionally occurred as early as early to mid-October, as observed during the 2008–2009 season. In the 1,500–1,000 m range, it occurs in the second half of November (November 23rd), while below 1,000 m, it occurs, on average, during the first half of December (December 11th). However, over the 24 years analysed, it has been recorded as early as late November and as late as mid-January (2003–2004 season), reflecting marked interannual variability, particularly in these lower altitudinal bands. FESD tend to occur earlier (-1.66 days/decade above 2,000 m), but later (-6.4 days/decade) below 1,000 m. This indicates that at lower altitudes, the occurrence of the first snowfall events becomes more concentrated, reducing differences between altitudes. However, notable interannual variability prevents these trends from being considered statistically significant at this stage. The earliest FESD are recorded in Cares (>2000 m, October 23rd) and Deva watersheds (>2000 m, October 20th), indicating the first snow occurrence in these high-elevation regions.

The LESD, which marks the last snowmelt date, is heavily influenced by altitude, as well as by other factors such as temperature, solar radiation, topography or presence of liquid precipitation following snowfall events in each watershed. Moreover, LESD values can vary by several weeks each year depending on the persistence of snow cover or the occurrence of an exceptionally early or late final snowfall event of the season. Snowmelt generally follows a gradual progression across elevation bands over time (Fig. 5). LESD first occurs at the lowest elevations, around late February or early March in the 500–1000 m range. It then progresses with a gradual gradient, occurring in late March for the 1000–1500 m range, late April for the 1500–2000 m range, and mid-May for elevations above 2000 m. It is important to note that these are mean values for altitudinal bands, and at the highest elevations, local topography plays a significant role in the persistence of small snow patches in favourable areas. Therefore, in these specific areas, snow cover duration can extend on average until July (Fig. 5).

Trends for LESD show an earlier melt date in the highest elevation bands (-2.9 days/decade above 2,000 m and 4.4 days/decade between 2000 – 1500 m), while elevations below 1500 m display stable or slightly (~1 day/decade) delayed trends, although with high interannual variability. It is important to note that these parameters do not fully define the overall snow season, as early snowfall or late snowmelt may occur even in seasons with limited snow accumulation.

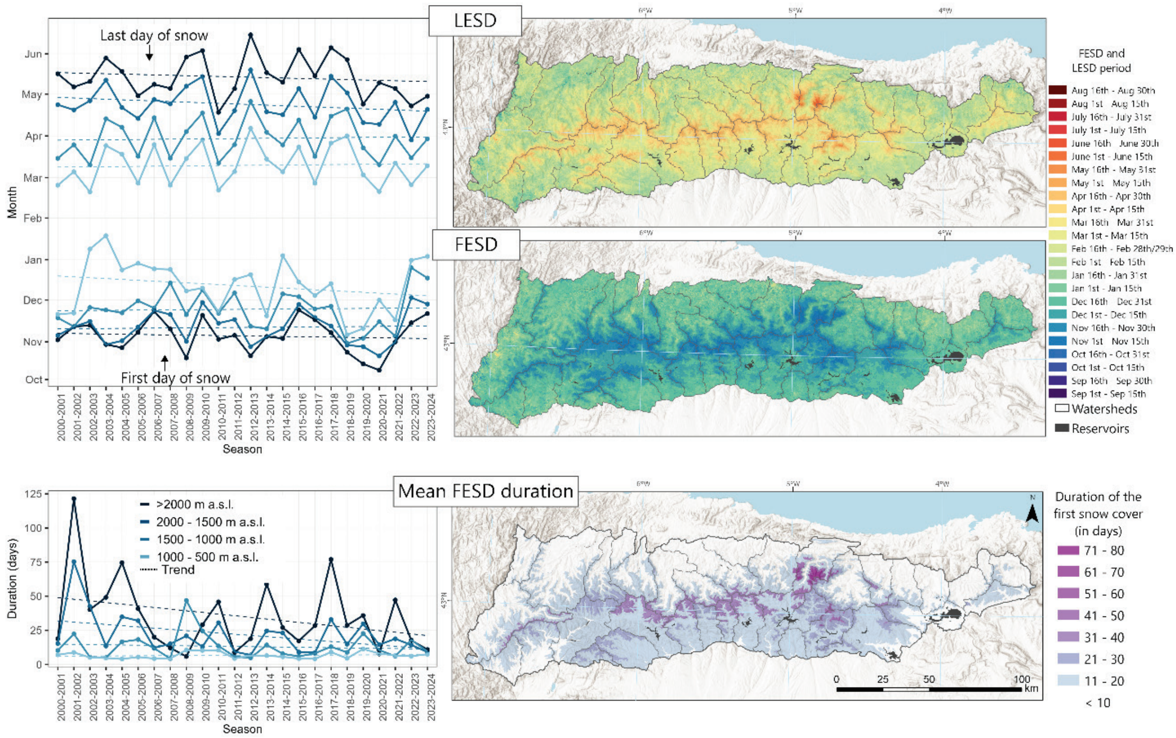

Figure 5. Timeseries of seasonal FESD, LESD and mean FESD duration (2000-2024) and mean values maps by watersheds.

Examining the duration of the first snow cover event detected (FESD), there is high variability, with some long-lasting first snow covers and others where it is ephemeral, lasting only a few days, particularly in low-altitude areas (Fig. 5). Mean FESD duration value of 12.8 days is recorded for the whole study area (Table 3), with a progressive increase from 6.7 days in areas below 1,000 m to an average of 35.1 days above 2,000 m. The average durations vary noticeably among watersheds in the different elevation bands, especially above 1,500 meters, where, for example, the Cares records an average of 42.6 days compared to 10.5 days in the Pas watershed in the 1,500-2000 m band (Table 3). Particularly noteworthy is the persistence of the first snow cover in the Picos de Europa (the longest durations are recorded in Cares (>2000 m, 74.8 days) and Deva (>2000 m, 54.2 days). Conversely, the shortest mean durations occur in Bernesga (500-1000 m, 3.5 days) and Luna watersheds (500-1000 m, 4.5 days), reflecting transient snow cover at lower elevations (Appendix 2). Notably, the snowfall of 9-10 November 2001 (Fig. 5) was exceptional for its intensity and extent, covering almost the entire Cantabrian Mountains. That year, FESD values were very similar across all altitudes, and at elevations above 1500 m, this first snow cover turned out to be the most persistent of the season, lasting over 120 days (four months) above 2000 m, despite its early occurrence.

Table 3. Mean FESD, LESD and FESD duration values and trends by altitudinal ranges.

	FESD		LESD		Mean FESD Duration	
	Mean DOY	**Trend (days/decade)**	**Mean DOY**	**Trend (days/decade)**	**Duration (in days)**	**Trend (days/decade)**
Cantabrian Mountains (all altitude ranges)	Nov 21st	-0.40	Apr 4th	-2.68	12.80	-3.22
>2000 m	Nov 3rd	-1.66	May 15th	-2.92	35.10	-12.10*
2000 - 1500 m	Nov 10th	0.93	Apr 25th	-4.44	21.70	-8.88*
1500 - 1000 m	Nov 23rd	0.90	Mar 30th	1.10	13.10	-1.54
1000 - 500 m	Dec 11th	-6.41	Mar 10th	1.10	6.94	0.46

* Trends statistically significant at the 95% confidence level ($p < 0.05$).

There has been a notable decline in the duration of the first snow cover during the 2000-2024 period, with reductions of -12.1 days/decade above 2,000 m and –8,9 days/decade in the 2000 – 1500 m band (statistically significant reductions) and more stable durations below 1500 m (±1 day/decade).

4.3. Longest snow cover of each season

The dominant snow cover episodes of each season (those with the longest duration) has been analysed using the Snow Onset Day (SOD) and Snow Melt Out Day (SMOD) variables. Like LESD and FESD, there is a greater temporal concentration in SOD dates than SMOD dates, as major snowfall events often affect all catchments and elevations, resulting in the longest-lasting snow cover of the season.

The SOD indicates the date when the first day of the longest-lasting snow cover is detected. This tends to occur earlier at higher elevations (Fig. 6), typically around late December for elevations above 1500 m and mid-January for elevations below 1500 m. Earliest SOD are recorded above 2,000 m in Cares and Deva (Nov 25th), indicating that the most lasting snow covers of the season result from early snowfall events. While marked altitudinal variability was observed during the 2002–2006 period, from 2006 onwards, there is a noticeable trend towards the concentration of SOD dates across all elevation bands, suggesting that a single important snowfall event often covers all altitudes. However, trends show a delay in SOD (Table 4) at elevations above 1000 m (4.8 days/decade above 2,000 m and 7.2 days/decade between 2,000 – 1,500 m) and an advancement below 1000 m (8.5 days/decade). Interannual variability remains high, depending on when the first major snowfall events occur, with SOD dates ranging from November to February across seasons.

The SMOD date, marking the end of the melt of the longest-lasting snow cover, is also strongly influenced by altitude (Fig. 6), which significantly affects snow cover durability. At lower elevations (below 1500 m), SMOD typically occurs in late January to mid-February (Table 4). For the 1500–2000 m band, it occurs in mid-March, while at elevations above 2000 m, it occurs in early April. Latest SMOD are recorded in Sella (>2,000 m, Apr 30th) and Cares (Apr 28th), indicating a later snow persistence. Earliest SMOD occur in Bajo Navia (500-1000 m, Jan 9th) and Trubia (Jan 12th), referring to the fact that the most significant snow covers tend to melt earlier in these areas of the northern slope of the mountain range. Trends reveal earlier occurrence of SMOD dates for the 500–1000 m (7.3 days/decade) and >2000 m bands (3.1 days/decade), whereas a later occurrence is observed between 2000-1500 m (5.2 days/decade) and 1500-1000 m (3 days/decade).

The Max SCF Day shows a strong altitudinal concentration, as it is closely linked to the most significant snowfall event of the season. Max SCF Day typically occurs in late January for elevations below 1500 m and early February for elevations above 2000 m. In this case, the differences between watersheds are not very significant, as the snow cover date tends to be driven by a major snowfall event affecting all or most of the watersheds. Therefore, little spatial variability is found (Fig. 6), with the earliest values in the 500-1000 m elevation zones of the western watersheds, such as Cúa (Jan 2nd), Burbia (Jan 3rd), or Alto Navia-Ibias (Jan 5th). The latest values occur, on average, only a month later above 2,000 m in some watersheds (Appendix 3). Trends indicate an earlier occurrence of Max SCF Day in all elevation bands, especially in lower altitudes: 3.5 days per decade in 1,500 – 1000 m and 8.2 days per decade below 1000 m (Table 4).

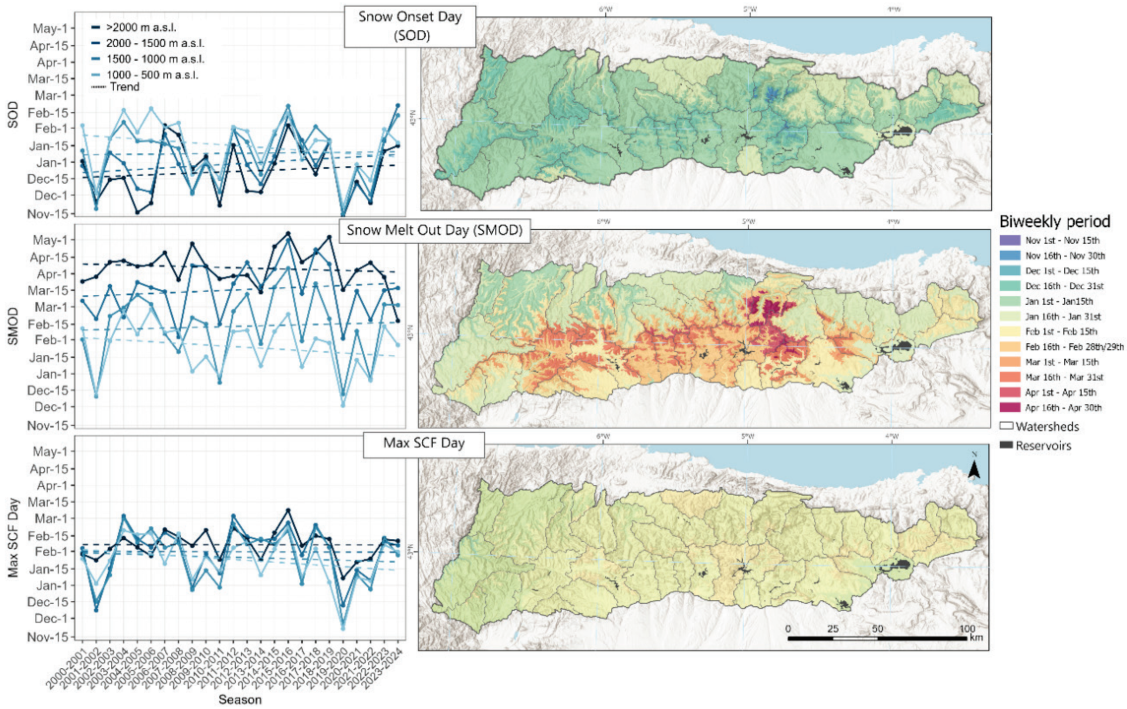

Figure 6. Timeseries of seasonal SOD, SMOD and max. SCF day (2000-2024) and mean values maps by watersheds.

Table 4. Mean SOD, SMOD and Max SCF Day values and trends by altitudinal ranges.

	SOD		SMOD		Max SCF Day	
	Mean DOY	**Trend (days/decade)**	**Mean DOY**	**Trend (days/decade)**	**Mean DOY**	**Trend (days/decade)**
Cantabrian Mountains (all altitude ranges)	Jan 7th	0.87	Feb 17th	2.00	Jan 24th	-3.89
>2000 m	Dec 22nd	4.83	Apr 5th	-3.12	Feb 5th	-0.10
2000 - 1500 m	Dec 29th	7.22	Mar 16th	5.19	Jan 29th	-0.27
1500 - 1000 m	Jan 7th	1.17	Feb 11th	3.03	Jan 24th	-3.54
1000 - 500 m	Jan 14th	-8.58	Jan 23rd	-7.31	Jan 22nd	-8.18

* Trends statistically significant at the 95% confidence level ($p < 0.05$).

4.4. Snow cover durability and persistence

Several variables are analyzed to define the durability and persistence of snow, as the longest snow cover duration, (LSCD, resulting from the difference between SMOD and SOD), the average duration of snow covers throughout the season (MED) and the Ratio of Duration/Length (RDL), which highlights areas where snow cover is more persistent (Fig 7).

The duration of the most important snow cover of the season (LSCD) varies considerably across altitudinal ranges (Table 5), being 13 days in the 500–1000 m range, 36.1 days for the 1000–1500 m range, 78.7 days for 1500–2000 m, and 106 days above 2000 m. The watersheds with the longest durations are Cares and Deva (above 2000 m), corresponding to the Picos de Europa massif, and Carrión (Fuentes Carrionas massif), where both exceed 140 days (155, 143.6 and 142.8, respectively, found in Appendix 4). These are the highest-altitude sectors of the Cantabrian Mountains. The shortest durations are found below 1,000 m in the Caudal watershed (8.8 days). In these lower elevation zones (500-1,000 m), the durations in the eastern part of the study area are higher than in the rest of the watersheds, as seen in the Miera watershed (20.2 days). Decreasing trends in duration are observed above 1500 m, with a -8 days per decade reduction above 2000 m and -2 days per decade between 1500–2000 m. Slight increases are observed below 1500 m (~1.5 days per decade).

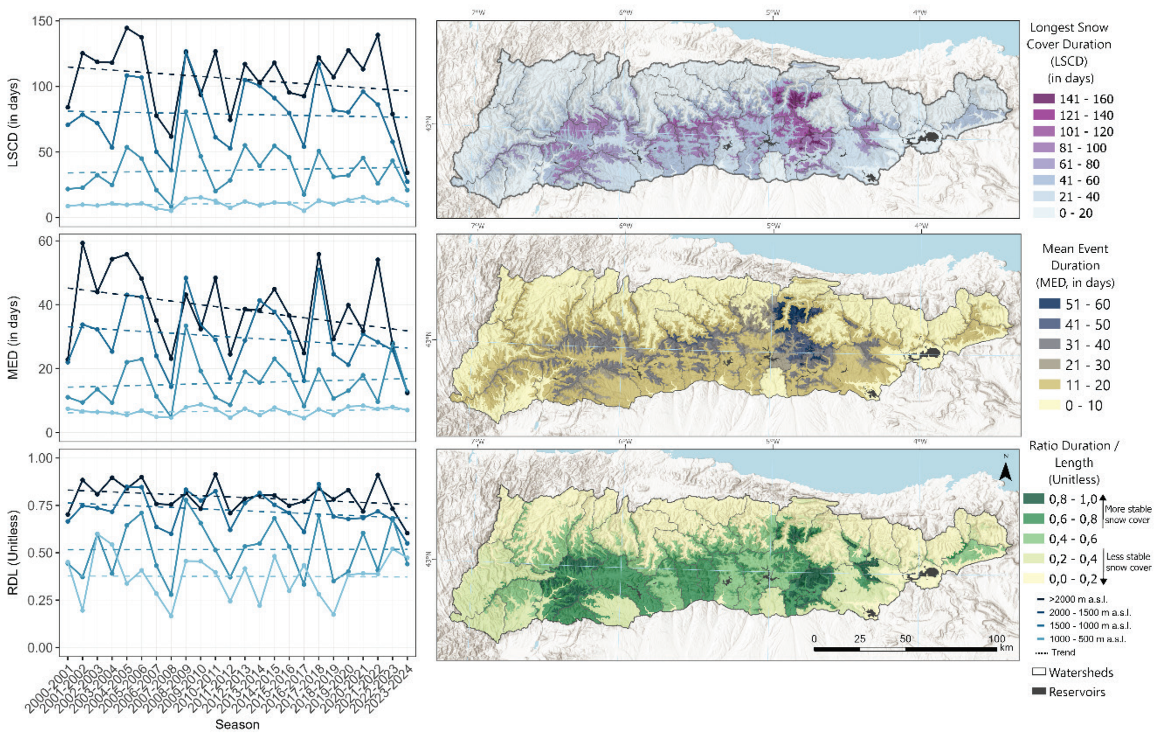

Figure 7. Timeseries of seasonal LSCD, MED and RDL values (2000-2024) and mean value maps by watersheds.

Table 5. Mean LSCD, MED and RDL values and trends by altitudinal ranges.

	LSCD		**MED**		**RDL**	
	Mean value (in days)	**Trend (days/decade)**	**Mean value (in days)**	**Trend (days/decade)**	**Mean value (Unitless)**	**Trend (%/decade)**
Cantabrian Mountains (all altitude ranges)	42.1	1.1	16.4	-0.9	0.56	-1.2
>2000 m	106	-8	38.5	-5.8	0.79	-3.3
2000 - 1500 m	78.7	-2	29.8	-2.9	0.72	-3.5
1500 - 1000 m	36.1	1.9	15.5	1.2	0.52	0.1
1000 - 500 m	13	1.3	6.67	0.4	0.19	-0.2

* Trends statistically significant at the 95% confidence level ($p < 0.05$).

The average duration of snow covers (MED) follows the same trend as LSCD, although with lower absolute values, as ephemeral snowfalls are also considered here. The areas with the highest average snow cover persistence are found above 2,000 m in the Cares (55.9 days), Sella (55.5 days), Deva (52 days), Carrión (51.7 days) and Yuso (51.2 days) watersheds, all of them above 50 days of MED (Appendix 4). The MED shows a decreasing trend above 1500 m (-5.8 days/decade above 2,000 m and -2.9 days/decade between 2,000-1,500 m) and persistence under 1,500 m.

Regarding the RDL (Ratio duration-length), this variable considers both the frequency of snow cover detection (SCD) and the Snow Season Length (SSL), which is useful for assessing the persistence of snow cover. Higher RDL values are observed at higher elevations (0.79 above 2,000 m) and lower values at lower elevations (0.38 below 500 m). The watersheds with the most stable snow cover are the high-altitude areas (>2,000 m) of the Cares, Deva, Sella, Alto Sil, Carrión, Curueño, Porma, Pisuerga, and Yuso watersheds, all of them with RDL values above 0.8. Low values, below 0.4, are common in low-altitude areas (<1,000 m) of the watersheds on the northern slopes, where snowfall can occur over several months during the season but lasts only a few days. RDL trends remain stable at lower elevations, but above 1,500 m, there is a decrease in snow persistence at a rate of approximately ~-3.4% per decade.

5. Discussion

The results show that snow cover in the Cantabrian Mountains experiences high interannual variability across all analysed variables, with pronounced altitudinal gradients. Since 1940, the succession of snowy and less snowy years has been observed in the Cantabrian Mountains, with a trend towards a decrease in snowfall days and an increase in interannual variability (Ortega Villazán and Morales Rodríguez, 2015). The most extensive, durable, and stable snow covers are found in areas above 1,500 m, which also show the most regressive trends for these parameters. It should be noted that the area above 2000 m is limited in many catchments, particularly when working at a spatial resolution of 500 m (MODIS). While trends were still computed for this elevation band for completeness, results at this altitude should be interpreted with caution in basins where the available surface is minimal. This limitation is inherent to the hypsometry of the Cantabrian Mountains, where the distribution of surface area across elevation bands is highly uneven, with a sharp decrease in extent above 2000 m.

The extent of snow cover has significantly decreased (Table 2) during the winter months (DJF), particularly on the southern slope of the Cantabrian Mountains and in areas above 1,500 m, with reductions of up to 16% per decade in some watersheds in the southwestern study area and other areas south of the watershed divide. This reduction aligns with previous studies that have observed a general decrease in SCF and SCD in these areas (Melón-Nava, 2024) and allows us to identify that this decline occurs particularly in the winter months, as reported by Hidalgo-Hidalgo *et al.* (2024). They indicate that the greatest reductions in snow cover in the Cantabrian Mountains occur in December (4.3% per five-year period) and January (6.3% per five-year period), with an average decline of 3.5% when considering the entire winter season, based on optical and radar sensor data for the same study period, starting in the year 2000. These rates of decline are slightly higher than those generally recorded in this study, which are around 2% per decade across all elevations during the same period (Table 2). However, the study areas are not exactly the same, as that study also includes the Montes de León and some foothill areas. In the same regions, declines of approximately 2% per decade are observed in autumn, with some areas also experiencing reductions in spring, which aligns with the low rates of change in snow cover extent detected by Hidalgo-Hidalgo *et al.* (2024) during the spring and autumn months.

These changes are likely driven by increasing temperatures and alterations in precipitation patterns, influenced by large-scale atmospheric variability such as the North Atlantic Oscillation (NAO) (Merino *et al.*, 2014). The most negative trends occur in the western (Alto Sil, Boeza, Omaña, Luna) and south slope watersheds (Yuso, Carrión, Pisuerga), where precipitation is mainly associated with westerly and south-westerly weather types, which have decreased in frequency since the mid-20th century in favour of anticyclonic patterns during winter months, significantly reducing precipitation (Fernández-González *et al.*, 2012). This is consistent with other studies, highlighting the southern slope of the Cantabrian Mountains as having a strong negative correlation between the NAO index and winter precipitation, as well as snowpack duration (Alonso-González *et al.*, 2020). These regions also exhibit higher (more irregular distribution) snowfall concentration indices (CI) compared to the northern slope (Lemus-Canovas *et al.*, 2024), making them more sensitive to synoptic pattern changes and resulting in significant reductions in snow extent, duration, and persistence. It is estimated that 85% of snowfall events originate from low-level flow from the N or NE in northern Spain (de Pablo Dávila *et al.*, 2021).

The date of the FESD shows a later occurrence at lower altitudes, while the first ephemeral snow cover duration has decreased notably, with reductions of more than 8.8 days per decade above 1,500 m and 12 days per decade above 2,000 m Similarly, LESD shows an earlier melting date at higher altitudes (3 days/decade above 2,000 m and 4.4 days/decade between 1,500 and 2,000 m). These changes indicate a slight shift towards earlier and shorter snow seasons above 1,500 m It should be noted that the FESD in this study refers to the first snow cover detected in cloud-free satellite images, which generally occurs one or more days before the actual event, introducing greater uncertainty compared to LESD. Early snowfall at lower elevations, such as the exceptional event (Gallinar Cañedo *et al.*, 2022) in late October 2018 (2018–2019 season, Fig. 5), can have negative environmental and economic effects. This event, which accumulated 50 cm of snow at 1,000 m in Asturias on the northern slope of the Cantabrian Mountains and covered areas below 500 m, caused road disruptions and power outages due to fallen branches and trees still retaining foliage.

SOD and SMOD tend to occur later, with SMOD occurring up to 2 days later per decade. At higher altitudes, above 2,000 m, there is a notable shortening of snow cover duration due to delayed SOD and earlier SMOD. The values of SMOD and FESD can be highly dependent on both the overall snow accumulation throughout the season and the presence of late snowfall events, which can influence the season's variability. Broader studies (Peng *et al.*, 2013) warn of a high sensitivity due to the correlation between the melting date and the presence of positive temperature anomalies during the melt months. The mean of the maximum SCF date is occurring earlier, particularly at lower altitudes, ranging between January 22nd and February 5th, depending on elevation. February, followed by January, was identified as the month with the highest number of snowfall events on the northern slope of the Cantabrian Mountains during the period from 1988 to 2018 (de Pablo Dávila *et al.*, 2021). The duration of the longest snow cover (SMOD – SOD) has decreased by up to 2 days per decade above 1,500 m and 8 days per decade above 2,000 m, where the five ski resorts in the Cantabrian Mountains are located. These resorts have faced challenges due to notable declines in snow cover duration in the last decades, directly impacting the socio-economic activity of nearby areas by reducing visitor numbers. In nearby mountains, evident reductions in snow availability for these infrastructures are observed, with warnings that even the effectiveness of snowmaking for their maintenance may be compromised if temperature increases are very high (Pons *et al.*, 2015). Below 1,500 m, the duration of the longest snow covers has slightly increased, by up to 1.9% per decade.

Average snow cover duration also shows slight positive trends below 1,500 m, while above this elevation, significant declines are observed, with reductions of -2.9 days per decade between 1,500–2,000 m and up to 5.8 days per decade above 2,000 m These values are comparable to those detected in other studies, such as declines of 5–7 days per decade in the Alps during the 1968–2017 winter period (Monteiro and Morin, 2023) or significant declines in the Pyrenees above 2,100 m, with non-significant trends at 1,500 m due to high interannual variability (López-Moreno *et al.*, 2020). Snow cover persistence, as quantified by the RDL index, shows a non-significant decreasing trend (3.4% per decade) above 1,500 m This indicates that snow cover is becoming increasingly intermittent within the snow season at these elevations. Southern slope basins experiencing the greatest reductions in snow extent and duration also exhibit high RDL values, exceeding 0.8 in some cases. This suggests that these reductions are not due to rapid melting or unstable snow covers but are likely driven by decreases in snowfall events, as explained earlier due to changes in synoptic patterns.

These findings are consistent with broader regional analyses. Alonso-González *et al.* (2020), using MODIS data and physically-based snow modelling, demonstrated that the Cantabrian Mountains, together with the Pyrenees, exhibit the deepest and most persistent snowpacks in the Iberian Peninsula at similar elevations. Despite this, the high interannual variability in snowpack parameters observed in the Cantabrian Mountains suggests a strong sensitivity to climatic factors.

The different temporal coverage of satellite sensors represents a key limitation when assessing long-term trends in snow cover duration. While MODIS provides a continuous record since 2000, the Landsat archive includes earlier data but with lower temporal frequency and less consistent availability. In this study, Landsat data were used only from 2000 onwards to align with the start of the MODIS time series and ensure consistency when comparing trends across sensors. Sentinel-2, meanwhile, covers only the most recent years, albeit with higher spatial resolution. These differences in temporal coverage affect the length of the available time series and must be considered when interpreting trend results. We addressed this by aggregating data at the scale of watersheds and altitudinal bands, which helps reduce local variability and improve robustness. Additionally, although MODIS offers a longer time series, its coarse resolution makes it particularly sensitive to spatial heterogeneity in mountainous terrain. In steep areas, where snow distribution changes rapidly over short distances, this may introduce uncertainty in the classification. This is consistent with recent findings (Bayle *et al.*, 2024), which highlight how changes in observation availability and environmental complexity can lead to artificial trends in satellite-based time series. A further limitation concerns the length of the time series. Our dataset covers 24 years (2000–2024), which is shorter than the 30-year period typically recommended as a standard climatological baseline. Caution is required when interpreting trends, and future work should aim to integrate longer and more homogeneous time series, as well as complementary observational sources (e.g., time-lapse cameras), to validate and refine satellite-derived trends.

The implications of these trends extend beyond snow dynamics, affecting hydrological systems, socio-economic activities (Beniston *et al.*, 2018) and alpine ecosystems (Espinosa del Alba *et al.*, 2025). The earlier snowmelt and shorter snow season could reduce spring and summer water availability, impacting river discharge and water resources for agriculture, hydroelectric power, and human consumption. Alpine vegetation and fauna adapted to stable snow conditions may also experience disruptions in their life cycles. Furthermore, the declining snow cover duration above 1,500 m presents a challenge for winter tourism, particularly for ski resorts, which are already facing operational difficulties due to unreliable snow conditions.

6. Conclusions

This study provides a detailed analysis of snow cover variability in the Cantabrian Mountains based on satellite imagery from 2000 to 2024. The results indicate a significant reduction in snow cover extent, particularly during the winter months, with declines of up to 16% per decade in some watersheds. These reductions are more pronounced above 1,500 m and on the southern slopes of the mountain range. Snow cover duration is also decreasing, especially at higher altitudes, where the longest snow cover events have shortened by 8 days per decade above 2,000 m The timing of key snow seasonal indicators has shifted, with the LESD occurring earlier (2.7 days/decade), while the FESD remains relatively stable. Additionally, the date of maximum snow cover is shifting earlier, particularly at lower elevations.

The results suggest a growing trend toward shorter and less stable snow seasons in the region. These changes are likely linked to rising temperatures and modifications in precipitation patterns, which influence the interannual variability of snow accumulation and persistence. Although some biases exist due to cloud cover, forested areas, and rapid snowmelt events undetected by satellites, the findings highlight a decreasing trend of snow cover extent, duration, and stability over the past two decades, with implications for ecosystems and human activities, particularly in high-altitude areas and regions reliant on snow for tourism and water supply.

Future work will involve analysing longer satellite data series, comparing them with other observational data sources such as webcam images and manual records, and relating current temperature and precipitation trends to changes in snow variability. Further monitoring and analysis are essential to better understand and predict these changes.

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Landsat-8 data (USGS Landsat 8 Level 2, Collection 2, Tier 1) courtesy of the U.S. Geological Survey (https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2, accessed on 10 January 2025).

Landsat-5 data (USGS Landsat 5 Level 2, Collection 2, Tier 1) courtesy of the U.S. Geological Survey (https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LT05_C02_T1_L2, accessed on 10 January 2025).

Imagery from the NASA MODIS instrument (MOD10A1.061 Terra Snow Cover Daily Global 500m), courtesy NASA NSIDC DAAC (https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MOD10A1#description, accessed on 10 January 2025).

Imagery from Sentinel-2 (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR_HARMONIZED, accessed on 10 January 2025) courtesy of Copernicus Services (https://dataspace.copernicus.eu/explore-data/data-collections/sentinel-data/sentinel-2, accessed on 10 January 2025).

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Appendix 1. SCF mean values (2000-2024) by watersheds and seasons

	SCF Autumn (S-O-N)					SCF Winter (D-J-F)					SCF Spring (M-A-M)				
	500-1000 m	1000 - 1500 m	1500 - 2000 m	>2000 m	Watershed mean	500-1000 m	1000 - 1500 m	1500 - 2000 m	>2000 m	Watershed mean	500-1000 m	1000- 1500 m	1500- 2000 m	>2000 m	Watershed mean
Aller	0.00	0.03	0.09	0.14	0.03	0.03	0.26	0.60	0.82	0.19	0.01	0.09	0.31	0.54	0.08
Alto Ebro	0.01	0.03	0.08	0.13	0.02	0.04	0.26	0.61	0.80	0.19	0.01	0.06	0.26	0.44	0.05
Alto Navia - Ibias	0.00	0.02	0.05		0.01	0.03	0.17	0.43		0.10	0.00	0.04	0.18		0.02
Alto Sil	0.00	0.03	0.07	0.11	0.04	0.03	0.21	0.49	0.73	0.26	0.00	0.06	0.20	0.43	0.10
Asón	0.00	0.02	0.04		0.00	0.04	0.31	0.57		0.10	0.01	0.08	0.24		0.02
Bajo Navia	0.01	0.02			0.01	0.03	0.15			0.07	0.01	0.03			0.01
Bernesga	0.00	0.02	0.07	0.13	0.03	0.01	0.18	0.50	0.78	0.24	0.00	0.05	0.20	0.48	0.08
Besaya	0.01	0.02			0.01	0.04	0.22			0.07	0.01	0.06			0.02
Boeza	0.00	0.01	0.04	0.05	0.02	0.02	0.12	0.31	0.66	0.15	0.00	0.03	0.13	0.39	0.06
Burbia	0.00	0.02	0.04		0.01	0.02	0.12	0.39		0.09	0.00	0.02	0.16		0.02
Cares	0.01	0.03	0.09	0.15	0.04	0.05	0.32	0.63	0.80	0.27	0.01	0.10	0.33	0.61	0.12
Carrión		0.03	0.06	0.13	0.04		0.23	0.47	0.78	0.30		0.05	0.19	0.51	0.12
Caudal	0.00	0.02	0.07	0.11	0.01	0.02	0.22	0.56	0.77	0.12	0.01	0.06	0.22	0.45	0.03
Cea	0.00	0.01	0.03		0.01	0.01	0.07	0.21		0.07	0.00	0.02	0.06		0.02
Cúa	0.00	0.02	0.06		0.02	0.02	0.16	0.43		0.12	0.00	0.04	0.18		0.03
Cubia	0.00	0.02			0.01	0.02	0.17			0.05	0.00	0.05			0.01
Curueño		0.02	0.07	0.13	0.04		0.24	0.54	0.80	0.29		0.06	0.25	0.53	0.13
Deva	0.00	0.02	0.09	0.15	0.03	0.03	0.22	0.60	0.82	0.19	0.01	0.06	0.28	0.59	0.07
Esla	0.00	0.02	0.06	0.12	0.03	0.02	0.22	0.49	0.78	0.25	0.00	0.07	0.23	0.46	0.10
Luna	0.00	0.02	0.07	0.11	0.03	0.01	0.19	0.48	0.73	0.27	0.00	0.05	0.18	0.42	0.09
Miera	0.00	0.02			0.01	0.03	0.29			0.09	0.01	0.09			0.02
Nalón	0.00	0.03	0.08		0.01	0.03	0.26	0.57		0.12	0.01	0.09	0.28		0.04
Nansa	0.00	0.03	0.09	0.13	0.02	0.04	0.31	0.62	0.79	0.15	0.01	0.10	0.30	0.51	0.05
Narcea	0.00	0.02	0.07		0.01	0.02	0.19	0.47		0.10	0.00	0.05	0.20		0.03
Nela	0.01	0.03	0.07		0.02	0.04	0.31	0.56		0.18	0.01	0.10	0.25		0.05
Omaña	0.00	0.01	0.05	0.08	0.02	0.02	0.11	0.35	0.71	0.14	0.00	0.02	0.12	0.39	0.04
Pas	0.00	0.02	0.05		0.01	0.03	0.24	0.51		0.07	0.01	0.07	0.19		0.02
Pigüeña	0.00	0.03	0.09	0.13	0.03	0.02	0.23	0.58	0.82	0.20	0.00	0.06	0.26	0.54	0.07
Piloña	0.00	0.01			0.00	0.02	0.17			0.04	0.01	0.06			0.01
Pisuerga	0.00	0.02	0.06	0.11	0.02	0.03	0.15	0.42	0.78	0.16	0.01	0.04	0.15	0.40	0.04
Porma	0.00	0.02	0.07	0.11	0.03	0.01	0.17	0.53	0.75	0.23	0.00	0.05	0.27	0.44	0.10
Saja	0.00	0.02	0.08		0.01	0.04	0.30	0.61		0.13	0.01	0.09	0.28		0.05
Sella	0.00	0.03	0.09	0.15	0.02	0.03	0.27	0.57	0.81	0.16	0.01	0.09	0.29	0.66	0.07
Torío	0.00	0.02	0.07	0.14	0.03	0.01	0.19	0.51	0.79	0.26	0.00	0.05	0.22	0.52	0.10
Trubia	0.00	0.02	0.07	0.11	0.02	0.02	0.21	0.51	0.74	0.15	0.01	0.06	0.21	0.45	0.05
Yuso		0.03	0.08	0.14	0.05		0.28	0.57	0.82	0.34		0.08	0.26	0.55	0.14
Mean	0.00	0.02	0.07	0.12	0.02	0.03	0.21	0.50	0.77	0.16	0.01	0.06	0.22	0.48	0.05

Appendix 2. Mean FESD, LESD and Mean FESD duration values (2000-2024) by watersheds and seasons

	FESD					LESD					Mean FESD duration (in days)				
	500-1000 m	1000 -1500 m	1500 -2000 m	>2000 m	Watershed mean	500-1000 m	1000 -1500 m	1500 -2000 m	>2000 m	Watershed mean	500-1000 m	1000-1500 m	1500-2000 m	>2000 m	Watershed mean
Aller	Nov 29th	Nov 19th	Nov 05th	Nov 09th	Nov 12th	Feb 21st	Apr 14th	May 05th	May 09th	Apr 19th	7.3	12.5	33.7	45.7	9.8
Alto Ebro	Dec 18th	Nov 19th	Nov 07th	Nov 03rd	Nov 17th	Mar 03rd	Apr 04th	Apr 27th	May 11th	Apr 10th	8.2	11.1	25.2	35.0	9.7
Alto Navia -Ibias	Nov 28th	Nov 23rd	Nov 12th		Nov 21st	Jan 23rd	Mar 25th	Apr 23rd		Mar 23rd	6.6	16.1	33.3		15.0
Alto Sil	Dec 01st	Nov 22nd	Nov 06th	Nov 01st	Nov 11th	Feb 04th	Mar 29th	Apr 19th	May 11th	Apr 17th	7.5	15.7	18.2	23.4	11.7
Asón	Dec 13th	Nov 29th	Nov 26th		Dec 07th	Feb 25th	Apr 07th	Apr 03rd		Mar 17th	7.7	13.1	15.4		9.6
Bajo Navia	Nov 27th	Nov 25th			Nov 30th	Feb 05th	Mar 14th			Feb 21st	7.2	13.9			7.8
Bernesga	Nov 18th	Nov 23rd	Nov 07th	Nov 06th	Nov 10th	Dec 17th	Apr 06th	Apr 30th	May 12th	Apr 14th	3.5	14.6	22.1	29.0	11.9
Besaya	Dec 15th	Dec 06th			Dec 17th	Mar 05th	Mar 21st			Mar 08th	7.7	11.5			9.5
Boeza	Dec 02nd	Nov 23rd	Nov 09th	Nov 20th	Nov 14th	Jan 13th	Mar 06th	Apr 13th	Apr 15th	Apr 07th	8.4	10.8	26.3	15.9	14.3
Burbia	Nov 24th	Nov 22nd	Nov 13th		Nov 27th	Dec 26th	Mar 10th	Apr 18th		Mar 18th	6.4	13.0	15.7		10.2
Cares	Nov 30th	Nov 11th	Nov 02nd	Oct 23rd	Nov 05th	Mar 06th	Apr 09th	May 06th	Jun 07th	May 04th	7.7	11.0	42.6	74.8	31.3
Carrión		Nov 17th	Nov 08th	Oct 27th	Nov 07th		Mar 27th	Apr 25th	May 22nd	Apr 27th		15.2	27.3	45.1	18.8
Caudal	Nov 28th	Nov 20th	Nov 08th	Nov 09th	Nov 19th	Feb 01st	Apr 04th	Apr 29th	May 05th	Apr 03rd	5.2	8.1	23.5	27.3	10.5
Cea	Nov 18th	Dec 07th	Nov 29th		Dec 07th	Dec 16th	Mar 09th	Apr 03rd		Mar 09th	5.6	7.0	11.1		7.4
Cúa	Dec 04th	Nov 23rd	Nov 13th		Nov 19th	Jan 26th	Mar 26th	Apr 18th		Mar 28th	5.5	13.9	23.0		9.3
Cubia	Dec 02nd	Nov 28th			Dec 09th	Jan 21st	Mar 19th			Feb 29th	6.4	11.0			8.2
Curueño		Nov 21st	Nov 06th	Nov 04th	Nov 06th		Mar 29th	Apr 30th	May 15th	Apr 23rd		9.7	20.8	26.9	12.3
Deva	Dec 04th	Nov 18th	Nov 03rd	Oct 20th	Nov 11th	Feb 15th	Apr 03rd	May 04th	Jun 08th	Apr 18th	6.3	11.3	21.1	54.2	17.7
Esla	Nov 26th	Nov 17th	Nov 05th	Nov 04th	Nov 10th	Jan 07th	Apr 09th	Apr 22nd	May 08th	Apr 15th	5.3	9.6	23.1	26.2	12.3
Luna	Nov 20th	Nov 22nd	Nov 07th	Oct 31st	Nov 14th	Dec 18th	Mar 27th	Apr 25th	May 10th	Apr 15th	4.5	14.6	11.8	23.7	24.4
Miera	Dec 23rd	Nov 28th			Dec 08th	Mar 12th	Apr 05th			Mar 23rd	6.8	13.8			7.3
Nalón	Dec 06th	Nov 15th	Nov 07th		Nov 20th	Feb 27th	Apr 08th	Apr 29th		Apr 08th	8.3	11.1	23.7		11.6
Nansa	Dec 08th	Nov 18th	Nov 05th	Nov 05th	Nov 22nd	Mar 02nd	Apr 06th	May 01st	May 04th	Apr 09th	6.8	18.9	31.4	28.9	13.3
Narcea	Dec 01st	Nov 25th	Nov 10th		Nov 24th	Feb 05th	Mar 24th	Apr 16th		Mar 26th	6.4	14.1	15.6		10.6
Nela	Dec 12th	Nov 21st	Nov 19th		Nov 23rd	Mar 17th	Apr 03rd	Apr 19th		Mar 31st	9.3	19.8	18.9		14.2
Omaña	Dec 17th	Nov 25th	Nov 13th	Nov 10th	Nov 17th	Feb 01st	Mar 01st	Apr 14th	Apr 26th	Mar 30th	6.3	10.8	27.1	19.1	11.9
Pas	Dec 18th	Nov 30th	Nov 23rd		Dec 17th	Mar 02nd	Mar 26th	Apr 12th		Mar 17th	7.6	11.6	10.5		10.5
Pigüeña	Nov 27th	Nov 23rd	Nov 05th	Nov 04th	Nov 12th	Feb 02nd	Apr 04th	May 02nd	May 09th	Apr 15th	7.8	16.3	21.2	33.8	16.8
Piloña	Dec 05th	Nov 28th			Dec 09th	Feb 10th	Mar 29th			Feb 14th	5.8	9.8			5.5
Pisuerga	Dec 12th	Nov 21st	Nov 06th	Nov 06th	Nov 21st	Feb 13th	Mar 20th	Apr 19th	May 07th	Apr 01st	6.5	10.9	11.9	36.2	12.5
Porma	Nov 22nd	Nov 18th	Nov 04th	Nov 05th	Nov 07th	Dec 21st	Apr 06th	Apr 29th	May 10th	Apr 18th	8.4	13.5	19.1	25.3	11.3
Saja	Dec 10th	Nov 25th	Nov 06th		Nov 26th	Feb 16th	Apr 07th	Apr 20th		Apr 04th	7.1	19.0	21.2		14.7
Sella	Nov 30th	Nov 15th	Nov 05th	Oct 31st	Nov 13th	Feb 21st	Apr 07th	Apr 30th	Jun 05th	Apr 12th	7.2	13.8	19.0	55.3	11.5
Torio	Nov 25th	Nov 24th	Nov 06th	Nov 03rd	Nov 09th	Dec 14th	Mar 31st	Apr 26th	May 10th	Apr 20th	5.9	15.2	15.8	33.2	12.6
Trubia	Dec 03rd	Nov 22nd	Nov 08th	Nov 06th	Nov 16th	Feb 17th	Apr 01st	Apr 22nd	May 25th	Apr 07th	4.7	11.4	19.2	38.2	13.4
Yuso		Nov 20th	Nov 04th	Oct 27th	Nov 07th		Mar 28th	Apr 24th	May 18th	Apr 23rd		19.6	25.0	40.2	22.7
Mean	Dec 11th	Nov 23rd	Nov 10th	Nov 3rd	Nov 21st	Mar 10th	Mar 30th	Apr 25th	May 15th	Apr 4th	6.7	13.1	21.7	35.1	12.8

Appendix 3. Mean SOD, SMOD and Max SCF Day (2000-2024) by watersheds and seasons

	SOD					SMOD					Max SCF day				
	500-1000 m	1000 -1500 m	1500 -2000 m	>2000 m	Watershed mean	500-1000 m	1000 -1500 m	1500 -2000 m	>2000 m	Watershed mean	500-1000 m	1000-1500 m	1500-2000 m	>2000 m	Watershed mean
Aller	Jan 11th	Jan 3rd	Dec 18th	Dec 24th	Jan 3rd	Jan 22nd	Feb 15th	Apr 6th	Mar 26th	Feb 24th	Jan 17th	Jan 26th	Feb 03rd	Feb 05th	Jan 23rd
Alto Ebro		Jan 10th	Dec 23rd	Dec 23rd	Dec 29th		Feb 15th	Mar 20th	Mar 19th	Mar 9th	Jan 11th	Jan 29th	Feb 02nd	Feb 01st	Jan 18th
Alto Navia - Ibias	Jan 5th	Dec 25th	Dec 29th		Jan 1st	Jan 15th	Jan 22nd	Mar 2nd		Jan 28th	Jan 05th	Jan 12th	Jan 12th		Jan 09th
Alto Sil	Jan 6th	Jan 7th	Dec 19th	Dec 23rd	Dec 29th	Jan 16th	Feb 16th	Mar 16th	Apr 7th	Feb 28th	Jan 13th	Jan 15th	Jan 25th	Feb 01st	Jan 10th
Asón	Jan 20th	Jan 8th	Jan 7th		Jan 12th	Feb 1st	Feb 14th	Feb 17th		Feb 5th	Jan 30th	Jan 30th	Feb 02nd		Feb 04th
Bajo Navia	Dec 30th	Dec 31st			Jan 5th	Jan 9th	Jan 21st			Jan 17th	Jan 08th	Jan 07th			Jan 15th
Bernesga	Jan 9th	Jan 5th	Dec 23rd	Dec 22nd	Dec 30th	Jan 13th	Feb 15th	Mar 25th	Mar 31st	Feb 27th	Jan 27th	Jan 22nd	Jan 23rd	Feb 03rd	Jan 28th
Besaya	Jan 14th	Jan 14th			Jan 14th	Jan 26th	Feb 10th			Jan 29th	Jan 17th	Jan 31st			Feb 02nd
Boeza	Jan 15th	Jan 16th	Dec 29th	Jan 9th	Jan 9th	Jan 24th	Feb 9th	Feb 27th	Mar 6th	Feb 16th	Jan 27th	Jan 17th	Jan 27th	Feb 06th	Jan 13th
Burbia	Jan 10th	Jan 13th	Jan 4th		Jan 7th	Jan 18th	Feb 6th	Feb 24th		Jan 29th	Jan 03rd	Jan 04th	Feb 05th		Jan 15th
Cares	Jan 5th	Jan 6th	Dec 26th	Nov 25th	Dec 29th	Jan 19th	Feb 23rd	Apr 18th	Apr 28th	Mar 7th	Jan 26th	Jan 28th	Jan 29th	Feb 06th	Jan 19th
Carrión		Jan 9th	Dec 23rd	Dec 5th	Dec 23rd		Feb 14th	Mar 23rd	Apr 25th	Mar 22nd		Jan 22nd	Jan 29th	Feb 06th	Jan 20th
Caudal	Jan 7th	Jan 2nd	Dec 23rd	Dec 26th	Jan 1st	Jan 15th	Feb 4th	Mar 7th	Mar 28th	Feb 12th	Jan 21st	Jan 25th	Jan 26th	Feb 03rd	Jan 18th
Cea	Feb 4th	Jan 20th	Jan 14th		Jan 23rd	Feb 11th	Feb 4th	Feb 15th		Feb 10th	Jan 14th	Jan 17th	Jan 24th		Jan 21st
Cúa	Jan 8th	Jan 5th	Jan 6th		Jan 7th	Jan 17th	Feb 4th	Mar 12th		Feb 10th	Jan 02nd	Jan 10th	Jan 19th		Jan 08th
Cubia	Jan 8th	Jan 6th			Jan 10th	Jan 16th	Jan 28th			Jan 21st	Jan 13th	Feb 02nd			Jan 24th
Curueño			Dec 19th	Dec 25th	Dec 22nd			Mar 26th	Apr 19th	Apr 7th		Jan 25th	Jan 27th	Feb 09th	Jan 29th
Deva	Jan 18th	Jan 7th	Dec 19th	Nov 25th	Dec 29th	Jan 29th	Feb 13th	Apr 4th	Apr 17th	Feb 28th	Jan 29th	Jan 21st	Jan 26th	Feb 08th	Jan 23rd
Esla	Jan 17th	Jan 6th	Jan 4th	Jan 3rd	Jan 10th	Feb 4th	Feb 20th	Mar 25th	Mar 26th	Mar 5th	Feb 01st	Feb 05th	Feb 07th	Feb 04th	Jan 31st
Luna	Jan 10th		Jan 1st	Dec 18th	Dec 30th	Jan 16th		Mar 21st	Apr 9th	Mar 6th	Jan 24th	Jan 19th	Feb 06th	Jan 29th	Jan 26th
Miera		Jan 4th	Dec 22nd		Dec 31st		Feb 10th			Dec 10th	Jan 28th	Feb 02nd			Jan 28th
Nalón	Jan 19th	Jan 9th	Dec 27th		Jan 11th	Jan 29th	Feb 26th	Mar 28th		Feb 19th	Jan 25th	Jan 22nd	Feb 01st		Jan 25th
Nansa		Dec 31st	Dec 26th	Dec 21st	Jan 1st		Feb 17th	Mar 25th	Mar 20th	Feb 27th	Jan 25th	Jan 28th	Jan 31st	Feb 06th	Feb 03rd
Narcea	Jan 5th	Jan 7th	Jan 8th		Jan 8th	Jan 14th	Feb 4th	Mar 7th		Feb 3rd	Jan 12th	Jan 16th	Jan 18th		Jan 05th
Nela		Dec 26th	Jan 7th		Jan 1st		Feb 12th	Feb 26th		Feb 19th	Jan 19th	Feb 03rd	Feb 01st		Jan 31st
Omaña	Jan 17th	Jan 11th	Dec 26th	Dec 24th	Jan 4th	Jan 26th	Feb 4th	Feb 28th	Mar 15th	Feb 17th	Jan 28th	Jan 21st	Jan 22nd	Feb 04th	Jan 19th
Pas		Jan 7th	Jan 7th		Jan 11th		Feb 8th	Feb 18th		Feb 6th	Feb 01st	Feb 05th	Feb 03rd		Jan 24th
Pigüeña		Dec 28th	Dec 27th	Jan 5th	Jan 6th		Jan 30th	Mar 25th	Apr 8th	Mar 2nd	Jan 13th	Jan 30th	Jan 25th	Feb 06th	Jan 30th
Piloña	Jan 19th	Jan 18th			Jan 18th	Jan 29th	Feb 10th			Jan 30th	Feb 02nd	Jan 31st			Jan 31st
Pisuerga		Jan 7th	Jan 2nd	Dec 17th	Dec 29th		Feb 6th	Mar 7th	Mar 21st	Mar 2nd	Jan 13th	Jan 20th	Feb 04th	Feb 01st	Jan 22nd
Porma	Jan 14th	Jan 13th	Dec 25th	Jan 5th	Jan 6th	Jan 25th	Feb 20th	Mar 28th	Apr 6th	Mar 6th	Feb 04th	Jan 28th	Feb 03rd	Feb 06th	Jan 31st
Saja	Jan 15th	Jan 2nd	Dec 19th		Dec 10th	Jan 27th	Feb 16th	Mar 12th		Jan 8th	Jan 26th	Feb 01st	Feb 02nd		Jan 30th
Sella	Jan 6th	Jan 5th	Dec 28th	Dec 15th	Dec 31st	Jan 19th	Feb 19th	Apr 1st	Apr 30th	Feb 27th	Jan 23rd	Jan 28th	Feb 05th	Feb 08th	Jan 20th
Torio	Jan 17th		Dec 26th	Dec 28th	Jan 4th	Jan 26th		Mar 29th	Apr 12th	Mar 13th	Jan 28th	Jan 23rd	Jan 29th	Feb 08th	Jan 18th
Trubia	Jan 4th	Jan 2nd	Dec 28th	Dec 28th	Jan 3rd	Jan 12th	Feb 4th	Mar 10th	Apr 4th	Feb 15th	Jan 25th	Jan 24th	Jan 23rd	Jan 29th	Jan 20th
Yuso		Jan 2nd	Dec 23rd	Dec 10th	Dec 22nd		Feb 18th	Apr 3rd	Apr 24th	Mar 26th		Jan 29th	Feb 07th	Feb 04th	Jan 12th
Mean	Jan 14th	Jan 7th	Dec 29th	Dec 22nd	Jan 7th	Jan 23rd	Feb 11th	Mar 16th	Apr 5th	Feb 17th	Jan 22nd	Jan 24th	Jan 29th	Feb 5th	Jan 24th

Appendix 4. Mean SCD, MED and RDL values (2000-2024) by watersheds and seasons

	LSCD					MED					RDL				
	500-1000 m	1000 - 1500 m	1500 - 2000 m	>2000 m	Watershed mean	500-1000 m	1000 - 1500 m	1500 - 2000 m	>2000 m	Watershed mean	500-1000 m	1000- 1500 m	1500- 2000 m	>2000 m	Watershed mean
Aller	12.2	44.0	89.8	93.0	52.9	6.7	17.4	45.9	34.2	21.7	0.05	0.53	0.73	0.79	0.43
Alto Ebro		37.3	88.3	87.4	71.0		14.3	35.3	35.5	28.4	0.35	0.29	0.55	0.65	0.46
Alto Navia - Ibias	11.2	29.0	63.4		27.4	7.5	13.6	25.1		12.8	0.32	0.37	0.72		0.40
Alto Sil	11.0	40.7	88.7	105.9	61.6	7.9	18.0	34.0	34.6	23.6	0.30	0.74	0.81	0.91	0.69
Asón	14.0	38.0	42.3		24.8	7.8	14.7	21.3		12.2	0.21	0.35	0.38		0.25
Bajo Navia	11.3	21.8			13.1	6.8	10.9			7.4	0.18	0.32			0.23
Bernesga	15.5	41.2	92.6	99.9	59.8	5.9	17.3	30.2	33.0	21.1	0.05	0.59	0.78	0.70	0.53
Besaya	13.3	28.0			15.4	8.0	14.2			8.8	0.20	0.29			0.18
Boeza	10.4	25.3	61.2	67.2	38.5	7.4	12.5	23.2	24.4	16.9	0.19	0.73	0.76	0.87	0.64
Burbia	12.0	25.0	52.8		22.6	6.8	12.1	20.1		10.6	0.35	0.45	0.53		0.34
Cares	15.2	49.6	114.3	155.0	68.7	7.9	18.5	50.5	55.9	27.7	0.26	0.42	0.61	0.92	0.45
Carrión		37.2	91.3	142.8	90.4		16.9	35.0	51.7	34.5		0.72	0.81	0.92	0.82
Caudal	8.8	34.0	74.8	93.3	42.9	5.4	14.7	25.7	34.1	16.6	0.05	0.49	0.53	0.59	0.34
Cea	10.0	31.0	68.3		35.8	5.4	9.4	13.0		9.2	0.05	0.42	0.80		0.42
Cúa	10.0	31.5	65.0		35.5	6.4	15.7	23.5		15.2	0.28	0.47	0.64		0.46
Cubia	9.1	22.7			12.5	6.1	11.8			7.5	0.20	0.28			0.18
Curueño		52.1	98.0	115.6	106.8		17.8	33.5	44.5	39.0		0.71	0.69	0.88	0.76
Deva	13.9	38.0	107.4	143.6	61.2	7.0	14.8	45.4	52.0	24.7	0.26	0.30	0.69	0.93	0.45
Esla	18.4	46.3	80.3	83.2	54.8	6.1	18.4	27.2	30.3	20.5	0.20	0.52	0.69	0.79	0.55
Luna	16.3	43.1	80.0	112.5	66.3	6.8	17.6	30.4	38.4	24.5	0.05	0.61	0.65	0.86	0.54
Miera	20.2	38.4			14.8	7.4	15.5	32.2		6.8	0.26	0.28	0.31		0.22
Nalón	12.6	49.7	92.2		40.1	6.4	18.9	32.5		15.9	0.05	0.50	0.70		0.32
Nansa		48.9	89.1	90.3	57.9	4.8	19.8	33.1	35.8	23.0	0.30	0.47	0.56	0.70	0.42
Narcea	11.5	28.2	59.8		26.9	6.7	12.9	23.3		12.4	0.30	0.53	0.57		0.36
Nela		48.3	50.8		49.5		19.9	20.4		20.2		0.53	0.72		0.62
Omaña	9.9	24.7	64.5	81.8	45.2	7.0	11.7	24.2	29.6	18.1	0.44	0.45	0.56	0.67	0.53
Pas	19.2	32.8	43.0		27.2	6.2	15.6	16.8		12.4	0.26	0.71	0.57		0.40
Pigüeña	12.4	33.8	89.2	94.7	55.8	6.4	14.8	33.8	38.3	22.8	0.20	0.46	0.61	0.68	0.40
Piloña	11.2	23.9			13.1	6.2	10.8			6.8	0.05	0.21			0.10
Pisuerga		31.3	65.5	94.3	63.7		13.0	23.5	35.3	23.9	0.35	0.40	0.65	0.78	0.55
Porma	14.9	39.7	94.2	92.0	59.5	8.8	16.1	32.8	29.9	21.9	0.05	0.49	0.56	0.82	0.48
Saja	14.9	46.1	83.9	0.0	29.6	7.4	19.5	32.2	0.0	12.8	0.05	0.41	0.59	0.89	0.40
Sella	14.3	45.8	95.2	136.9	59.6	7.5	20.6	33.2	55.5	24.2	0.05	0.49	0.62	0.81	0.40
Torío	17.5	50.1	94.2	106.4	69.4	5.2	18.8	33.8	41.9	27.0	0.05	0.60	0.71	0.71	0.52
Trubia	9.4	33.8	72.7	97.3	43.9	5.2	13.6	25.9	24.5	14.9	0.05	0.42	0.64	0.83	0.40
Yuso		47.7	102.5	135.3	95.2		21.6	40.1	51.2	37.6		0.59	0.75	0.89	0.74
Mean	13	36.1	78.4	106	42.1	6.7	15.5	29.8	38.5	16.4	0.19	0.52	0.72	0.79	0.56