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## Long-term trends (1958–2017) in snow cover duration and depth in the Pyrenees

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1 **LONG TERM TRENDS (1958–2017) IN SNOW COVER DURATION AND**  
2 **DEPTH IN THE PYRENEES**

3 **Running title: Trends in snow cover in the Pyrenees**

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23

25 **Abstract.** This study investigated the temporal variability and changes in snow cover  
26 duration and the average snow depth from December to April in the Pyrenees at 1500  
27 and 2100 m a.s.l. for the period 1958–2017. This is the first such analysis for the entire  
28 mountain range using SAFRAN-Crocus simulations run for this specific purpose. The  
29 SAFRAN-Crocus simulations were evaluated for the period 1980–2016 using 28 in situ  
30 snow depth data time series, and for the period 2000–2017 using MODIS observations  
31 of the snow cover duration. Following confirmation that the simulated snow series  
32 satisfactorily reproduced the observed evolution of the snowpack, the Mann-Kendall  
33 test showed that snow cover duration and average depth decreased during the full study  
34 period, but this was only statistically significant at 2100 m a.s.l. The temporal evolution  
35 in the snow series indicated marked differences among massifs, elevations, and snow  
36 variables. In general, the most western massifs of the French Pyrenees underwent a  
37 greater decrease in the snowpack, while in some eastern massifs the snowpack did not  
38 decrease, and in some cases increased at 1500 m a.s.l. The results suggest that the trends  
39 were consistent over time, as they were little affected by the start and end year of the  
40 study period, except if trends are computed only starting after 1980, when no significant  
41 trends were apparent. Most of the observed negative trends were not correlated with  
42 changes in the atmospheric circulation patterns during the snow season. This suggests  
43 that the continuous warming in the Pyrenees since the beginning of the industrial  
44 period, and particularly the sharp increase since 1955, is a major driver explaining the  
45 snow cover decline in the Pyrenees.

46 **Keywords:** Snow, Trends, Weather Types, Pyrenees

47

## 48 **1. Introduction**

49 Seasonal snow is essential for most environmental, hydrological, and geomorphological  
50 processes in mountain areas. The insulation effect whereby snow cover protects the  
51 underlying substrate from atmospheric temperatures directly controls the thermal  
52 regime of soils, and determines the phenological cycles of plants and animals living at  
53 high elevations (Kankaanpää *et al.*, 2018; Wang *et al.*, 2018; Serrano *et al.*, 2019). The

54 snowpack also acts as a natural reservoir of water, formed during the cold season from  
55 the accumulated precipitation. The water is released during the melt period, and this  
56 governs the timing of river flows and also provides mountain basins with a greater  
57 temporal regularity compared with areas dominated by liquid precipitation (Barnett et  
58 al. 2005; López-Moreno et al. 2017; Sproles et al. 2018). The state of the snow cover  
59 also has clear implications for local communities, as it is a source of major hazards  
60 including avalanches, heavy snowfall events, and rain on snow events that affect the  
61 security of people and infrastructure (Eckert *et al.*, 2013; Surfleet and Tullos, 2013;  
62 Navarro-Serrano and López-Moreno, 2017). In addition, its reliable presence is the  
63 main factor for various winter tourism activities that have become the primary source of  
64 economic income in many mountain regions worldwide (Gilaberte-Búrdalo *et al.*, 2014;  
65 Spandre *et al.*, 2019).

66 There is growing concern about the consequences of ongoing climate warming on the  
67 mountain snow cover, evident in the growing body of published research devoted to  
68 identifying changes in the duration and thickness of snowpack in various regions of the  
69 world (Hock et al., in press), including the Mediterranean mountains (García-Ruiz *et al.*,  
70 2011; Marchane *et al.*, 2015) and the Alps (Klein et al., 2016; Marty et al., 2017,  
71 Schöner *et al.*, 2019). Many studies have involved sensitivity analyses and predictions  
72 of the impact of various climate scenarios on the snowpack in coming decades (Rasouli  
73 *et al.*, 2014, 2019; Musselman *et al.*, 2017, Verfaillie et al., 2018, Beniston et al., 2018).  
74 However, the study of past snowpack trends is highly constrained by the generally  
75 limited number of long-term measurements at high elevation sites, where the snowpack  
76 plays the most important role (Hock et al., in press). In addition, the stations providing  
77 long-term observations are generally unevenly distributed, which makes it difficult to  
78 obtain data at regional scales or for entire mountain ranges (Rohrer *et al.*, 2013).  
79 Another difficulty in snow trend analyses comes from the very high interannual and  
80 decadal variability commonly evident in snowpack series (Wegmann *et al.*, 2017); such  
81 data can only be adequately analyzed from multidecadal snow series (Mankin and  
82 Diffenbaugh, 2015). Successful analyses have only been achieved based on data from  
83 very dense networks having long-term observations, including that recently published  
84 for Switzerland and Austria (Schöner *et al.*, 2019). The European Alps are arguably the  
85 European mountain region richest in terms of data availability, and where these type of

86 studies have been conducted (Laternser and Schneebeli 2003; Marty 2008; Morán-  
87 Tejada et al. 2013; Marke *et al.*, 2018; Schöner et al. 2019; Marty et al., 2017). Studies  
88 on the evolution of snow cover based on remote sensing data have provided information  
89 on the regional temporal variability of snow cover and snow line elevation, but their  
90 limited temporal extent prevents robust assessment of significant trends (Bormann *et*  
91 *al.*, 2018). An alternative to the use of observed snow series is the use of simulated  
92 snow series driven by atmospheric reanalyses or observations (Alonso-González et al.  
93 2019; van Pelt et al. 2016; Durand et al. 2009; Mote et al., 2018; Marke et al. 2018).  
94 Although the results can differ from those based on snow observations, they have been  
95 shown to adequately reproduce the interannual evolution of the duration and thickness  
96 of the snowpack (Martin and Etchevers 2005; Durand et al. 2009; Alonso-González et  
97 al. 2018). Thus, they can provide long-term and spatially distributed information on the  
98 snow cover over large areas, enabling regional assessment of snow changes despite  
99 limited availability of direct snow cover observational data.

100 The main objective of this study is to analyze the temporal evolution of snow cover  
101 duration and average snow depth in the Pyrenees and to assess to which extent the  
102 variability is controlled by regional atmospheric circulation. This work also aims to  
103 identify spatial differences in the temporal evolution of snow depth series, and to assess  
104 the temporal consistency of the trends when different study periods are considered. We  
105 used simulated snow series from the combined application of the atmospheric reanalysis  
106 SAFRAN and the snowpack model Crocus for the period 1958–2017. The temporal  
107 consistency of the trends in the snow series was tested by analyzing the dependence of  
108 the trend patterns on the chosen start and end year of the study time series. We then  
109 investigated changes in the frequency of weather types (synoptic situations) over the  
110 Pyrenees during each analyzed snow season to assess whether the detected trends were  
111 dependent on shifts in atmospheric circulation patterns, which are subject to natural  
112 variability, or whether the trends could be attributed to other drivers, in particular the  
113 observed regional climate warming. This is relevant because recent temperature data  
114 compiled by weather agencies in France, Spain, and Andorra have shown that the  
115 Pyrenees has undergone an increase in annual temperature of 1.3°C since 1955  
116 (Pyrenean Observatory of Climate Change, 2019).

117

118 **2. Study area**

119 The Pyrenees is the northern limit of the Iberian Peninsula and creates a natural border  
120 between Spain and France. It extends from west to east over 400 km from the Atlantic  
121 Ocean to the Mediterranean Sea, and is 150 km at its widest point (along a north–south  
122 axis) in the central area (Figure 1). It is a transboundary mountain area, including the  
123 territory of three countries: France, Spain, and Andorra. The Pyrenean headwaters  
124 include the main tributaries of large rivers including the Ebro River, which flows to the  
125 Mediterranean Sea, and the Garonne River, which flows to the Atlantic Ocean. The  
126 Pyrenean range is a key source of runoff meeting the water demands of 7 million people  
127 and supplying hydropower and large irrigation areas on both sides of the mountain  
128 range. The highest peaks of the Pyrenees are in the central and eastern parts of the  
129 range, where more than 150 peaks exceeding 3000 m occur (the maximum elevation is  
130 reached in the Aneto peak: 3404 m a.s.l.), and large areas are above 2000 m a.s.l.

131 -Figure 1-

132

133 The climate of the Pyrenees is highly variable in the east–west direction, as it reflects  
134 the transition from Atlantic to Mediterranean climates. There is also a marked climatic  
135 difference between the northward and southward slopes along the main axis of the  
136 range, with the former being markedly more humid. Annual precipitation ranges from  
137 600 mm in the dryer areas in the eastern part of the Spanish Pyrenees, to up to 3000 mm  
138 in the most humid parts of the western Pyrenees and on slopes facing north and  
139 northwest in the most elevated central massifs (Serrano-Notivoli *et al.*, 2017). The  
140 elevation of the annual 0°C isotherm ranges from 2700 to 3000 m a.s.l. (López-Moreno  
141 *et al.* 2019), while the winter 0°C isotherm is located at approximately 1500 m a.s.l.,  
142 which is the approximate limit for the seasonal snowpack during the coldest months of  
143 the year (López-Moreno 2005; Gascoin *et al.* 2015). Above 2000 m a.s.l. the duration of  
144 snowpack often exceeds six months (López-Moreno *et al.* 2017; Gascoin *et al.* 2015).  
145 Snow is a key resource for the region; López-Moreno and García-Ruiz (2004) estimated  
146 that the snowmelt contributes > 40% of the spring runoff for the Ebro headwaters, and  
147 noted that it is a major complement to dams for synchronizing water demand and water  
148 availability, mainly for agriculture and hydropower production. The snowpack has been

149 also reported to have a significant influence on forest growth and health in several  
150 Pyrenean areas at 1300–2300 m a.s.l. (Sanmiguel-Vallelado *et al.*, 2019). There are  
151 more than 30 ski resorts in the Pyrenees, serving a mean annual population of 5 million  
152 skiers, and is the major source of income for many Pyrenean valleys (Gilaberte-Búrdalo  
153 *et al.*, 2017). The communities involved depend directly on the quantity and duration of  
154 the snowpack, and there is growing concern about its reliability given the climate  
155 warming projections for the coming decades (Pons *et al.* 2015), and the extent to which  
156 snowmaking and other snow management techniques will be able to address the  
157 increasing snow scarcity suggested by climate change scenarios (Spandre *et al.*, 2019).

158

### 159 **3. Methods**

#### 160 3.1 SAFRAN Crocus simulations

161 SAFRAN is a reanalysis system combining in-situ meteorological observations,  
162 remotely sensed cloud cover information and large scale meteorological predictions, in  
163 order to provide a consistent and gap-free estimate of the meteorological conditions in  
164 mountainous regions, here the Pyrenees (Durand *et al.*, 2009). The Pyrenees are  
165 decomposed in 23 regions (shown in Figure 1) so called “massifs”, considered  
166 climatologically homogeneous, within which SAFRAN provides meteorological  
167 information at hourly time resolution and by elevation steps of 300 m elevation. In  
168 addition, SAFRAN can also provide meteorological information with adjustments of  
169 temperature and radiations considering the exact elevation of a given location and its  
170 surrounding topographic masks (but the spatial scale of the meteorological analysis  
171 remains the massif). In this work, SAFRAN data are used for all massifs in the Pyrenees  
172 for 300 m elevations bands on flat terrain. Model simulations used in this study span the  
173 time period from 1958 to 2017. This corresponds to a version almost identical to the  
174 dataset available made available by Vernay *et al.*, (2019). The last corrections made  
175 before the publication of this dataset are sufficiently minor to not modify the  
176 conclusions of this study.

177 The SAFRAN meteorological reanalysis was used to force the detailed snowpack model  
178 Crocus (Vionnet *et al.*, 2012) which provides estimates of snow cover depth, amount

179 and various other properties using a multi-layer modelling approach. In this study, we  
180 used the spatial configuration for Crocus forced by SAFRAN (massifs/elevations and  
181 corresponding to observation stations) used operationally in France in support for  
182 avalanche forecasting as described in Morin et al. (2020).The SAFRAN-Crocus  
183 simulations were also used in the gap filling procedure of 28 long-term snow  
184 observation series used in the model evaluation process (section 3.2). For this purpose,  
185 at observation stations, observed snow depth data were used to correct the simulated  
186 snow depth and re-initialize the following simulations, with the same method as applied  
187 by Revuelto et al. (2016) with snow depth data from a Terrestrial Laser Scanner. Here,  
188 this method was implemented on a daily basis, i.e. simulations were stopped every day,  
189 snow depth was compared to observed snow depth, and in the case where snow depth  
190 values existed, the observed snow depth value was used to adjust the thickness of all  
191 simulated snow layers in Crocus so that the snow depth values match, keeping constant  
192 the other state variables of each layer (density, temperature, liquid water content,  
193 microstructure properties). In cases where snow observations were missing, Crocus  
194 prognostic variables were left unchanged. In the case where observations indicated 0,  
195 the Crocus snowpack was removed, and in the case where Crocus predicted 0 snow  
196 depth while observations indicated non-zero values, Crocus was reinitialized with a  
197 generic, snowpack structure matching the observed snow depth. This typical snowpack  
198 structure was generated, using a Crocus model run driven by a SAFRAN forcing file  
199 and stopped when the snow depth reached approximately 5 and 50 cm, respectively.  
200 Depending on the observed snow depth, either of these two files were used, in order to  
201 initialize Crocus with a snowpack structure which is consistent with the corresponding  
202 snow depth. While this method of direct insertion is not as advanced as proper data  
203 assimilation, it allows for gap-filling, taking advantage of the fact that the snow cover  
204 evolves with a large auto-correlation in time and that the SAFRAN-Crocus model chain  
205 already provides an appropriate estimate of the daily snow cover evolution for trend  
206 analysis, based on previous studies (Lafaysse et al., 2013, Durand et al., 2009, Spandre  
207 et al., 2019). Meanwhile, this method allowed us to detect and remove outliers in  
208 observed snow depth time series, warranting further investigations (combining other  
209 data sources, such as temperature, precipitation and wind speed), where the observed  
210 snow cover deviates strongly from the simulated one. The outcome of this method is a  
211 gap-filled observed snow depth time series, corresponding exactly to the observed

212 values when they are present, and filled with physically consistent values in the case of  
213 data gaps, including during the melt season at the end of the winter, when many manual  
214 observations are not performed anymore due to the seasonal closure of ski resorts where  
215 the observations are carried out by specially trained ski patrollers. Figure 2 shows four  
216 examples of simulated snow series with SAFRAN Crocus approach before (Sims) and  
217 after applying the re-initialization procedure explained in this section (Sims-Assim).

218

219 -Figure 2-

### 220 3.2 Evaluation of SAFRAN Crocus simulations

221 Before doing the trend analysis, the ability of SAFRAN Crocus to reproduce the annual  
222 average snow depth (HS) and annual snow cover duration (SCD) was specifically  
223 evaluated for this study.

224 The simulated HS was compared to the HS obtained from reconstructed snow depth  
225 observations at 28 long term stations over the period 01 August 1979 to 31 July 2016  
226 (hereinafter referred to as “station HS”). These reconstructed snow depth series were  
227 considered as “ground truth” since these reconstructed time series do not differ from the  
228 observations when there are observations, and although the method introduces some  
229 artificial errors correlations during the reconstructed periods (after the closure of a ski  
230 resort performing observations, the error is constant by construction as the melting rates  
231 are identical in the simulation and in the reference). The station HS dataset was made  
232 from stations which have a record longer than 20 years and whose average missing data  
233 fraction in the daily series is greater than 60% during the months December to April  
234 (DJFMA). From these gap-free station series, the mean annual snow depth was  
235 computed as the mean snow depth during the months DJFMA. The advantage of using  
236 this reconstructed station HS instead of the raw HS data is that it enables to compute a  
237 mean annual snow depth without having to deal with unevenly distributed data gaps. HS  
238 values at a station were compared to HS value in the corresponding massif and  
239 elevation band.

240 The simulated annual SCD was evaluated using a daily gap-filled snow cover

241 climatology from MODIS snow products MOD10A1.005 and MYD10A1.005 (Gascoin  
242 et al., 2015). The MODIS dataset covers the period 01 August 2000 to 31 July 2016.  
243 For a given hydrological year, the SCD was defined by pixel as the total number of days  
244 labeled as snow. The same metric was extracted from the SAFRAN-Crocus reanalysis  
245 by computing the number of days with a mean daily snow depth higher than 15 cm. We  
246 chose 15 cm because it is the optimal threshold identified by Gascoin et al. (2015) from  
247 the comparison of MODIS snow products with in situ measurements in the Pyrenees.  
248 For a given massif, SAFRAN-Crocus provides one value of the annual snow cover  
249 duration by elevation band (only the flat slope class was considered). However, MODIS  
250 provides one value per 500 m pixel, which means that there is an ensemble of SCD  
251 values to compare to this SAFRAN-Crocus SCD value. Hence, the SRTM DEM was  
252 used to aggregate all annual SCD values from MODIS pixels by massif and elevation  
253 band using the median.

254

255

### 256 3.3 Statistical analysis

257 From the daily series of snow depth we calculated the annual duration of the snow cover  
258 as the number of days from October to September of the following year, and the  
259 average snow depth was calculated for the period from December to April, considered  
260 typically as the period where a seasonal snowpack can be found in the Pyrenees over  
261 1500 m a.s.l. (López-Moreno et al., 2005). We selected for further analysis those series  
262 corresponding to elevations of 1500 and 2100 m a.s.l. The former was selected because  
263 it is considered an elevation where the seasonal snowpack is normally present in all the  
264 massifs, while at lower elevations the snowpack is ephemeral with multiple melting  
265 events during winter (López-Moreno, 2005). Furthermore, the lowest elevation of many  
266 ski areas is at approximately 1500 m, which makes it a relevant elevation band on a  
267 winter tourism perspective (Pons *et al.*, 2012). At 2100 m a.s.l. the snowpack is much  
268 thicker and longerlasting, representing a significant water resource for the Pyrenees.  
269 Although snow is usually more abundant at higher elevations, the area at elevations of  
270 2400 m a.s.l. or higher is relatively small within the Pyrenean range, or absent in the  
271 westernmost massifs. The average values for the 23 massifs, for each elevation band

272 considered, were considered as the regional series for the Pyrenees. A varimax rotated  
273 principal component analysis (PCA) (Abdi, 2003; Hannachi, 2004) was then performed  
274 for each variable (snow cover duration and average snow depth for DJFMA) and  
275 elevation (1500 and 2100 m a.s.l.) to facilitate grouping of massifs (those exhibiting the  
276 maximum correlation with each PC) having a similar interannual evolution of the snow  
277 series.

278 The nonparametric Mann-Kendall (MK) test was used to detect trends in the temporal  
279 series (Mann, 1945; Kendall, 1948), using a significance level of  $p < 0.05$ . The MK  
280 trend test is rank-based, so it can also be applied to series that do not follow a normal  
281 distribution or contain outliers (Cunderlik and Ouarda, 2009). The Kendall's tau statistic  
282 (range  $-1$  to  $1$ ) was used to quantify the strength of the trends. We checked that the  
283 series were free of lag-1 autocorrelation, and determined that prewhitening of the series  
284 was not necessary (Yue and Wang, 2002). To check the temporal coherence of the  
285 detected trends we calculated a matrix of all possible combinations of starting and  
286 ending years (minimum of 20 years length) in the series for each snow variable and the  
287 corresponding elevation, based on those massifs that showed the highest correlation  
288 with the groups that exhibited major trends, as identified by the PCA. This procedure  
289 enabled us to assess whether the identified trends were dependent on the specific study  
290 period considered in our study, or were robust and independent of the interannual  
291 variability of the series.

### 292 3.4 Weather type classification

293 The daily synoptic conditions over the Pyrenees during the study period were calculated  
294 using the objective classification method of Jenkinson and Collison (1977), which has  
295 been widely applied in climatological studies (see the review of Navarro-Serrano and  
296 López-Moreno 2017). The method uses a grid of 16 points of atmospheric sea level  
297 pressure centered in the central Pyrenees ( $42^{\circ}\text{N}$ ,  $1^{\circ}\text{E}$ ) and spaced at  $5^{\circ}$  intervals, derived  
298 from NCEP/NCAR reanalysis (Basnet and Parker, 1997). This enabled calculation of  
299 the direction and vorticity of the geostrophic flow, which facilitated classification of  
300 each day as cyclonic (C) or anticyclonic (A), and into directional (8) and hybrid (16)  
301 types. Hybrid types were removed using the approach used proposed by Trigo and  
302 DaCamara (2000). The number of occurrences of each weather type recorded each year

303 from December to April was summed, and the 10 remaining series (C, A, and 8  
304 directions) were reduced using a varimax rotated PCA, as done for the snow series.

305

## 306 **4. Results**

### 307 4.1 Evaluation of the simulated snow series

308 A good correlation (Spearman  $R = 0.87$ ) was found between the reconstructed mean  
309 annual observed snow depth (station HS) and the simulated HS (Fig. 3A); the difference  
310 was very small between the two datasets (8 cm). It is important to note that  
311 discrepancies between observations and simulations are not only explained by  
312 modelling errors but also by the unresolved horizontal intra-massif variability. The  
313 performance of the model in relation to snow cover duration obtained from MODIS  
314 images was also good ( $R = 0.96$  and a difference of 20.6 days; Fig. 3B).

315

316 -Figure 3-

317

### 318 4.2 Trend analysis

319 Figure 4 (A and B) shows the temporal evolution of the regional series for the 23  
320 massifs in the Pyrenees, calculated as the annual average snow cover duration at 1500  
321 and 2100 m a.s.l. and the average snow depth from December to April. The snow cover  
322 duration at 1500 m a.s.l. showed large interannual variability, because there were years  
323 when the snow did not last more than 1.5 months, while in other years the snow cover  
324 duration exceeded three months. Over the period 1958–2017 the series showed a  
325 negative trend, but this was not statistically significant ( $p > 0.05$ ). At 2100 m a.s.l. the  
326 snow cover duration was also highly variable, with a duration in most years ranging  
327 from 4 to 6 months, but the long-term negative trend was statistically significant ( $p <$   
328  $0.05$ ). Very similar results were found for the average (DJFMA) snow depth at 1500  
329 and 2100 m a.s.l. (Fig. 4 C and D). At both elevations the snow depth showed high  
330 interannual variability, in most years ranging from 10 to 40 cm at 1500 m a.s.l., and

331 from 60 to 120 cm at 2100 m a.s.l.. Both series showed negative long-term trends, but  
332 this was only statistically significant ( $p < 0.05$ ) for 2100 m a.s.l.

333

334 -Figure 4-

335

336 The results for the regional series shown in Figures 4 did not demonstrate differences in  
337 interannual evolution that occurred among the 23 massifs. To assess the variability in  
338 snow evolution in the Pyrenees, the PCA classified two main groups of massifs  
339 according their similar temporal evolution of snow cover duration at 1500 m a.s.l. (Fig.  
340 5A); these explained 79% of the variance. Principal component 1 (PC1) was highly  
341 correlated with the snow cover duration in the central and western Pyrenees (Fig. 5B).  
342 Negative trends clearly dominated in these massifs, especially those located in the  
343 westernmost part of the French Pyrenees. Principal component 2 (PC2) reflected the  
344 snow cover duration in the eastern massifs, where no trend or a positive trend was  
345 apparent. Among the 23 massifs, eight showed statistically significant ( $p < 0.05$ )  
346 negative trends, and two showed statistically significant positive trends.

347 For 2100 m a.s.l. the PCA analysis identified four groups that explained 85% of the  
348 observed variance in the interannual evolution of snow cover duration at this elevation  
349 (Fig. 5C). PC1 represented the western massifs of the French Pyrenees and the Navarra  
350 region on the Spanish side (Fig. 5D). Patterns similar to PC2 were found for the  
351 eastern massifs; PC3 in central Pyrenees and the PC4 represents some massifs in  
352 transition from west to central Pyrenees. Negative Kendall's tau values were found for  
353 most of the massifs; 13 of the 23 showed statistically significant negative trends ( $p <$   
354  $0.05$ ), and none exhibited a statistically significant positive trend.

355

356 -Figure 5-

357

358 The interannual evolution of average snow depth at 1500 m a.s.l. in the 23 massifs was  
359 reflected by three principal components that explained 86% of the observed variance  
360 (Fig. 6A). PC1 represented the western and central massifs of the Pyrenees, which had  
361 generally negative trends, especially in the westernmost French massifs (Fig. 6B); PC2  
362 and PC3 represented massifs located to the east. The majority had Kendall's tau values  
363 close to 0, but several positive coefficients were found for the easternmost part. Overall,  
364 five of the 23 massifs showed statistically significant negative trends ( $p < 0.05$ ), and  
365 two showed statistically significant positive trends ( $p < 0.05$ ). The average snow  
366 accumulation (DJFM) at 2100 m a.s.l. was also classified into three PCA groups that  
367 explained 89% of the observed variance (Fig. 6C). PC1 represented the western French  
368 massifs, which showed marked negative trends (Fig. 6D), PC2 represented the eastern  
369 massifs, and PC3 represented the western Spanish Pyrenees and the central French  
370 Pyrenees. Negative Kendall's tau values also dominated the massifs represented by PC2  
371 and PC3, and overall 14 of the 23 massifs showed statistically significant negative  
372 trends ( $p < 0.05$ ), and no massif showed a statistically significant positive trend.

373

374 - Figure 6-

375

376 The observed negative trends in snow cover duration and snow depth, found particularly  
377 for the western Pyrenees, showed marked temporal consistency and little dependence on  
378 the study period. The three plots in Figure 7 show that there was a clear dominance of  
379 pairs of starting and ending years showing a statistically significant decrease. Only the  
380 upper right portions of the matrices lack any statistically significant trend, or showed a  
381 change in the sign of the Kendall's tau values. Thus, trend analyses starting from 1957  
382 to 1980 and finishing in recent years showed statistically significant negative trends that  
383 were not affected by decadal fluctuations of the snowpack. However, for series starting  
384 after 1980 there were no statistically significant trends, and the Kendall's tau  
385 coefficients were positive, as can be seen from the temporal evolution of snow depth  
386 and duration, shown in the lower right corner of each plot.

387

388 -Figure 7-

389

#### 390 4.3. Atmospheric circulations patterns and their impacts on snow trends

391 The winter (DJFMA) frequency for the eight weather types classified for the Pyrenees  
392 was simplified to four groups of years (PCA; Table 1) that explained 84% of the  
393 observed variance. PC1 was highly correlated with years characterized by a low  
394 frequency of anticyclonic conditions, and a high frequency of advections from the  
395 southwest and west. PC2 was highly correlated with years having a high frequency of  
396 advections from the east and northeast, and a low frequency from the northwest. PC3  
397 was characterized by a low frequency of cyclonic conditions and a high frequency of  
398 advections from the north. PC4 was characterized by a high frequency of advections  
399 from the south and a low frequency from the northwest.

400 - Table1-

401

402 Only PC1 showed a statistically significant negative trend (Mann-Kendall tau =  $-0.53$ ;  
403  $p < 0.05$ ), which indicated an increase in the frequency of anticyclonic days and a  
404 decrease of advections from the northwest and west. The factorial scores for the other  
405 three PCs did not shown significant changes (Figure 8), with Mann-Kendall tau values  
406 very close to 0. Correlation analysis of PC1 with the groups discriminated according to  
407 the interannual evolution of snow indices only showed statistically significant  
408 correlations with Group 3 (average depth at 2100 m a.s.l.;  $r = 0.57$ ) and Group 1 (snow  
409 cover duration at 1500 m a.s.l.;  $r = 0.29$ ).

410

411 -Figure 8-

412

### 413 **5. Discussion**

414 This study showed that the Crocus snow cover model driven by the atmospheric  
415 SAFRAN model satisfactorily reproduced the snow evolution over the Pyrenees during  
416 the period 1980–2017, enabling the first assessment of long-term trends (1958-2017)  
417 for this entire mountain range in the absence of comprehensive observational data. This  
418 method has previously been used and evaluated in a study in the French Alps (Durand *et*  
419 *al.*, 2009), although it is known that local discrepancies between simulated and observed  
420 trends are possible (Lafaysse *et al*, 2011, Verfaillie *et al*, 2018). Indeed, simulated  
421 trends are affected by various sources of temporal heterogeneity along the simulation  
422 period. First, the surface meteorological observations assimilated by the SAFRAN  
423 reanalysis have changed over time and it is known that these heterogeneities can  
424 significantly affect local trends (Vidal *et al*, 2010). This effect is expected to be reduced  
425 when considering larger scale trends, as done in this paper when considering the whole  
426 Pyrenees mountain range. Then, the guess of the reanalysis is also heterogeneous over  
427 time. The two main heterogeneities are due to the onset of satellite observations in the  
428 1980s known to be responsible for temporal breaks in ERA-40 reanalysis (Sterl, 2004),  
429 and the switch from ERA-40 reanalysis to ARPEGE operational analyses for years after  
430 2001. Although these limitations can not be completely removed, it can be reduced in  
431 future works by updating the SAFRAN reanalysis by using more recent large scale  
432 reanalyses for the guess, such as ERA5.

433 Regional series for the Pyrenees revealed declining snow cover duration and average  
434 snow accumulation during the study period, but the trends were only statistically  
435 significant at 2100 m a.s.l., but not at 1500 m. This finding appears counterintuitive, as  
436 previous studies have reported greater sensitivity of the snowpack to climate warming  
437 in areas near the 0°C isotherm during the snow season compared with colder areas  
438 (Pierce and Cayan 2013; Marty *et al.* 2017). The most likely explanation for our results  
439 is the different rates of climate warming reported for the Pyrenees on a seasonal basis.  
440 The report recently published by the Pyrenean Observatory of Climate Change (OPCC,  
441 2019) and Serrano-Notivoli *et al.* (2019) notes that warming rates since 1955 have been  
442 lower during winter months (+0.1°C per decade;  $p > 0.05$ ) and greater in spring and fall  
443 (+0.3 and +0.2°C, respectively;  $p < 0.05$ ). A similar seasonal pattern was reported by  
444 Pérez-Zanón *et al.* (2017) for the period 1970–2013. No statistically significant change  
445 in precipitation occurred during the study period (OPCC, 2019), and its interannual

446 evolution has been found to be closely related to interannual variability in the frequency  
447 of weather types (Buisan *et al.*, 2016). In this climate context, snowpacks that lasts after  
448 March (the case for the snowpack at 2100 m a.s.l.) are expected to show stronger trends  
449 than snowpacks restricted to the colder winter months (the case for the snowpack at  
450 1500 m a.s.l.). This consideration has not yet been taken into account in interpreting the  
451 response of snowpacks to climate warming. The same explanation applies to the evident  
452 decrease in snow cover duration, affecting to the start and end of the snow cover, and  
453 accumulation in the westernmost massifs and massifs to the north of the range  
454 compared with the remainder of the Pyrenees. Apprndix T1 shows that the snow lasts  
455 longer on these massifs, and hence is exposed to the higher warming rates observed  
456 outside of the coldest months.

457 Some of the significant trends found in this study can also be related to an increase in  
458 the occurrence of anticyclonic conditions and a decrease in advections from the west  
459 and south west, as evidenced by the statistically significant decrease of PC1. PC1 was  
460 clearly linked to the positive evolution of the North Atlantic Oscillation index (NAOi),  
461 as previously shown for the Iberian Peninsula by López-Moreno and Vicente-Serrano  
462 (2007). In that study it was noted that the interannual evolution of the snowpack in the  
463 central Spanish Pyrenees is controlled by the NAO, especially at elevations above 2000  
464 m. Thus, the negative trend in snow accumulation at several observatories in the study  
465 area can be explained by such changes in atmospheric circulation. Alonso-González *et*  
466 *al.* (submitted) recently analyzed the effect of the NAO on the snowpack over the entire  
467 Iberian Peninsula, and showed that it only has an evident effect in this portion of the  
468 Pyrenees, and its effect is very limited or nonexistent in the northern massifs and at low  
469 elevations throughout the entire range. Thus, many of the negative trends reported in  
470 this study cannot be directly explained by changes in atmospheric circulation patterns,  
471 as the other patterns identified did not show any significant trend. In the absence of  
472 clear trends for precipitation, this finding strongly suggests that the main driver of the  
473 decline in the snowpack in the Pyrenees is long-term climate warming.

474 The major trends in the Pyrenees during the study period seemed to be consistent over  
475 time and not significantly affected by the selected start and end years when long-term  
476 time series were considered. However, for analysis periods starting after 1980, no  
477 significant trends in the snowpack were found. A very similar finding has been reported

478 for the Swiss and Austrian Alps, where only small changes since the end of the 1980s  
479 have been observed (Marty, 2008; Schöner *et al.*, 2019). This result illustrates the  
480 importance of using sufficiently long observation records when assessing trends of  
481 snow series (Fassnacht and Hulstrand, 2015).

482 For the Pyrenees, the temporal series of temperature evolution in the evolution provides  
483 an explanation (OPCC, 2019). The temperature increase since 1955 is mostly evident in  
484 the stark contrast between the cold decades of the 1960s and 1970s, and the much  
485 warmer following decades. However, the temperature trends after 1980 have been  
486 weaker or nonexistent (López-Moreno *et al.*, 2019). This explains why some studies  
487 using snow data for the Spanish Pyrenees since 1986 have found no trends in the  
488 snowpack (Buisan *et al.* 2015; Morán-Tejeda *et al.* 2017); for this specific part of the  
489 Pyrenees this finding is reinforced by the relatively high frequency of winters having  
490 negative NAOi values (Añel *et al.* 2014; Buisan *et al.* 2016), which is associated with  
491 frequent humid conditions in the massifs located southwards.

492

## 493 **6. Conclusions**

494 The main findings of this work can be summarized as follows:

495 1. SAFRAN-Crocus satisfactorily reproduced the main space and time variations in the  
496 snow cover in the Pyrenees from 1980 to 2017 based on in-situ and remote sensing  
497 observations, providing confidence in the trends in simulated values from 1958 to 2017  
498 although the temporal homogeneity of the data is not fully guaranteed.

499 2. In general, the snowpack decreased during the period 1958–2017, and the decline has  
500 been clearer at 2100 m a.s.l. This is consistent with the climate trends detected in the  
501 study, as warming during the study period was greater in fall and spring compared with  
502 winter (when the snowpack is limited at 1500 m).

503 3. There was marked spatial variability among massifs, and this differed for the two  
504 analyzed indices (snow cover duration and average snow depth DJFMA) and the two  
505 analyzed elevation bands (1500 and 2100 m a.s.l.). Overall, the western Pyrenees  
506 showed the most statistically significant decline in the snowpack.

507 4. Most of the significant trends detected showed high temporal consistency during the  
508 study period, and low dependence on the period selected, provided this was sufficiently  
509 long. The results suggest that only trends for snow accumulation at 2100 m a.s.l. in the  
510 central Pyrenees are linked to changes/variability in atmospheric circulation patterns  
511 (increase in the NAOi).

512 5. This study highlights the need for using long-term records and evenly distributed  
513 spatial data in the analysis of snow trends.

514

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521

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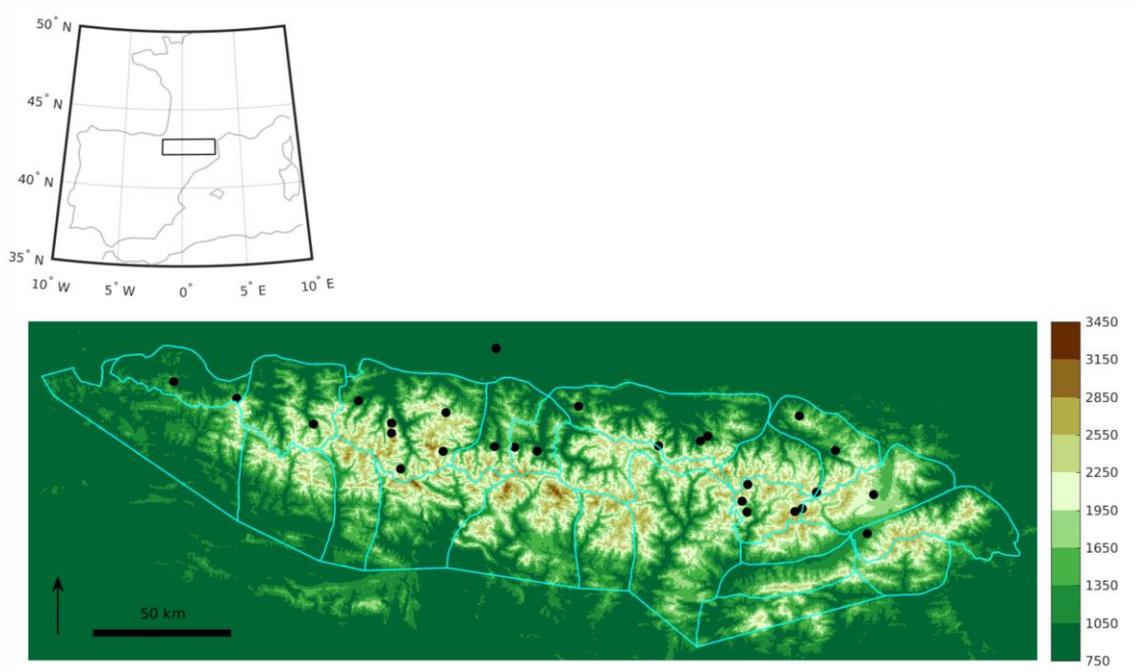
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762

763 **Appendix T1.** Average snow duration and snow depth (DJFMA) for each analyzed  
764 massif, their corresponding group and Tau-Kendall values for the period 1958-2017.  
765 Bold numbers indicate statistically significant trends.

Massif	Average values				Kendall-Tau and classified group							
	Dur. 1500	Dur. 2100	Depth 1500	Depth 2100	Dur. 1500	PC	Dur. 2100	PC	Depth 1500	PC	Depth 2100	PC
Pays Basque	106	150	0.31	1.70	<b>-0.42</b>	1	-0.10	1	<b>-0.38</b>	1	<b>-0.33</b>	1
Aspe-Ossau	134	150	0.37	1.71	<b>-0.27</b>	1	<b>-0.17</b>	1	<b>-0.22</b>	1	<b>-0.23</b>	1
Hte. Bigorre	122	148	0.18	0.93	-0.15	1	<b>-0.18</b>	1	-0.10	1	<b>-0.20</b>	1
Aure-Louron	112	148	0.19	0.93	<b>-0.21</b>	1	-0.15	1	<b>-0.19</b>	1	<b>-0.28</b>	1
Luchonnais	116	148	0.23	1.03	<b>-0.22</b>	1	<b>-0.17</b>	1	<b>-0.18</b>	1	<b>-0.26</b>	1
Couserans	126	148	0.25	1.11	<b>-0.19</b>	1	<b>-0.17</b>	3	-0.08	1	-0.11	3
Aran	99	146	0.17	0.84	-0.09	1	-0.16	3	0.07	2	<b>-0.17</b>	1
Hte. Ariege	122	146	0.20	0.91	-0.15	2	<b>-0.21</b>	2	-0.14	2	<b>-0.18</b>	3
Andorre	66	126	0.04	0.31	0.01	1	<b>-0.23</b>	3	0.06	1	<b>-0.25</b>	3
Orlu-StBarthe	118	146	0.19	0.94	-0.10	2	<b>-0.23</b>	2	-0.09	2	<b>-0.21</b>	2
Capcir-Puymorens	67	127	0.06	0.36	-0.02	2	<b>-0.18</b>	2	0.00	3	<b>-0.18</b>	2
Cerdagne	85	120	0.05	0.40	<b>-0.18</b>	2	-0.13	4	<b>0.17</b>	3	-0.01	2
Navarra	108	149	0.31	1.72	<b>-0.31</b>	1	<b>-0.21</b>	1	<b>-0.18</b>	1	<b>-0.19</b>	3
Jacetania	109	149	0.22	1.44	<b>-0.17</b>	1	-0.13	4	-0.11	1	<b>-0.20</b>	3
Gállego	120	148	0.24	1.40	-0.10	1	-0.08	4	0.00	1	-0.15	3
Sobrarbe	127	147	0.18	1.09	-0.06	1	-0.02	4	0.06	1	0.03	3
Ésera	96	147	0.17	0.94	-0.11	1	<b>-0.18</b>	3	-0.03	1	-0.14	3
Ribagorza	85	146	0.16	0.89	-0.11	2	-0.14	3	0.01	2	<b>-0.17</b>	2
Pallaresa	100	139	0.09	0.50	-0.13	2	-0.11	2	<b>0.17</b>	2	-0.02	2
Perafita	60	125	0.05	0.35	-0.01	2	<b>-0.31</b>	2	0.02	3	<b>-0.25</b>	2
Teruel-Frese	48	123	0.06	0.40	<b>0.18</b>	2	-0.06	2	<b>0.17</b>	2	0.09	2
Cadi-Moixero	52	126	0.05	0.39	<b>0.17</b>	2	<b>-0.22</b>	2	0.11	3	-0.11	2
Prepirene	75	130	0.07	0.48	0.08	2	<b>-0.21</b>	4	0.04	3	-0.10	3

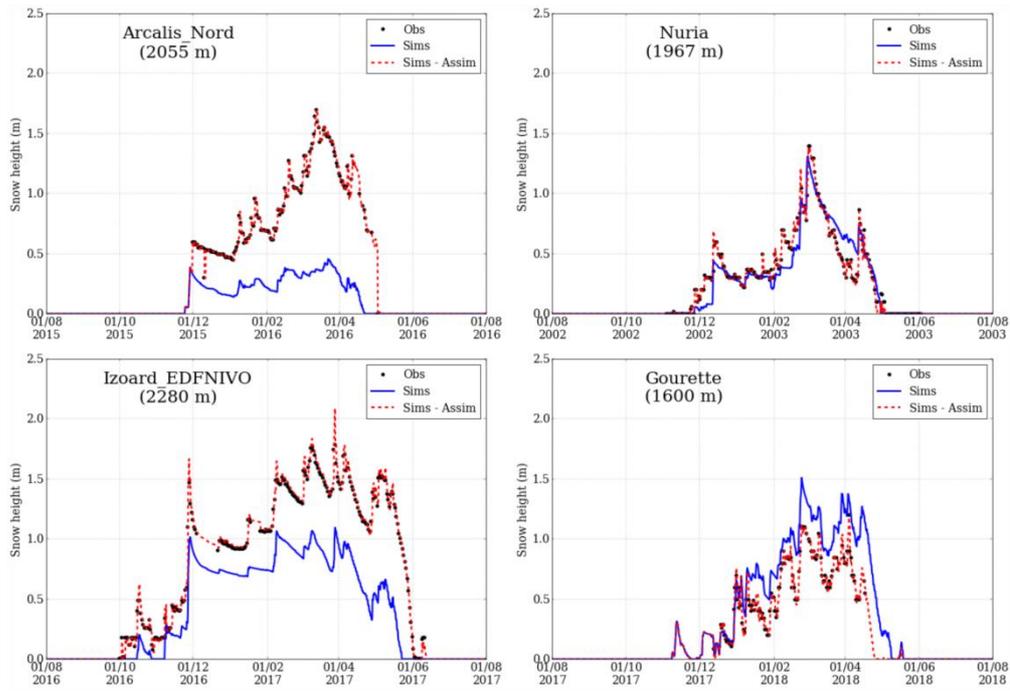
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767

768 **Figure 1.** The study area, and delimitation of the 23 massifs into which the Pyrenees  
769 was divided for the SAFRAN-Crocus simulation. Black dots indicate the location of the  
770 snow depth observation stations (full list given in the Appendix T1).

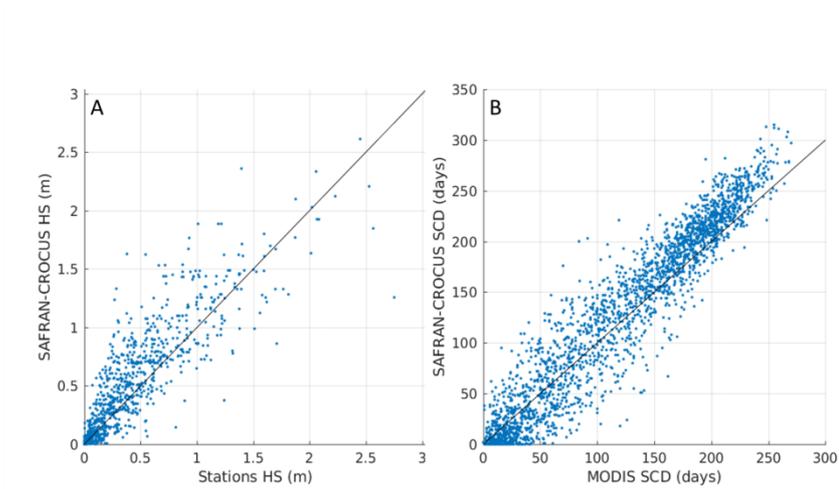
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773 **Figure 2.** Examples of observed and simulated snow series with SAFRAN Crocus  
 774 approach in four observatories before (Sims) and after applying the correction  
 775 procedure explained in this section (Sims- Assim).

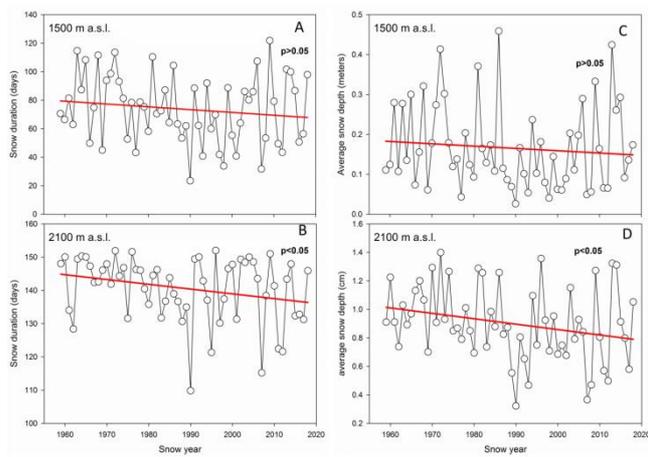
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778 **Figure 3.** A: Comparison of the mean annual snow depth, as simulated by SAFRAN-  
 779 Crocus and from the reconstructed station dataset. B: Comparison of the mean annual  
 780 snow cover duration, as simulated by SAFRAN-Crocus and from the MODIS dataset.  
 781 Each dot corresponds to a triplet (massif, elevation band, hydrological year).

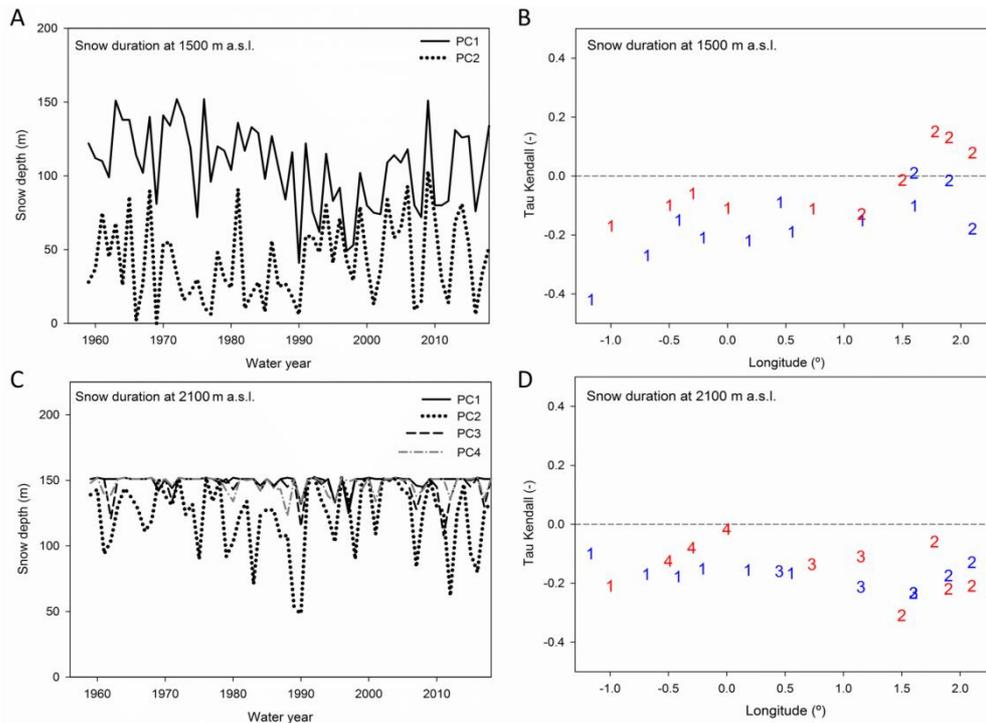
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784 **Figure 4.** Evolution of annual snow cover duration (A and B) and average snow depth  
 785 from December to April (C and D) at 1500 and 2100 m a.s.l. respectively.

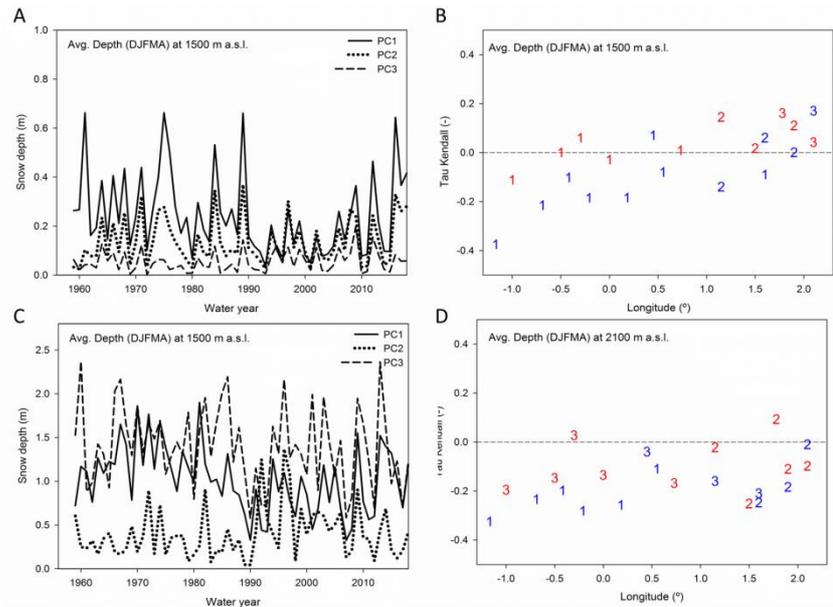
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788 **Figure 5.** Temporal evolution of the factorial scores for the groups of massifs identified  
 789 by PCA for the annual evolution of snow cover duration at 1500 m a.s.l. (A) and 2100  
 790 m a.s.l. (C). Kendall's tau coefficients for the massifs classified in the various groups  
 791 (numbers) from west to east at 1500 m a.s.l. (B) and 2100 m a.s.l. (D). Those massifs  
 792 located north of the main divide are shown in blue, and those to the south are shown in  
 793 red.

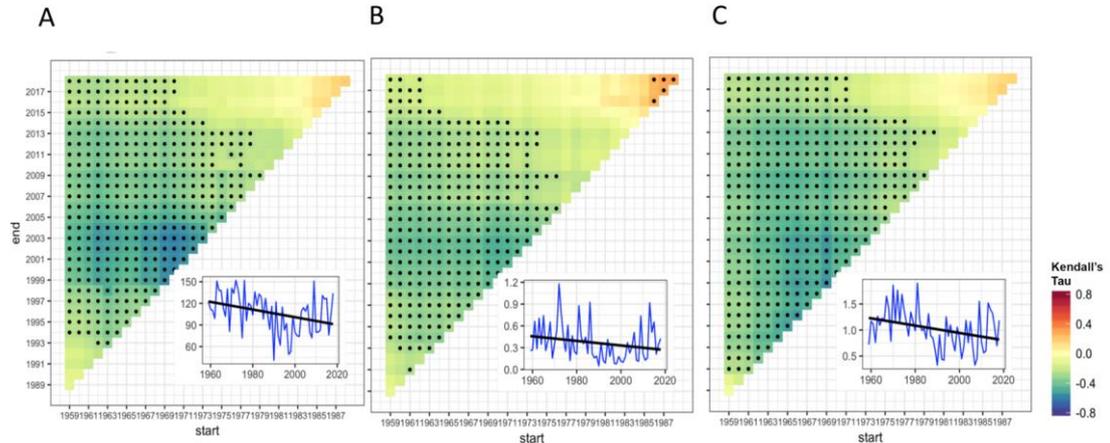
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796 **Figure 6.** Factorial scores for the groups of massifs identified by principal component  
 797 analysis for the evolution of snow depth (DJFM) at 1500 m a.s.l. (A) and 2100 m a.s.l.  
 798 (C). Kendall's tau coefficients for the massifs classified in the various groups (numbers)  
 799 from west to east at 1500 m a.s.l. (B) and 2100 m a.s.l. (D). Those massifs located north  
 800 of the main divide are shown in blue, and those to the south are shown in red.

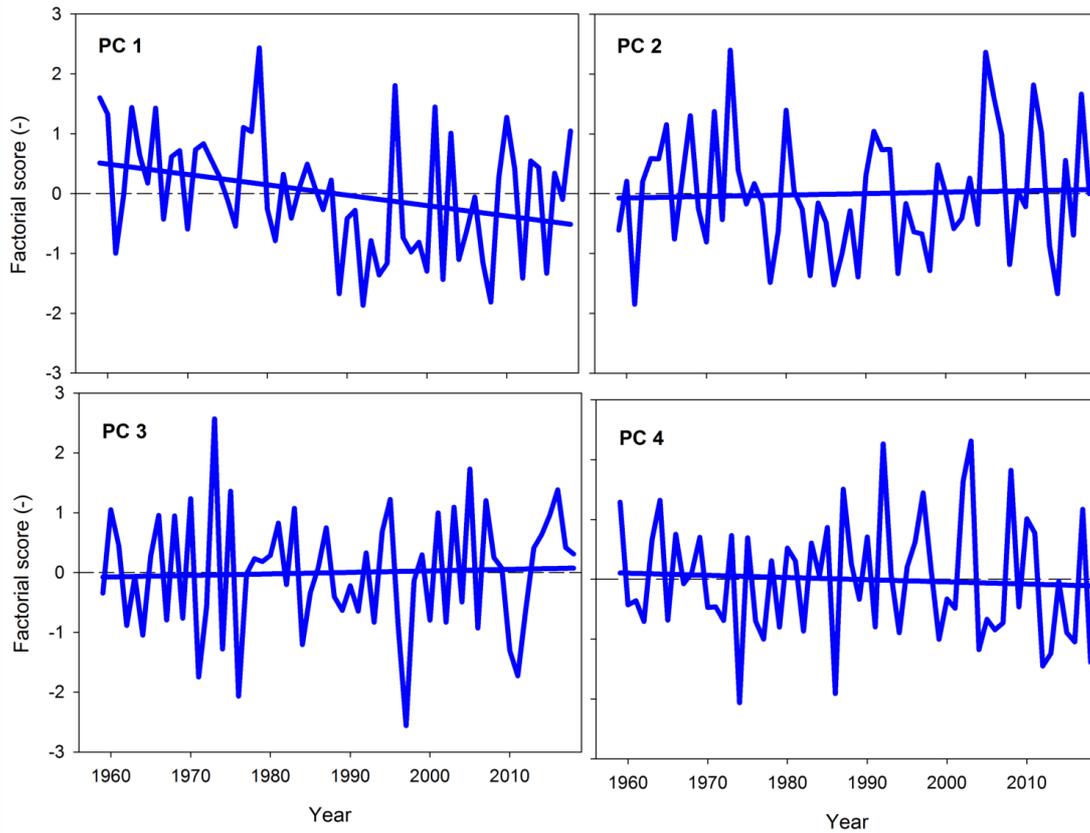
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803 **Figure 7.** Results of the Mann-Kendall test applied to the observatories that exhibited  
 804 the largest correlation with those principal components characterized by the strongest  
 805 negative trends. The matrix shows all possible combinations of start and ending dates  
 806 involving at least 20 years duration during the period 1958–2017. A) Aspe-Ossau  
 807 massif for PC1 for snow cover duration at 1500 m a.s.l. B) Navarra massif for PC1 for  
 808 average snow depth (DJFMA) at 1500 m a.s.l. C) Luchonnais massif for PC1 for  
 809 average snow depth (DJFMA) at 2100 m a.s.l. Colors indicate the magnitude of the  
 810 Kendall's tau, and points mark the series that showed statistically significant trends ( $p <$   
 811 0.05).

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813

814 **Figure 8.** Temporal evolution of the factorial scores for the four principal components  
 815 that summarized the frequency of weather types over the Pyrenees during the study  
 816 period.