Combined influence of maximum accumulation and melt rates on the duration of the seasonal snowpack over temperate mountains

Esteban Alonso-González[1], Jesús Revuelto[1] Steven R. Fassnacht[2,3,4], Juan Ignacio López-Moreno[1]

1- Instituto Pirenaico de Ecología, Spanish Research Council (IPE-CSIC), Zaragoza, Spain.
2- ESS-Watershed Science, Colorado State University, Fort Collins, CO 80523, USA.
3- Natural Resources Ecology Laboratory, Fort Collins, CO 80523, USA.
4- Cooperative Institute for Research in the Atmosphere, Fort Collins, CO 80523, USA.

Abstract

The duration of the seasonal snowpack determines numerous aspects of the water cycle, ecology and the economy in cold and mountainous regions, and is a balance between the magnitude of accumulated snow and the rate of melt. The contribution of each component has not been well quantified under contrasting topography and climatological conditions although this may provide useful insights into how snow cover duration could respond to climate change. Here, we examined the contribution of the annual peak snow water equivalent (SWE) and the seasonal melt rate to define the duration of the snowpack over temperate mountains, using snow data for mountain areas with different climatological characteristics across the Iberian Peninsula. We used a daily snowpack database for the period 1980–2014 over Iberia to derive the seasonal peak SWE, melt rate and season snow cover duration. The influence of peak SWE and melt rates on seasonal snow cover duration was estimated using a stepwise linear model approach.

The stepwise linear models showed high R-adjusted values (average R-adjusted = 0.7), without any clear dependence on the elevation or geographical location. In general, the peak SWE influenced the snow cover duration over all of the mountain areas analysed to a greater extent than the melt rates (89.1%, 89.2%, 81.6% 93.2% and 95.5% in the areas for the Cantabrian, Central, Iberian, Pyrenees and Sierra Nevada mountain ranges, respectively). At these colder sites, the melt season occurs mostly in the spring and tends to occur very fast. In contrast, the areas where the melt rates dominated snow cover duration were located systematically at lower elevations, due to the high interannual variability in the occurrence of annual peak SWE (in winter or early spring), yielding highly variable melt rates. However, in colder sites the melt season occurs mostly in spring and it is very fast in most of the years. The results highlight the control that the seasonal precipitation patterns, in combination with temperature, exert on the seasonal snow cover duration by influencing the peak SWE and suggest a future increased importance of melt rates as temperatures increase. Despite the high climatological variability of the Iberian mountain ranges, the results showed a

consistent behaviour along the different mountain ranges, indicating that the methods and results may be transferrable to other temperate mountain areas of the world.

Keywords: snowpack, mountains, peak SWE, snow cover duration, melt rate

Introduction

Snowpack quantity and snow cover duration determine the annual freshwater budget and its seasonalityfor mountain regions (Barnett et al., 2005). In addition, snow cover duration directly affects plant and animal phenology, especially the timing and annual magnitude of forest growth, as Sanmiguel-Vallelado et al., (2021) demonstrated in Iberia for the Pinus uncinata forests of the Pyrenees. Furthermore, snow dictates the duration and success of winter tourism, which is becoming one of the main sources of income for many mountain regions of the world (Gilaberte-Búrdalo et al., 2017; Steiger et al., 2019).

The snowpack over temperate mountain ranges exhibits unique characteristics compared with other mountain areas of the world. Despite the relatively mild winter temperatures, the snowpack tends to be deeper than at higher latitudes; it also exhibits rapid densification, thus being an effective freshwater storage system (Fayad et al., 2017). The snowpack has nearly isothermal conditions for most of the snow season, receiving abundant incoming solar radiation due to the latitude of the temperate mountain ranges (between ~30° and ~40° in the Northern and Southern Hemispheres), and high sublimation rates (Herrero and Polo, 2016). The snowpack exhibits a high interannual variability, due to spatial differences in precipitation and large elevation gradients (Alonso-González et al., 2020a, 2020b).

As a consequence of their lack of cold content and their sensitivity to precipitation-phase partitioning, the snowpacks over temperate mountain ranges are highly vulnerable to the ongoing climate warming (Alonso-González et al., 2020c; Evan and Eisenman, 2021; López-Moreno et al., 2017a; Yilmaz et al., 2019). A major risk of decline in snow cover duration over these temperate regions exists, which endangers the availability of freshwater resources during the long, dry months (García-Ruiz et al., 2011). All these changes are being observed across the Iberian Peninsula, where its mountainous terrain leads to a well-developed seasonal snowpack in various mountain ranges (Cantabrian, Central, Iberian, Pyrenees, and Sierra Nevada mountain ranges) (Alonso-González et al., 2020b). However, the snowpack exhibits high variability in terms of duration and amount, especially at the lower elevations. Such variability is explained by the high climatological diversity

of the Iberian mountain ranges and the seasonal synoptic conditions (Alonso-González et al., 2020a).

Snowpack magnitude, which is often quantified by the peak snow water equivalent (SWE) or accumulated SWE (Fassnacht and López-Moreno, 2020), strongly controls the amount of water available during the melting period. However, the duration of snow cover dictates many of the biochemical processes controlled by the snowpack, such as soil temperature (Bender et al., 2020; Zhang et al., 2018), microbial activity (Zhang et al., 2014), vegetation growth (Sanmiguel-Vallelado et al., 2019) and animal phenology (Robinson and Merrill, 2012). In addition, the snow cover duration determines the seasonality of different hydrological processes, such as soil moisture (Williams et al., 2009), hydrograph depletion (Julander and Clayton, 2018) and the occurrence of rain-on-snow events (Morán-Tejeda et al., 2016). Snow cover duration can be more accurately derived from remote sensing products (Gascoin et al., 2020) compared to SWE or snow depth that require direct observations or modelling approaches (Painter et al., 2016; Revuelto et al., 2016). Thus, it is important to study the relation between the snow cover and the amount of snow, as it provides an interesting basis for future studies. The duration of the snow cover over the ground at a given location and in a given year depends on the combination of the amount and timing of snowfall and the seasonal melt rate after the occurrence of peak SWE (Harpold et al., 2017). In other words, the duration of the snow cover depends on the maximum amount of snow to be melted and the rate of said melt. The quantification of the contribution of the two factors, namely peak SWE and melt rate, is relevant in understanding the spatiotemporal variability of snow cover duration and, more importantly, to consider how climate change could impact snow cover duration at any given location. Previous research has revealed that the effect of temperature or precipitation on snow cover durations changes over space, with a marked elevational pattern; temperature is the main control at low elevations, whereas the main control in terms of accumulation shifts to precipitation at high elevations (Morán-Tejeda et al., 2013; Sospedra-Alfonso and Merryfield, 2017), illustrating the correlation between faster melt rates and lower snow accumulations. However, if snow cover duration mostly depends on accumulated snow, the response of snow cover duration to a climate warming will be strongly influenced by the seasonal timing of the precipitation, the seasonal differences in projected precipitation changes and the timing of peak SWE. Notably, the projected changes in precipitation are highly uncertain in most mountainous areas (Nogués-Bravo et al., 2008). If peak SWE generally occurs at the end of the coldest period of the year, the effect of warmer temperatures might be dampened. Conversely, for locations where peak SWE occurs later in the season because of snowfall during the spring (Caesar et al., 2006),

97 snow cover duration might be strongly affected by higher temperatures since the occurrence of
98 rainfall will be much higher than snowfall (López-Moreno et al., 2020a). In addition, if melt rates
99 dominate snow cover duration, the latter will be controlled more by temperature changes; in this
100 case, melt rates might be less intense as the climate warms due to an earlier occurrence of melting
101 and, thus, less solar loading (Alonso-González et al., 2020c; Musselman et al., 2017; Wu et al.,
102 2018).

103 In the present study, we use a long-term (1980–2014) gridded snow database for the mountains of
104 the Iberian Peninsula (Alonso-González et al., 2018). The Iberian Peninsula exhibits large
105 climatological variability, with its mountain ranges being a good representation of the temperate
106 mountains of the world. To investigate whether seasonal snow cover duration interannual variability
107 is controlled more by the amount of snow accumulation (peak SWE) or by the intensity of the melt
108 rate, we tried to find differences among different-analysed mountain ranges since they exhibit
109 contrasting climatic and snow conditions (Alonso-González et al., 2020b). Such differences may
110 provide useful information to foresee how projected climate change might affect, and with what
111 uncertainty, snow cover duration at different areas of temperate mountain ranges, thereby helping to
112 anticipate the related effects on different environmental and socioeconomic sectors.

113 **Study Area**

114 The Iberian Peninsula is located at the southwestern edge of Europe. Its climatology is strongly
115 influenced by its complex topography and proximity to both the Mediterranean Sea and the Atlantic
116 Ocean, covering a full transition from Mediterranean to Oceanic climates and therefore being one of
117 the areas of Europe with high climatological variability (Peel et al., 2007). Although some locations
118 in Iberia can receive large amounts of annual precipitation, precipitation exhibits high interannual
119 variability and Iberia is generally considered a water-scarce region. Moreover, large areas of the
120 peninsula are highly dependent on water resources from mountain areas and much of this water
121 comes from the snowpack. Total precipitation varies from less than 300 mm yr^{-1} to more than 1500
122 mm yr^{-1} and may exceed 2500 mm yr^{-1} locally in specific locations (Palacios and De Marcos,
123 1998). In the Mediterranean climate, where most precipitation occurs during the winter months
124 (López-Moreno et al., 2011, 2017a), the snowpack becomes critical because it breaks the strong
125 seasonality of the available freshwater resources, resulting in a better synchronization of the water
126 availability with the high demand during the dry and warm season (López-Moreno and García-Ruiz,
127 2004). Atmospheric circulation controls the interannual variability of the precipitation (Trigo et al.,
128 2004). Droughts are frequent and affect the streamflow of the main Iberian basins (Lorenzo-Lacruz

et al., 2013). This large precipitation and streamflow variability makes Iberia highly dependent on the water management, and Spain is one of the countries with the most hydrological regulation (Berga-Casafont, 2003).

Snow is common over Iberia, including some snowfall events at lower elevations (Aran et al., 2010; Mora et al., 2016). Snowfalls are common every year over wide areas of Iberia due to the presence of a central plateau with an average elevation of 650 m above sea level. In addition, there are five main mountain systems that exceed 2000 m a.s.l. ranging from west to east across Iberia; two of them (Pyrenees and Sierra Nevada) surpass 3000 m a.s.l. (Fig. 1). Mountain ranges exhibit seasonal, long-lasting and deep snowpacks whose characteristics differ due to the climatological particularities of each region (Alonso-González et al., 2020b). Specifically, in Iberia, snow has important implications in different key features of the region, including its hydrology (López-Moreno and García-Ruiz, 2004; Sanmiguel-Vallelado et al., 2017), ecology (Sanmiguel-Vallelado et al., 2021), economy (Lasanta et al., 2007) and risk management (Muntán et al., 2009).

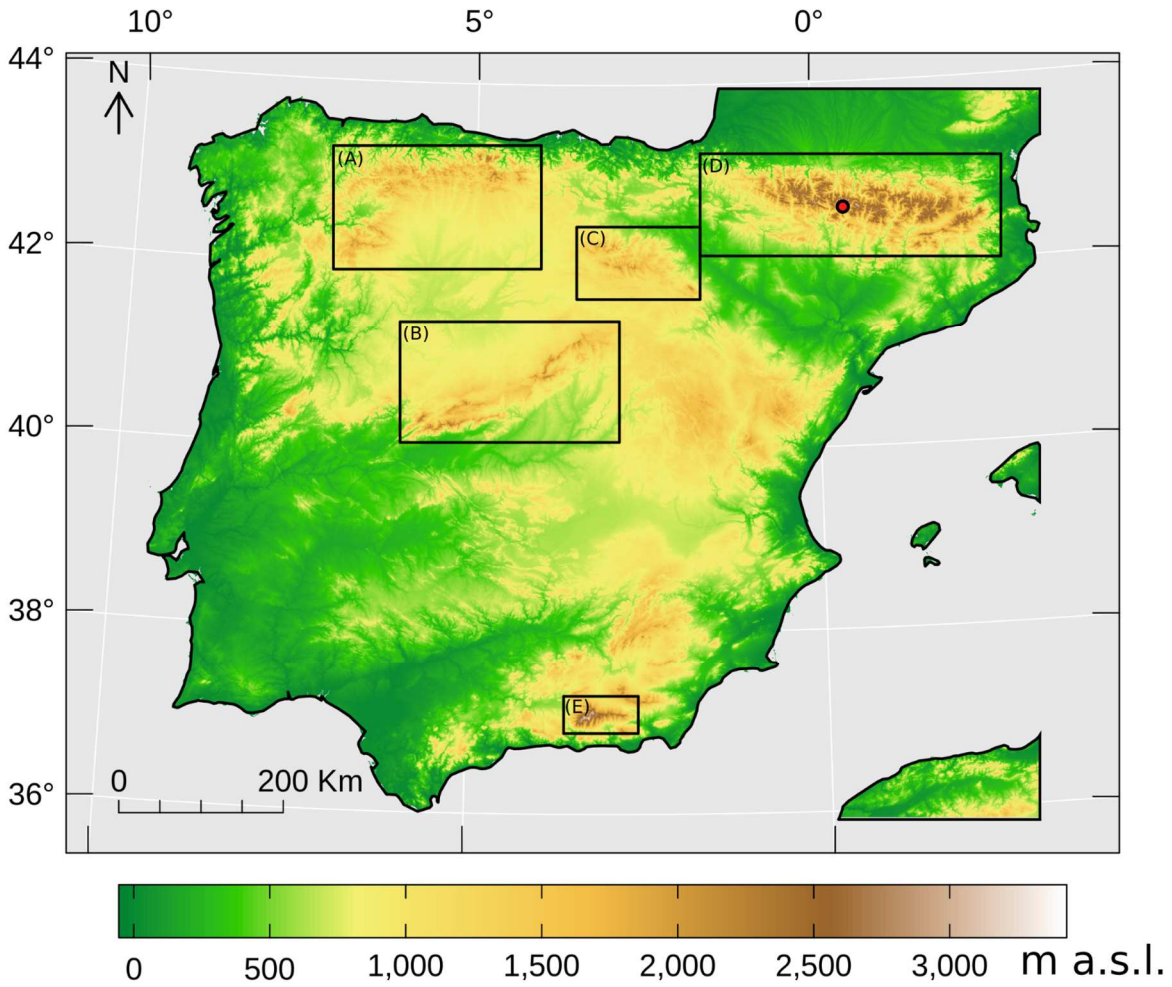

Figure 1: Main mountain ranges of the Iberian Peninsula; A) Cantabrian, B) Central, C) Iberian, D) Pyrenees and E) Sierra Nevada. The red circle indicates the location of the SWE simulated time series shown as an example in this paper.

Data and Methods

We used a daily gridded snowpack database covering the entire Iberian Peninsula for the period from 1980 to 2014 (Alonso-González et al., 2018). The database was developed using a regional atmospheric simulation (García-Valdecasas Ojeda et al., 2017) from the Weather Research and Forecast (WRF) model version 3.8 (Skamarock et al., 2008), at a 10 km spatial resolution as the meteorological forcing for the Factorial Snow Model (FSM 1.0, Essery, 2015). Given the coarse spatial resolution (10 km) WRF outputs were corrected from the elevation of the native grid of the simulation to different elevation bands at 100 m intervals for each simulated grid cell using a combination of radiative, barometric and psychrometric formulae, as well as lapse-rates. Thus, the simulated 2 m temperature of the WRF was corrected using the standard air temperature lapse rate (β = 0.0065 K m^{-1}) and the surface pressure was adjusted using the barometric formula. The long-

wave radiation was estimated according to the Stefan–Boltzmann law, using an all-sky conditions parametrization of the emissivity based on the relative humidity (RH) at the elevation of 700 mb to estimate the cloud cover. The RH was projected by correcting the dew-point temperature for the elevation. Both the RH and long-wave-radiation parametrizations have been widely used in the literature and have also been implemented in meteorological distribution models (Liston and Elder, 2006). Finally, the precipitation phase partitioning was calculated on the basis of the estimated temperature of the surface of the hydrometeors using the equations proposed by Harder and Pomeroy (2013). A detailed description of the mathematical formulae as well as a graphical scheme can be found in Alonso-González et al. (2018). To disaggregate the semi-distributed fashion (i.e., elevation bands distribution) of the snowpack database, we interpolated the snowpack series over a DEM of 1km resolution. The distributed snow series over each objective cell of the 1 km DEM was generated by the weighted average of eight neighbour cells in the nearest two elevation bands (directly higher and lower). The distance between each objective cell and four cells in the nearest two elevation bands inside the three-dimensional space of the semi-distributed database was used to generate the new series from the weighted average of the semi-distributed series.

Alonso-González et al. (2018) compared the database with both remote sensing imagery and in situ observations of snow height (HS) and SWE and illustrated the database's spatial and temporal consistency. A comparison with MODIS gap-filled snow cover products showed a mean absolute error of 6.07%, and a coefficient of determination (R^2) of 0.76. In addition, the available SWE and HS series for the Iberian Peninsula were used to validate the intra-annual patterns of accumulation at different percentiles, with Cohen´s kappa value (k) greater than 0.6. The database has been used for different studies over Iberia, including climatology (Alonso-González et al., 2020b, 2020a), hydrology (Morán-Tejeda et al., 2019) and ecology (Sanmiguel-Vallelado et al., 2019). An example of a time series of SWE for a single cell (red circle in Figure 1) across different elevation bands retrieved from the database is shown in Figure 2.

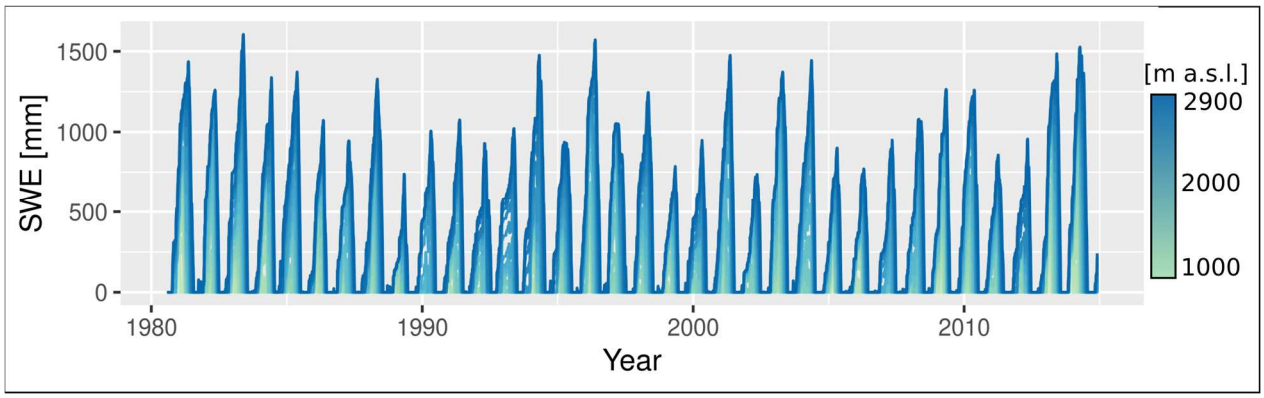

Figure 2: SWE time series retrieved for the Pyrenees from the snowpack database at different elevation bands (represented by the colour palette) covering the whole study period daily.

To remove ephemeral snowpacks for any year, we only considered snow as seasonal when more than 30 mm of SWE remained for more than 30 consecutive days. These thresholds were selected on the basis of Sturm et al. (1995) but were adapted to the study area on the basis of the snow climatology created by Alonso-González et al. (2020b). This processing was performed for each season for each cell; cells having less five snow season respecting the above mentioned criteria (SWE > 30 mm for more than 30 consecutive days) where removed from the analysis. For each year and for each cell in we calculated the peak SWE [mm], the snow cover duration [days] and the seasonal melt rate [mm day^{-1}]. The seasonal melt rate was computed in millimetres per day as the peak SWE divided by the time from the date of peak SWE to the date of the end of the snow season, or snow disappearance. The duration was defined as the number of days with continuous snow cover; thus, no early or late season accumulation and complete melt events were considered. In addition, in the rare case of a complete mid-season melt, the latest snow season was used.

To determine the relative influence of the peak SWE and the melt rate (independent variables) to explain the duration of snow cover (dependent variable) (Figure 3), we used a backward stepwise linear regression model in the form

$$D = \beta_0 + \beta_P * P + \beta_M * M \qquad (1),$$

where β_0 is the y-intercept; β_P is the coefficient associated with peak SWE, P; and β_M is the coefficient associated with the seasonal melt rate, M. Since the regression was stepwise, the best-fitting independent variable (i.e. either the peak SWE or the melt rate) was chosen first. Iteratively, each variable was considered for removal/addition on the basis of the variations of the Akaike information criterion (AIC). The coefficients were then standardized by multiplying the regression-based coefficient by the ratio of the standard deviation of the dependent variable (D) by the standard deviation of the independent variable (P or M), providing a simple quantification of the weight of

each independent variable on the duration of snow cover. We then evaluated how β_P and β_M were distributed along the elevations in the main mountain ranges of Iberia. We then extracted the elevation values of the DEM using the β_P and β_M values, to evaluate the β-coefficients variation with the elevation. Thus, we studied the elevations where one of the β-coefficients was greater than the other, or only one variable was selected by the stepwise approach . All the calculations were performed using the R programming language (R Core Team, 2020) at the supercomputing facilities of the Spanish Research Council. We use one location in the Pyrenees as an example (the same location indicated in Figure 2) to illustrate the specific results and then provide the results of the distributed analyses over the Iberian mountains.

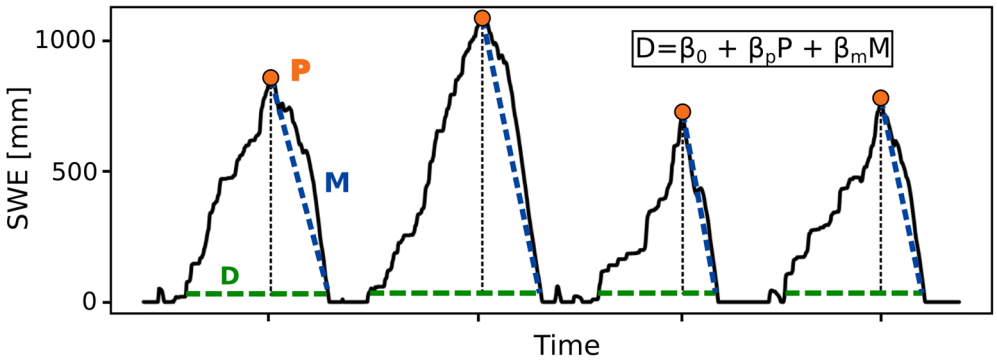

Figure 3: Conceptual explanation of the stepwise linear correlation used for all the cells of the snowpack database. The snowpack duration (D) is modelled from the peak SWE (P) and the seasonal melt rate (M) for each cell of the snowpack database.

Results and Discussion

The main temporal patterns and the relationship with elevation of the three snow indexes (fig. 4) can be exemplificated by a single cell of the Pyrenees (red dot in Figure 1). Peak SWE exhibits noticeable temporal variability at all elevations but with a decrease with increasing elevation (coefficient of variation (CV) of 0.48, 0.30 and 0.23 at 2000, 2400 and 2900 m a.s.l., respectively). This result is mainly attributed to the snowpacks in temperate regions being consistently close to the zero degree isotherm since they are highly sensitive to the precipitation partition phase (Fayad and Gascoin, 2020). Thus, the elevation ensures colder temperatures and more constant peak SWE

values, which are mostly regulated by the precipitation, which is why several studies have found the higher areas (or colder locations) of mountain ranges to be less affected by climate warming worldwide (Alonso-González et al., 2020c; Marty et al., 2017; Matiu et al., 2021; Pierce and Cayan, 2013; Sproles et al., 2013). As in the case of peak SWE, an obvious relation exists between the duration of the snow cover and the elevation, with longer durations at higher elevations (Figure 4); the interannual variability of the snow cover duration also decreases with increasing elevation (CV of 0.33, 0.11 and 0.09 at 2000, 2400 and 2900 m a.s.l., respectively, in this particular example). The melt rates showed a more complex spatial and temporal behaviour. The lower CV for the snow cover duration compared with that for the peak SWE might explain the inversions in the relation of the melt rates with the elevation in some particular years. The seasons with thicker (shallower) snowpacks do not increase (decrease) linearly with the snow cover duration since the melt rates show different values as the snow season progresses. On average, the melt rates tend to increase with increasing elevation (average of 14.1, 19.5 and 19.0 mm day^{-1} at 2000, 2400 and 2900 m a.s.l., respectively, in this particular example); however, this relation is not as clear as that observed for the peak SWE and the snow cover duration. This pattern occurs because an effective melt not only requires temperature warmer than 0°C but also a considerable increase in incoming solar radiation and decreased albedo at the end of the winter (Musselman et al., 2017).

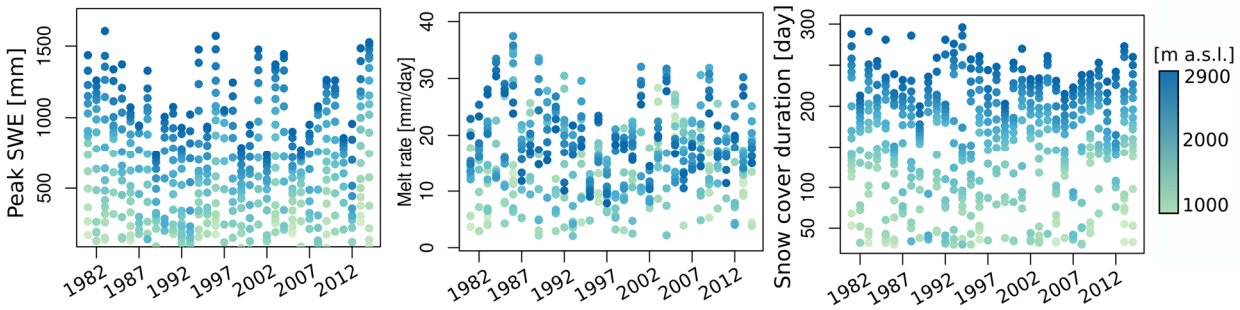

Figure 4: Peak SWE (left), melt rate (middle) and snow season duration (right) at different elevations (represented by the colour palette), as derived from the single-cell snow series in Figure 2.

At the sample location in the Pyrenees (Figures 1 and 4), the β-coefficients of the peak SWE and melt rate as well as the adjusted R^2 of the stepwise regression model are correlated with the elevation (Figure 5), most likely due to local particularities of this specific location. The peak SWE exhibited a higher β-coefficient than the melt rates at all elevation bands. At the 1400–1800 and 2400–2900 m elevation bands, the melt rate was not even included in the model by the stepwise

algorithm as a predictor variable. Thus, the model suggests that, for this single cell example (Figure 4), the peak SWE exerts greater control of the snow cover duration than the melt rates. Here, the maximum explained variance of the model is found at low and medium elevations and the overall evolution of adjusted-R^2 follows the evolution of the β-coefficients of peak SWE, with a negligible effect when the melt rate is also included in the model as a predictor variable.

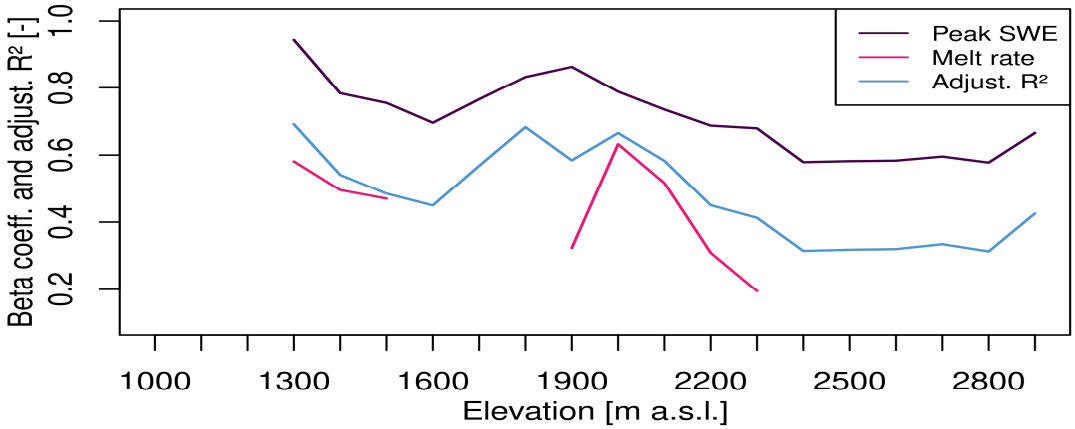

Figure 5: Adjusted R2 and β-coefficients of the model's results for a single cell (the one used as an example in Figs. 2 and 4) at different elevations.

We extended the previously methodology described for a single cell (Figure 5) to the all study area. A large spatial variability is observed in the peak SWE, melt rate and the snow cover duration over Iberia (Figure 6), with strong differences also observed within the same mountain ranges, even at similar elevations, as reported in previous studies(Alonso-González et al., 2020b). Among the five main mountain ranges of Iberia, the Pyrenees and Cantabrian mountains receive the most snow, with a maximum SWE approaching 2000 mm and a snow cover duration as long as 290 days in the most favourable locations (Figure 6). By contrast, the Sierra Nevada exhibited lower values when similar elevation bands were compared. A complete description of the snow climatology and the differences between mountain ranges can be found in the work of Alonso-González et al. (2020b).

As expected, the snow season duration and peak SWE are mostly controlled by elevation. In addition, melt rates tend to be faster at the higher elevations (Figure 6), consistent with other studies that found faster melt rates occurring later in the snow season under conditions of greater incoming radiation (Musselman et al., 2017; Wu et al.,2018). Peak SWE is more variable at lower than at higher elevation, leading to very different melt-rates having a significant influence on the snow

cover duration. The interannual CV estimated for the snow cover duration and peak SWE follows a similar spatial pattern, with a clear decrease with increasing elevation (Figure 6). This effect might be a consequence of the low values of each index (low elevations) that can lead to extremely large CV values; however, the preprocessing of the snow series where each snow season must meet the minimum accumulation and duration criteria prevents the standard deviation from being divided by small mean values. Differences in CV values were observed between the three snow indexes. The CV values for the mean season duration were lower than for the peak SWE, whose CV values were, in turn, lower than those for the melt rates.

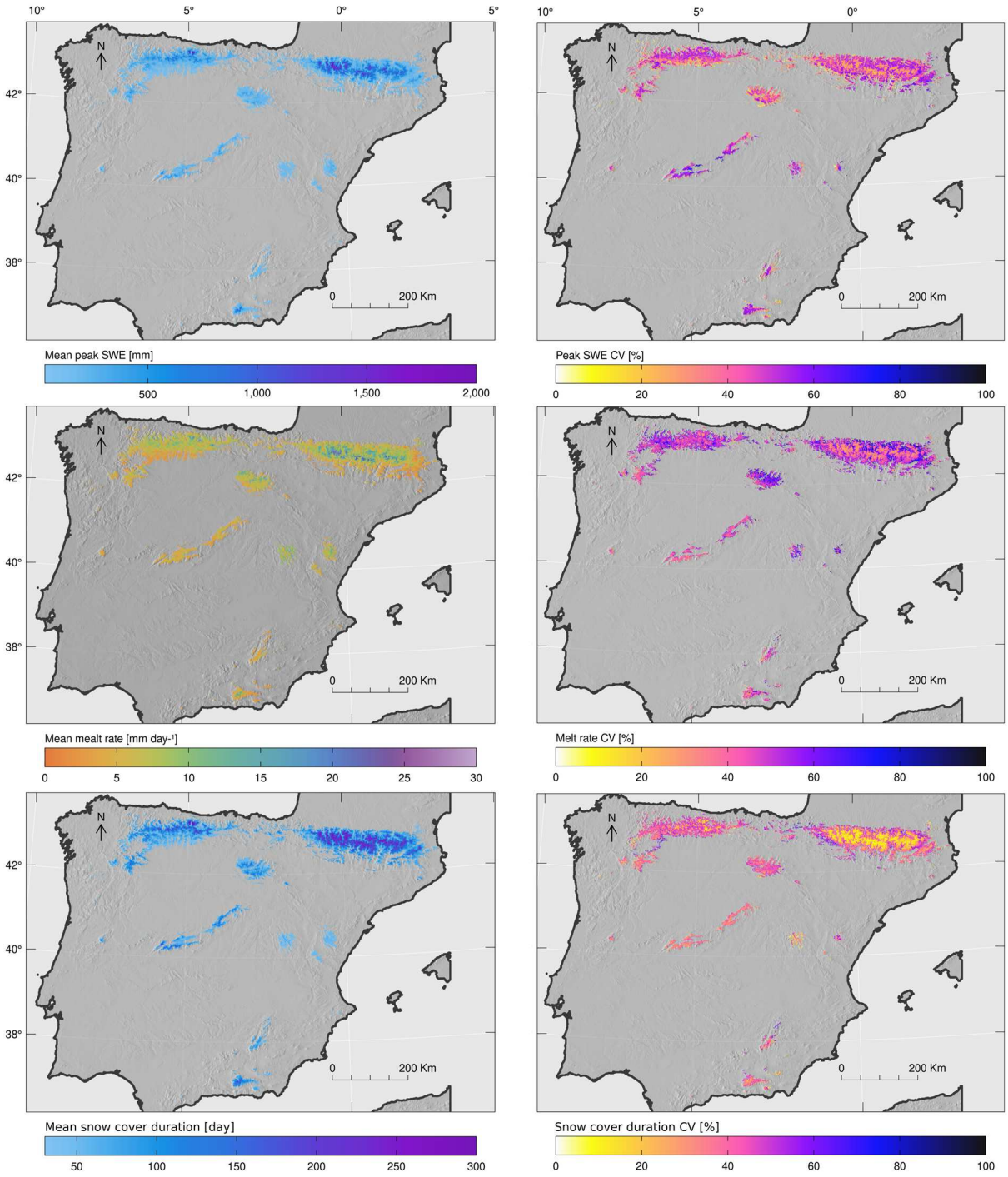

Figure 6: Mean peak SWE and its CV(upper panels), melt rate and its CV (middle panels), and snow season duration and its CV (bottom panels) in the Iberian peninsula.

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278 The stepwise models used to predict the snow cover duration from the peak SWE and the melt rate
279 showed an average coefficient of determination (R^2-adjust) of 0.5. The adjusted R^2 values of the
280 models showed no clear dependence on the elevation or differences between mountain ranges,
281 although the highest determination coefficients were found in the band between 1500 and 2000 m
282 a.s.l. and the variability of the adjusted R^2 values tended to decrease with increasing elevation

283 (Supplementary Figure 1). This greater variability at the lower elevations was likely caused by the
284 fact that there were more cases at the lower elevations, in addition to a higher variability in the
285 snow indexes.

286 Focusing on the Pyrenees, modelling results showed that snow cover duration is more sensitive to
287 peal SWE than to melt rates (Figure 7). The peak SWE was excluded by the stepwise approach
288 (Figure 7 left panel) in only 2.4% of the cells. Moreover, considering the subset of cells where
289 either peak swe and melt rate (P&M) or only melt rate (M) were selected by the stepwise model,
290 melt rate β-coefficients were higher than peak swe one in only 6.8% of the cases" (Figure 7 right
291 panel). By contrast, the cases where the model considered only the peak SWE represented 35.6% of
292 cells (Figure 7a), increasing to 93.2% of cells when both indexes were included and the peak SWE
293 exhibited higher β-coefficients (Figure 7 right panel).In addition, the cells where the melt rates
294 exhibited a higher influence were concentrated at the lower elevations, with an average elevation of
295 1180 m a.s.l., in contrast with the 1740 m a.s.l. elevation in the cells where the peak SWE exhibited
296 a higher β-coefficient (Figure 7 right panel). Surprisingly, despite the strongly contrasting
297 climatological characteristics of the five Iberian mountain ranges (Alonso-González et al., 2020b),
298 this spatial pattern of the β-coefficient of the peak SWE (β-P) and melt rate (β-M) is similar over the
299 other Iberian mountain ranges (Table 1 and Supplementary Figure 2). Slight differences are
300 observed in the average elevation values as a consequence of the different hypsography of each
301 range (Table 1). This finding is consistent with the results of similar studies developed in the
302 western United States (Trujillo and Molotch, 2014), where deeper snowpacks lead to longer snow
303 seasons and higher melt rates. Thus, the relative areas where the β-M is higher than the β-P decrease
304 regularly from the lower (Iberian, Central and Cantabrian ranges with 81.6%, 89.2% and 89.1%,
305 respectively) to the higher (Pyrenees and Sierra Nevada with 93.2% and 95.5%, respectively)
306 elevation mountain ranges. Independently from the elevation, the accumulation (i.e. peak SWE)
307 dominates the snow cover duration. However, at the lower areas the melt rates increase its
308 importance in controlling the snow cover duration. This result is particularly relevant, as the Iberian
309 snowpacks have shown contrasting behaviours due to the climatological variability of the Iberian
310 Peninsula (Alonso-González et al., 2020b). Thus, this finding suggests that the results of the present
311 study could be extrapolated to other regions of the planet at comparable latitudes where the peak
312 SWE is reached with a low cold content because the pattern remains similar over the different
313 mountain ranges. However, snowpacks over high-latitude sites may present different behaviours
314 because of different partitioning of the energy and mass balance of the snowpacks, including a

315 completely different seasonal distribution of the incoming solar radiation combined with (in
316 general) a shallower snowpack.

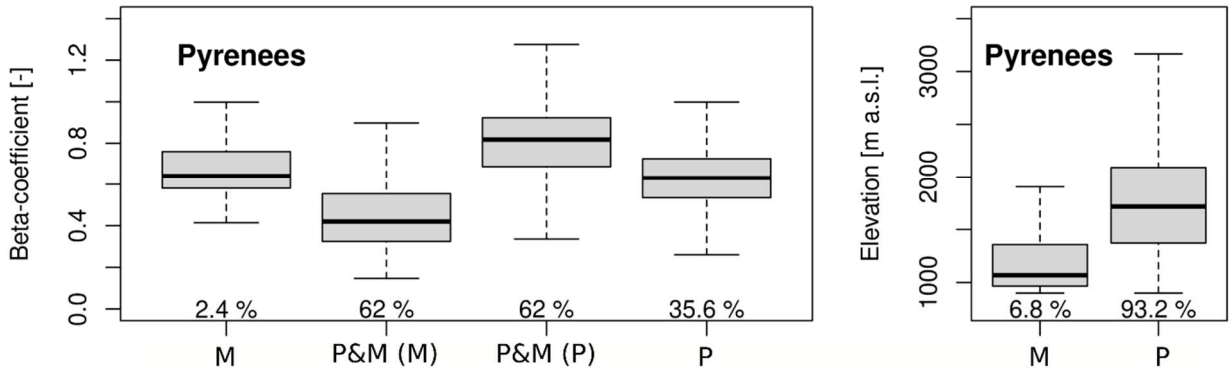

Figure 7: β-Coefficients for the peak SWE and the melt rate (left panel) for different model configurations, and the altitudinal distribution of the β-coefficients in the Pyrenees (right panel). M indicates model configurations when only melt rate is selected (2.4% of cells), P indicates model configurations when only peak SWE is selected (35.6%) and P&M indicates model configurations when both predictors are included (62%). The distribution of the β-coefficients with the elevations indicates the elevations where one of the predictors showed a higher β-coefficient; (left boxplot) altitudinal distribution of the cells where melt rate β-Coefficients > peak swe β-Coefficients, including M and P&M models; (right boxplot) altitudinal distribution of the cells where peak swe β-Coefficients > melt rate β-Coefficients including P and P&M models The percentages showed in both panels are the relative are of the range where it is possible to find its correspondent model.

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Table 1: Averaged β-coefficients for the peak SWE and the melt rate and the average elevation of the cells where higher peak SWE or melt rate β-coefficient were found.

Ranges	Melt rate		Melt rate and Peak SWE			Peak SWE		Elevation Melt rate		Elevation Peak SWE	
	β_m (β_p is 0)	%	β_m	β_p	%	β_p	%	m	%	m	%
Cantabrian	0.70	2.4	0.65	1.00	62.0	0.73	35.5	1230	10.9	1470	89.1
Central	0.72	5.5	0.54	0.91	41.9	0.70	52.6	1520	10.8	1727	89.2
Iberian	0.67	4.6	0.60	0.90	84.4	0.75	11.0	1312	18.4	1517	81.6

Pyrenees	0.67	2.4	0.47	0.82	62.0	0.63	35.6	1180	6.8	1740	93.2
S. Nevada	0.71	1.2	0.45	0.91	50.8	0.74	48.0	1892	4.2	2187	95.8

The greater dependency of the snow season duration on the peak SWE than on the melt rate (Table 1) indicates that the precipitation is a mayor driver of the snow season duration. As despite the whole energy balance has its own influence, the peak SWE is mostly controlled by precipitation, especially at the higher elevations (Morán-Tejeda et al., 2013; Musselman et al., 2021). At high elevation, snow melts late in spring and the depletion curve rather steep as consequence of the rise of shortwave radiation; at lower elevations, melting occurs earlier and is a function of the date of peak SWE. Thus, the melt rates in the areas where the peak SWE occurs earlier tends to be more variable than in the areas where the peak SWE occurs latter (i.e. the higher and colder areas).

Despite most atmospheric models showing a high consensus to project a generalized warming, the climate change projections show large disagreements and uncertainties about how the precipitation could evolve in the next decades (Kharin et al., 2013). In addition, the sensitivity to warming of the snow accumulation may be different, even in areas with comparable climatological characteristics due to local effects (López-Moreno et al., 2017a). The seasonal precipitation patterns will play a key role, as the peak SWE is affected by the winter and spring precipitation and the surface temperatures of the Iberian Peninsula are expected to increase similarly for the winter and spring seasons (Carvalho et al., 2020). Lorenzo and Alvarez (2020) have reported differences in the future seasonal precipitation patterns of Iberia estimated from high-resolution atmospheric simulations extracted from the EURO-CORDEX project. Their results highlight the uncertainty of the projections to simulate the future evolution of the precipitation and the spatial variability of the accumulated precipitation changes. Nevertheless, they show a general increase in the total winter precipitation of approximately 15%, with a decrease as large as 20% in the spring total precipitation. These results suggest that the areas where the peak SWE is controlled by the total winter precipitation (warmer areas) will exhibit a different evolution than those controlled by the spring precipitation (colder areas). However, even under scenarios of substantial precipitation increases, the sensitivity of the peak SWE has proven to be negative in Iberia under warmer conditions (Alonso-González et al., 2020c), including in the higher elevations or colder areas. These results are consistent with a sensitivity analysis performed for most of the mountain climates of the world (López-Moreno et al., 2020a), where consistent projected climate warming led to a decrease in both the peak SWE and the snow cover duration in most of the mountains of the planet. Thus, a generalized decrease in the length of the snow seasons is expected on the basis of the decline of the

peak SWE as a consequence of warming, providing continuity with the reported ongoing trend estimated from long-term reanalysis simulations in the Pyrenees (López-Moreno et al., 2020b).

The results presented here suggest that the areas where the melt rates play a key role in controlling the snow seasonal duration are located at the lower elevations. These results are consistent for the different mountain ranges despite their climatological differences. The average elevations where the melt rates' dependency dominates the peak SWE dependency were similar in all the investigated mountain ranges, with larger differences in the Pyrenees. This effect is caused by the hypsometry of each mountain ranges. In most of the areas, the duration of the snow cover is controlled by the peak SWE, making the average elevation between both cases similar, as there are many more areas at low elevations than at high elevations. The slight differences between mountain ranges in the percentage of area where the melt rates exert greater control of the snow season duration can be easily explained by the differences in the hypsography of the mountain ranges (i.e. a higher percentage of the total area is at a low elevation). This difference in hypsography likely explains why the Pyrenees and Sierra Nevada exhibit a higher percentage of their area where the snow cover seasonal duration is controlled by the peak SWE (93.2% and 95.5%, respectively), as they have the higher elevational ranges among the Iberian mountain ranges. Our results may indicate that the control exerted by the melt rates over the snow cover seasonal duration could increase in the future because of the rise of the winter zero-degree isotherm. This finding is relevant, as previous studies have reported a generalized negative sensitivity of the melt rates to warming (Alonso-González et al., 2020c; Musselman et al., 2017). However, despite the lower melt rates, a generalized decrease in the snow cover duration as a consequence of the lower peak SWE values is expected. The lower melt rates will not compensate for lower peak SWE values, as they are the result of a different level of decrease in the peak SWE and the snow season length. The available projections for precipitation and temperature show different seasonal patterns in their expected future evolution and different increases in the role of the melt rate at the lower elevations. The snow cover duration at high elevations (greater than 2000–2200 m a.s.l.) could be more strongly influenced by climate change than those at medium and low elevations a result already observed in the Pyrenees over the last decades (López-Moreno et al., 2020b).

Despite the relatively high R^2 adjusted values found in the models (Supplementary Figure 1), there is an important part of the variance that it is unexplained by the models. It is obvious that other factors different form the melt rates and the peak SWE could condition the duration of the snow cover. For example, some winters may influence the shape of the daily snowpack time series, introducing some uncertainties in the models; specifically the accumulation and melt are often not

linear (Figure 3). It is possible to find some seasons where exceptionally dry periods followed by an intense precipitation period lead to a secondary but relevant peak SWE during the spring. These situations may delay the melt out day, increasing the impact on the length of the snow season duration. In addition, it may be possible to find seasons where the exact day of occurrence of the peak SWE could be difficult to identify because numerous days have the same SWE peak. This could have some influence in the estimation of the melt rates in those seasons. However, these situations are rare, due to the regional nature of the timeseries of the snowpack database. Thus, despite the uncertainties, the results of the present study are easy to generalize, being transferrable to other temperate climate mountain ranges of the world.The results presented here cannot be extrapolated to small spatial scales where the local climatology characteristics explain an important part of the spatial variability of the snowpack (López-Moreno et al., 2017b; Revuelto et al., 2020; Fassnacht, 2021). Such an effect is relevant even under warmer conditions, where slope and aspect could lead to more spatially variable snowpacks (López-Moreno et al., 2013) because of the control of the topography over the radiative surface fluxes, accumulation patterns and wind redistribution. In addition, the correlation between melt-rates and peak SWE might be different at the wind redistribution scales due to the local interactions with vegetation and landscape (Pomeroy et al., 2004).

Conclusions

We analysed the roles of the peak SWE and melt rates to explain the temporal and spatial variability of snow cover duration. We used a daily gridded snowpack database derived from numerical simulations; this database has proven to be consistent with both in situ measurements and remote sensing snow cover products. The long-term average and the interannual variability exhibited by the peak SWE, melt rate and snow cover duration highlight the varied conditions of the snowpack existing across the Iberian Peninsula, giving the results of the present study a wider geographical entity, as this snowpack is representative of many other snowpacks over temperate mountain ranges.

Using the combination of peak SWE and melt rates to explain the snow cover duration resulted in, on average, an adjusted R^2 of 0.5. We did not find a clear relation between different levels of explained variance with the geographical location, mountain range or elevation range. We found that, in most of the areas of the main mountain ranges of Iberia (~90% of the total area), the peak SWE exerts greater control than the melt rates to explain the interannual variability of the snow cover duration. The areas where the melt rates exerted greater control of the snow season duration were located at lower elevations.

Given the key role of the total precipitation in controlling the interannual variability of the peak SWE, the results presented here indicate notable uncertainty in the projections for the future evolution of the snow cover duration. The snow cover duration in colder areas—mostly at higher elevations, where the spring precipitations control much of the seasonal peak SWE—might be particularly uncertain compared with that in warmer areas, where the peak SWE is controlled by the wintertime accumulated precipitation. Nonetheless, the confidence of climate projections toward a warmer climate will lead to a clear generalized decrease of snow cover duration in all mountains of Iberia and most of the mountains of the world. Snow cover duration could be particularly reduced at mid and high elevations. The role of melt rates in controlling the snow seasonal duration may gain importance in the next few decades as a consequence of the rise of the winter zero-degree isotherm.

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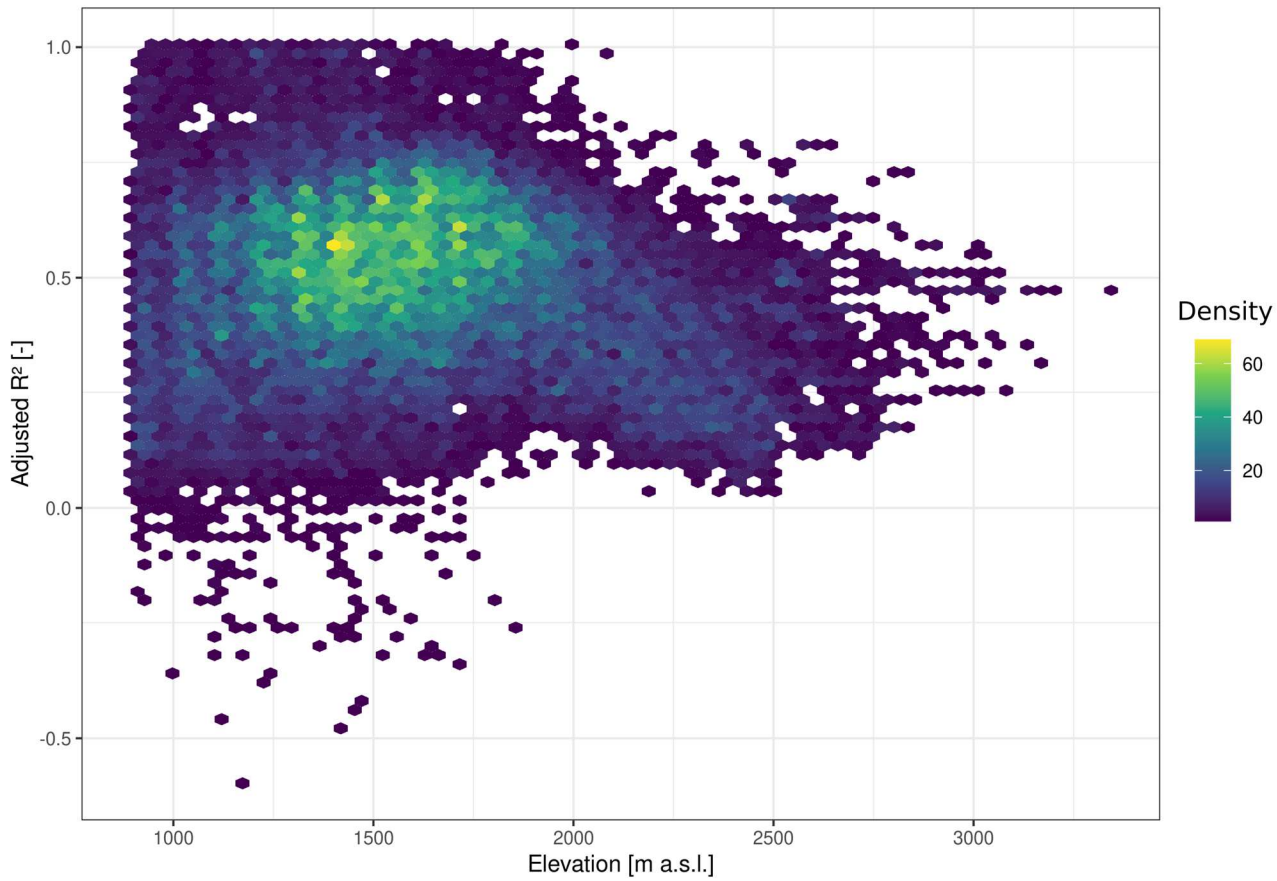
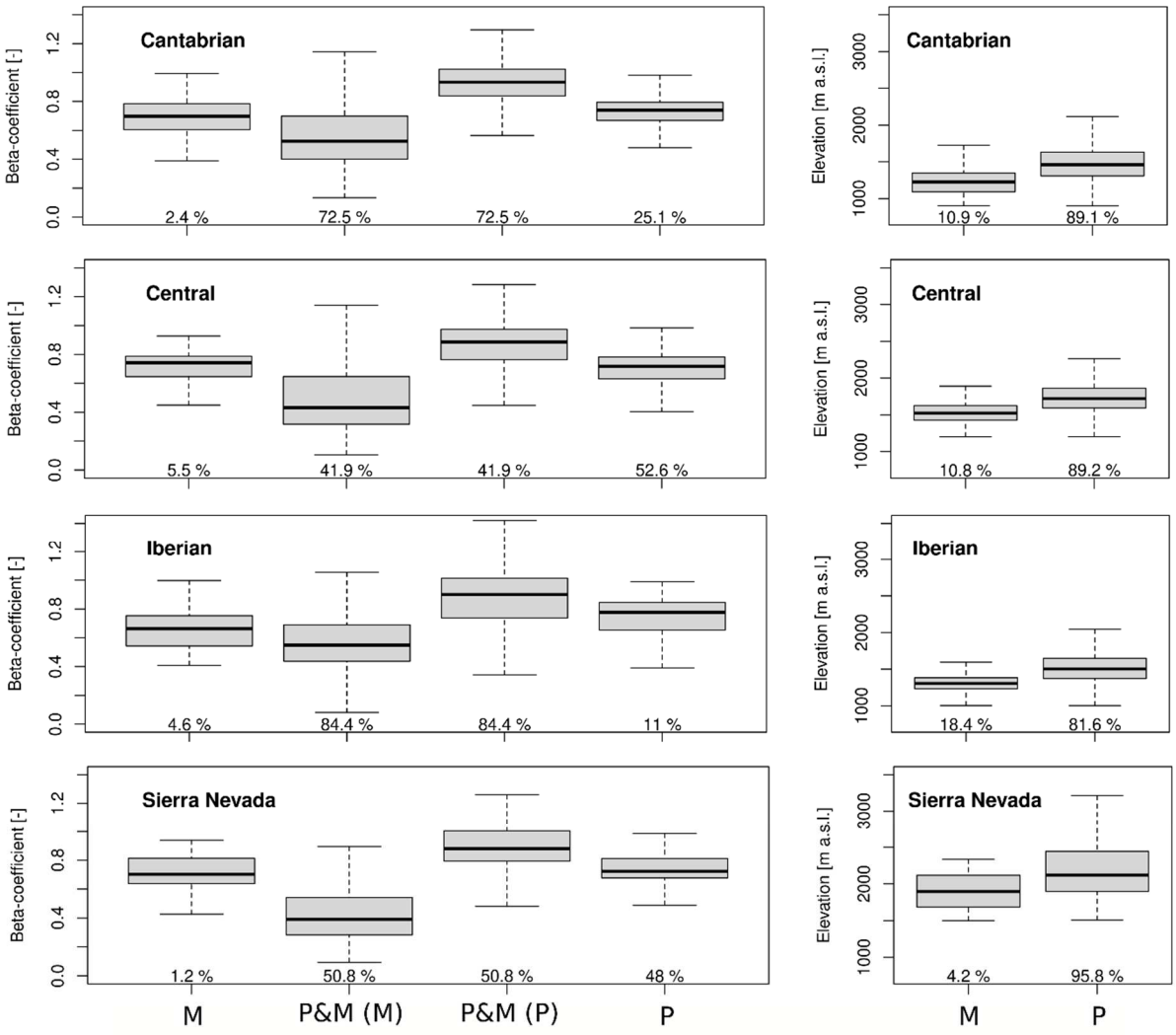


Supplementary Figure 1: Distribution of the adjusted R^2 values along the elevation range of the Iberian Peninsula.


Cantabrian
Central
Iberian
Sierra Nevada
Beta-coefficient [-]
Elevation [m a.s.l.]
0.0
0.4
0.8
1.2
1000
2000
3000
2.4 %
72.5 %
72.5 %
25.1 %
10.9 %
89.1 %
5.5 %
41.9 %
41.9 %
52.6 %
10.8 %
89.2 %
4.6 %
84.4 %
84.4 %
11 %
18.4 %
81.6 %
1.2 %
50.8 %
50.8 %
48 %
4.2 %
95.8 %
M
P&M (M)
P&M (P)
P

652

Supplementary Figure 2: β-Coefficients for the peak SWE and the melt rate and distribution of the β-coefficients by elevation in the Pyrenees. The figure shows the β-coefficients when one of the predictors is removed from the model (βx (βy = 0)) and when both are included with the percentage of the surface under these conditions. The distribution of the β-coefficients with the elevations indicates the elevations where one of the predictors showed a higher β-coefficient, including the situations when one of the predictors was removed from the analysis.

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