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Snow sensitivity to climate change during compound cold-hot and wet-dry seasons in the Pyrenees

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Abstract. The Mediterranean basin has experienced one of the highest warming rates on Earth over the last decades and climate projections anticipate water-scarcity future scenarios. Mid-latitude Mediterranean mountain areas such as the Pyrenees play a key role in the hydrological resources for intensely populated lowland areas. However, there are still large uncertainties about the impact of climate change on the snowpack in high mountain ranges of the Mediterranean region. Here, we provide a climate sensitivity analysis of the Pyrenean snowpack through five key snow climate indicators. Snow sensitivity is analyzed during compound temperature and precipitation extreme seasons, namely Cold-Dry (CD), Cold-Wet (CW), Warm-Dry (WD) and Warm-Wet (WW) seasons, for low (1500 m), mid (1800 m) and high (2400 m) elevation sectors of the Pyrenees. To this end, a physically-based energy and mass balance snow model (FSM2) is validated by ground-truth data, and subsequently applied to the entire range, forcing perturbed reanalysis climate data for the 1980 – 2019 baseline scenario. The results have shown that FSM2 successfully reproduces the observed snow depth (HS) values, reaching R^2 > 0.8, and relative RMSE and MAE lower than 10 % of the observed HS. Overall, climate sensitivity decreases with elevation and increases towards the eastern Pyrenees. When temperature is progressively warmed at 1ºC intervals, the largest seasonal HS decreases from baseline climate are found at +1ºC, reaching values of -47 %, -48 % and -25 % for low, mid and high elevations, respectively. Only an upward trend of precipitation (+10 %) could counterbalance temperature increases (<= 1ºC) at high elevations during the coldest months of the season, since temperature is far from the isothermal 0ºC conditions. The maximum (minimum) seasonal HS and peak HS max reductions are observed on WW (CD) seasons. During the latter seasons, the seasonal HS is expected to be reduced by -37 % (- 28 %), -34 % (-30 %), -27 % (-22 %) per ºC, at low, mid and high elevation areas, respectively. For snow ablation climate indicators, the largest decreases are observed during WD seasons, when the peak HS date is anticipated 10 days and snow duration (ablation) decreases (increases) 12 % per

ºC. The results suggest similar climate sensitivities in mid-latitude mountain areas; where significant snowpack reductions are anticipated, with relevant consequences in the ecological and socioeconomic systems.

Keywords: Snow, Climate change, Sensitivity, Alpine, Mediterranean Mountains, Mid-latitude, Pyrenees.

1 Introduction

Snow is a key element of the Earth climate system (Armstrong and Brun, 1998), since it cools the planet (Serreze and Barry, 2011) through altering the Surface Energy Balance (SEB), modifying the albedo, surface and air temperature (e.g., Hall, 2004). Since the 1980s, Northern-Hemispheric snowpack patterns are rapidly changing (e.g., Hock et al., 2019; Hammond et al., 2018; Nortarnicola et al., 2020). A better understanding and prediction of shifts in the snowpack quantity, patterns, as well as in snow accumulation and ablation timings due to changing climate conditions is crucial, since snow has relevant feedbacks in the social and environmental systems. From the hydrological point of view, snow melting controls high mountain runoff rates during spring (Barnett et al., 2005; Adams et al., 2009; Stahl et al., 2010), river flow magnitude and timings (Sanmiguel-Vallelado et al., 2017; Morán-Tejeda et al., 2014), water infiltration and groundwater storage (Gribovszki et al., 2010; Evans et al., 2018) or transpiration rates (e.g., Cooper et al., 2020). The presence and duration of the snowpack strongly conditions terrestrial ecosystem dynamics since the snowmelt offset dates controls photosynthesis (Woelber et al., 2018), forest productivity (Barnard et al., 2018), affects the freezing and thawing of the soil (Luetschg et al., 2008; Oliva et al., 2014) and active layer thickness in permafrost environments (Hrbáček et al., 2016; Magnin et al., 2017). Further, snow has remarkable economic impacts; in the highlands, as well as the surrounding areas, snow determines the economic success of many mountain ski-resorts (e.g., Scott et al., 2003; Gilaberte-Búrdalo et al., 2017; Pons et al., 2015). The impact of snow changes in the lowlands can be amplified, given that snow meltwater provides significant hydrological resources for water reservoirs, hydropower generation, agricultural, industrial and human uses (e.g., Beniston et al., 2018; Sturm et al., 2017).

Mid-latitude low elevation areas exhibit the largest snow sensitivities to climate warming; whereas in high latitudes and high elevation sectors, positive precipitation trends could counterbalance temperature increases to some extent (Brown and Mote, 2009). Climate

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warming decreases the maximum and seasonal snow depth (HS) and Snow Water Equivalent (SWE) (Trujillo and Molotch, 2014; Alonso-González et al., 2020a; López-Moreno et al., 2013; 2017), decreases the fraction of snowfall of the total precipitation (snowfall ratio; e.g., Mote et al., 2005; Lynn et al., 2020; Jeenings and Molotoch, 2020; Marshall et al., 2019) and triggers later snow onsets dates (Beniston, 2009; Klein et al., 2016). During the snow ablation phase, warming slows the snow ablation rate per season (Pomeroy et al., 2015; Rasouli et al., 2015; Jennings and Molotch, 2020; Bonsoms et al., 2022; Sanmiguel-Vallelado et al., 2022) due to early HS and SWE peak dates (Alonso-González et al., 2022), coinciding with low solar radiation periods (e.g., Pomeroy et al., 2015; Musselman et al., 2017a).

The Mediterranean basin is one of the primary climate Hot-Spots of the Earth (Giorgi, 2006), being densely populated (> 500 million of habitants) and affected by an intense anthropogenic activity. Warming across the Mediterranean basin is projected to accelerate for the mid-end 21st century, and temperature is expected to continue higher than the global average during the warm half of the year (e.g., Lionello and Scarascia 2018; Cramer et al., 2018; Knutti and Sedlacek, 2013; Evin et al., 2021; Cos et al., 2022), increasing atmospheric evaporative demands (Vicente-Serrano et al., 2020), drought severity (Tramblay et al., 2020) and implying a water-scarcity scenario over most of the basin (García-Ruiz et al., 2011). Mediterranean mid-latitude mountains, such as the Pyrenees, where this research focuses, are the main runoff-generation zones of the downstream areas (Viviroli and Weingartner, 2004), providing the majority of the water resources for major cities located in the lowlands (Morán-Tejeda et al., 2014).

Snow patterns in the Pyrenees are highly diverse (Alonso-González et al., 2019), due to internal climate variability of mid-latitude precipitation (e.g., Hawkins and Sutton 2010; Deser et al., 2012), the high interannual and decadal variability of precipitation in the Iberian Peninsula (Esteban-Parra et al., 1998; Peña-Angulo et al., 2020) as well as the abrupt topography and the different mountain exposition to the main circulation weather types (Bonsoms et al., 2021a). Thus, snow accumulation per season in the northern slopes almost doubles the recorded in the southern slopes (Navarro-Serrano and López-Moreno, 2017), there is a high interannual variability of snow in the lower stretches of the range (Alonso-González et al., 2020a), as well as in the southern eastern sector of the Pyrenees (Salvador-Franch et al., 2014; Salvador-Franch et al., 2016; Bonsoms et al., 2021b). Since the 1980s, snow ablation has statistically significantly increased (Bonsoms et al., 2022), but during the same temporal period, winter snow days and snow accumulation non-statically significantly increased (Buisan et al., 2016; Serrano-Notivoli et al., 2018; López-Moreno et al., 2020a; Bonsoms et al., 2021a) due to

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positive west and south-west advections frequency trends (Buisan et al., 2016). For the mid-end 21st century, climate change scenarios over the Pyrenees anticipate a temperature increase of > 1 to 4 ºC, and positive (negative) precipitation trends (~ 10 %, respect the 1980 – 2010 period) for the eastern (western) sectors of the range during winter and spring (Amblar-Frances et al., 2020). Therefore, snow evolution in the high elevations of the range is subject to major unknows, since winter snow accumulation is ruled by precipitation (e.g., López-Moreno et al., 2008), and Mediterranean basin winter precipitation projections are subject to large uncertainties, due to a large contribution of internal variability of the latter (up to 80 % of the total variance; Evin et al., 2021).

Mid-latitude snowpacks are highly sensitive to climate warming, showing one the highest climate sensitivities across the globe (e.g., Brown and Mote, 2009; López-Moreno et al., 2017; 2020b) Previous studies in the central Pyrenees (López-Moreno et al., 2013), Iberian Peninsula Mountain ranges (Alonso-González et al., 2020a) and mountain areas with Mediterranean climates (López-Moreno et al., 2017) have demonstrated that the climate sensitivity of the snowpack is mostly controlled by elevation. Despite the relevant impacts of climate warming in mountain hydrological processes, the climate sensitivity of mid-latitude Mediterranean mountain snowpacks as well as its seasonality is still poorly understood. To date, some studies pointed out different climate sensitivities on wet or dry years (e.g., López-Moreno et al., 2017; Musselman et al., 2017b; Rasouli et al., 2022; Roche et al., 2018). However, no study has yet analyzed the climate sensitivity of snow during compound temperature and precipitation extreme seasons, caused by high-low temperatures (Warm-Cold seasons) or precipitation (Wet-Dry seasons). The high interannual variability of the Pyrenean snowpack, which is expected to increase according to snowpack climate projections (López-Moreno et al., 2008), shows evidence of the need to examine climate sensitivities focused on the year-to-year variability; especially during warm seasons in the Mediterranean basin (e.g., Vogel et al., 2021; De Luca et al., 2020) that are likely to increase in the future (e.g., Meng et al., 2022). Further, the occurrence of different HS trends for mid and high elevation areas of the range (López-Moreno et al., 2020a), suggest the existence of a wide variety of climate sensitivities of snow depending on elevation and spatial factors.

Therefore, the main objective of this article is to better understand the sensitivity of snow accumulation, ablation and timing patterns due to climatic changes during compound temperature and precipitation extreme seasons.

2 Geographical area and climate setting

The Pyrenees is a mountain range located in the North of the Iberian Peninsula (South Europe; 42ºN-43ºN to 2ºW-3ºE), aligned East to West between the Atlantic Ocean and the Mediterranean Sea. The highest elevation peaks are found in the central zone (Aneto, 3,404 m asl), decreasing towards the West and East (Figure 1). The Mediterranean basin, including the Pyrenees, is located in a transition area between continental climate and subtropical temperate influences. Precipitation is majorly driven by large-scale circulation patterns (i.e., Zappa et al., 2015; Borgli et al., 2019) and the jet-stream oscillation during winter (e.g., Hurell, 1995), followed by thermodynamics and lapse-rate changes (Tuel and Eltahir, 2020). During the summer, the northward migration of the Azores high brings stable weather and precipitation is mainly convective (Xercavins, 1985). Precipitation is highly variable depending on the mountain exposition to the main circulation weather types, being ~ 1000 mm/year, reaching 2000 mm/year in the mountain summits and decreasing from North-West to South-East (Cuadrat et al., 2007). There is a slightly disconnection of the general climate circulation towards the eastern Pyrenees, where snow accumulation is more influenced by the Mediterranean climate and East Atlantic/West Russia (EA-WR) oscillations (Bonsoms et al., 2021a). In the southern western and central massifs of the range, snow accumulation is controlled by Atlantic climate and negative North Atlantic Oscillation (NAO) phases (W and SW wet air flows; López-Moreno, 2005; López-Moreno and Vicente-Serrano, 2007; Buisan et al., 2016; Alonso-González et al., 2020b). In the northern slopes, positive phases of the western eastern Mediterranean Oscillation linked with cold NW and N advections trigger the majority of the snow accumulation episodes (Navarro-Serrano and López-Moreno, 2018; Bonsoms et al., 2021a). The seasonal snow accumulation in the northern slopes almost doubles (~ 500 cm) the recorded in the southern slopes, for the same elevation (~ 2000 m; Bonsoms et al., 2021a). The elevation gradient is ~ 0.55ºC/100 m (Navarro-Serrano and López-Moreno, 2018) and the annual isotherm of 0ºC is found at ~ 2750 – 2950 m (López-Moreno and García-Ruiz, 2004). The energy available for snow ablation is governed by net radiation, increasing with elevation and towards the East (Bonsoms et al., 2022).

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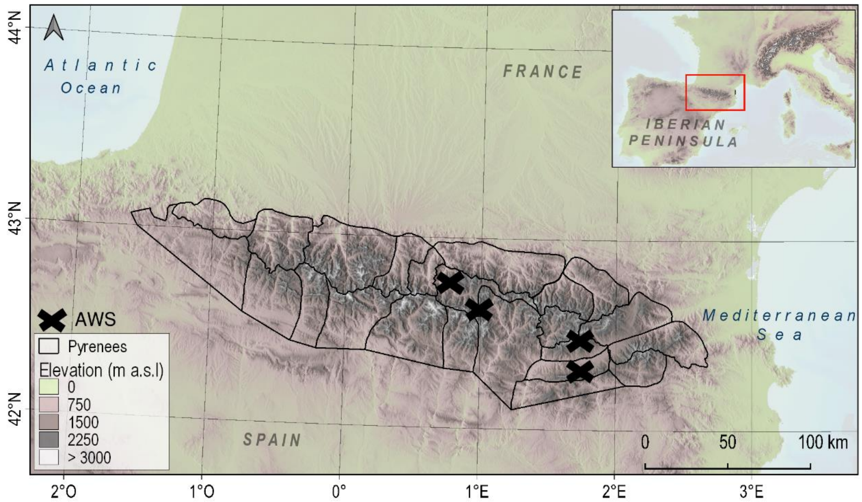

Figure 1. Geographical distribution of the Pyrenean massifs included in this work. We followed the spatial regionalization of the SAFRAN system, which groups the mountain massifs of the range by homogeneous topographical and meteorological areas (modified from Durand et al., 1999).

3 Data and methods

3.1 Snow model

Snowpack was modelled using a physical-based snow model, the Flexible Snow Model (FSM2; Essery, 2015). The FSM2 resolves the SEB and mass balance simulating the state of the snowpack. FSM2 has been tested (Krinner et al., 2018) and extensively applied in different forest environments (e.g., Mazzotti et al., 2021) and hydro-climatological mountain zones, such the Andes (Urrutia et al., 2019), the Alps (Mazzotti et al., 2020), Colorado (Smyth et al., 2022), Himalaya (Pritchard et al., 2020), Iberian Peninsula Mountains (Alonso-González et al., 2020a; Alonso-González et al., 2022) or Lebanese mountains (Alonso-González et al., 2021), among others, providing in all cases confidential results. In this work, the FSM2 model configuration was selected on a trial-and-error basis (not shown here), validated by in-situ snow records of four automatic weather stations (AWS) placed at high elevation areas of the Pyrenees. Then, the FSM2 was forced with the SAFRAN reanalysis dataset for the entire mountain range (see Section 3.2). The FSM2 requires forcing data of precipitation, air temperature, relative humidity, surface atmospheric pressure, wind speed, incoming shortwave radiation (SW_{inc}) and incoming long wave radiation (LW_{inc}). Precipitation in mountain and windy zones is usually

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affected by undercatch (Kochendorfer et al., 2020). Instrumental records of precipitation are corrected of undercatch effects by applying an empirical equation validated in the Pyrenees (Buisan et al., 2019). Precipitation type was classified based on a threshold method (e.g., Musselman et al., 2017b; Corripio and López-Moreno, 2017). It was quantified as snowfall when air temperature was < 1°C and as rain when air temperature was > 1°C, according to previous research in the study area (Corripio and López-Moreno, 2017). The LW_{inc} heat fluxes of the AWS (Table 1) were estimated following (Corripio and López-Moreno, 2017). The instrumental data without records (< 0.7 % of the total dataset) was excluded of the validation process. The HS records were measured each 30 minutes with an acoustic sensor. The meteorological data used in the validation process are open access, provided and managed by the local meteorological service of Catalonia. The data is quality checked through an automatic error filtering process in combination with a climatological, spatial and internal coherency control defined at SMC (2011).

Table 1. Characteristics of the AWS analyzed in this work.

Geographical Area	Code	X/Y (UTM)	Elevation (m)	Atlantic Ocean distance	Mediterranean Sea distance	Reference period	Years
Central-Pyrenees Northern slopes	A1	42.77/ 0.73	2228	200	190	2004 - 2020	16
	A2	42.61/ 0.98	2266	225	170	2001 - 2020	19
Eastern Pyrenees Southern slopes	A3	42.46/ 1.78	2230	295	115	2005 - 2020	15
Eastern Pre-Pyrenees Northern slopes	A4	42.29/ 1.71	2143	300	110	2009 - 2020	11

The model accuracy was estimated by the mean absolute error (MAE) and the root mean square error (RMSE), whereas the model performance was estimated by the coefficient of determination (R^2). The MAE and the RMSE summarise the mean differences between the modelled and the observed values. The FSM2 configuration calculates the albedo based on a prognostic function, increasing (decreasing) depending on snowfall (snow age). Snow compaction rate is estimated on the basis of overburden and thermal metamorphism. FSM2 configuration includes internal snowpack processes, runoff, refreeze rates and thermal conductivity, the latter estimated as function of the snow density. The atmospheric stability is simulated as function of the Richardson number.

3.2 Atmospheric forcing data

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We forced the FSM2 using the reanalysis climate dataset of Vernay et al. (2021), consisting in the modelled values from the SAFRAN meteorological analysis. The data includes flat slopes at low, mid and high elevation ranges and Pyrenean massifs (Figure 1) at hourly resolution. The SAFRAN system provides data by homogeneous meteorological and topographical mountain massifs every 300 m, from 0 to 3600 m (Durand et al., 1999; Vernay et al., 2021). Precipitation type was classified following the threshold approach presented at section 3.1. Atmospheric emissivity was derived from the SAFRAN LW_{inc}. The data was forced with numerical weather prediction models (ERA-40 reanalysis data from 1958 to 2002 and ARPEGE from 2002 to 2020). Meteorological data was calibrated, homogenized and improved by data assimilation of in-situ meteorological observations (Vernay et al., 2021). Further technical details of the SAFRAN system can be found at Durand et al. (1999; 2009a; 2009b). The SAFRAN system has been previously used and validated for the meteorological modelling of continental Spain (Quintana-Seguí et al., 2017), France (Vidal et al., 2010), extreme snowfall trends (Roux et al., 2021), snowpack climate projections (Verfaille et al., 2018), long-term HS trends (López-Moreno et al., 2020) and snow ablation trends (Bonsoms et al., 2022), among other works.

3.3 Climate sensitivity analysis

Climate sensitivity is analyzed through a delta-change methodology (e.g., López-Moreno et al., 2008; Beniston et al., 2016; Musselman et al., 2017b; Marty et al., 2017; Alonso-González et al., 2020a; Sanmiguel-Vallelado et al., 2022, among other works). Temperature and precipitation are perturbed for each massif and elevation range based the historical period (1980-2019). Temperature is perturbed from 1 to 4ºC by 1ºC intervals, assuming an increase of LW_{inc} accordingly (Jennings and Molotch, 2020). Precipitation is perturbed from -10 % to 10 %, by 10 % intervals, in accordance with climate models uncertainties, maximum and minimum precipitation projections for the Pyrenees (Amblar-Frances et al., 2020).

3.4 Compound temperature and precipitation extreme seasonal definition

Snow season includes all days between October to June (included). Snow season duration is defined according with snow onset and snow ablation dates (Bonsoms, 2021a). Compound temperature and precipitation extreme season (season type) is performed using a joint quantile approach (Beniston and Goyette, 2007; Beniston, 2009; López-Moreno et al., 2011a), for each massif and elevation ranges. Following López-Moreno et al. (2011a), compound temperature and precipitation extreme season are defined based on seasonal 40th percentile (T40 and P40, for temperature and precipitation, respectively) and 60th percentile (T60 and P60, for temperature

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and precipitation, respectively) percentiles. Seasons are classified into four categories: (i) CD seasons, when the seasonal temperature and precipitation (Tseason and Pseason, respectevly) are <= T40 and P40; (ii) CW seasons, when Tseason is <= T40 and Pseason >= P60; (iii) WD seasons, when Tseason is > T40 and Pseason is <= P40. Finally, (iv) WW seasons, when Tseason is > T60 and Pseason was > P60. The remaining seasons, are classified as average (Avg) compound temperature and precipitation extreme seasons. The number of seasons type by elevation and massifs is shown at Figure S1.

3.5 Snow-climatological indicators

Snowpack climate sensitivity is analyzed through five key snow indicators, including: (i) the seasonal average HS, (ii) the seasonal maximum absolute HS peak (peak HS max), (iii) the date when the maximum HS was reached (peak HS date), (iv) the number of days with HS (> 1 cm) on the ground (snow duration) and (v) the average seasonal daily snow ablation per season (snow ablation). Snow ablation is calculated by the difference between the maximum daily HS recorded between two consecutive days (Musselman et al., 2017a). We retained only the days when the difference was < -1 cm. Seasonal HS and peak HS max are snow accumulation indicators, whereas snow ablation, snow duration, and peak HS date are snow ablation indicators. All the indicators are computed by massif and elevation range.

4. Results

4.1 Snow model validation

Snow model validation (Figure 2 and 3) confirms that FSM2 accurately reproduces the observed HS values. On average, the FSM2 performance reached a R2 > 0.83 for all stations. In general, the snow model slightly overestimates the maximum HS values. The best performance is observed at A4 and A2 (R2 = 0.85 in both stations), whereas the lowest values are observed at A3 and A1 (R2 = 0.79 and R2 = 0.82, respectively). The better performance was obtained at A4 (RMSE = 18.5 cm, MAE = 8.9 cm), whereas the largest errors are measured at A2 (RMSE = 45.8 cm, MAE = 29.0 cm).

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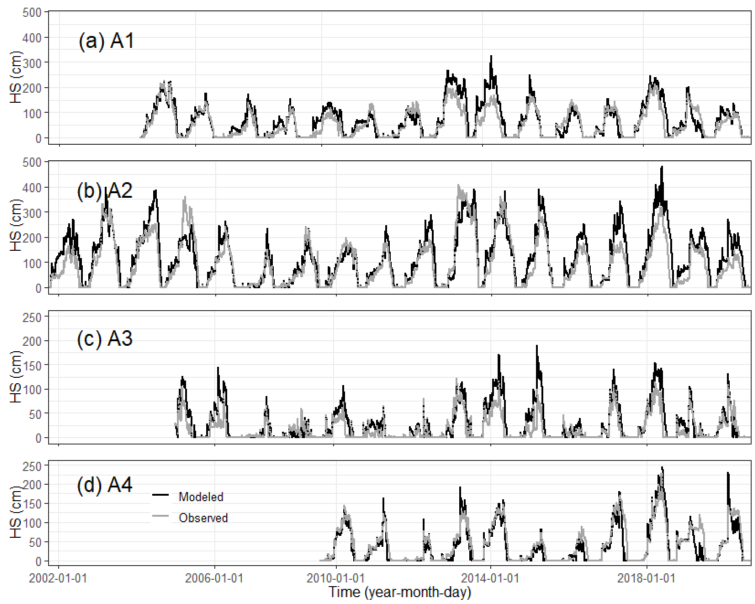

Figure 2. Time series of the observed and modelled HS values grouped by AWS.

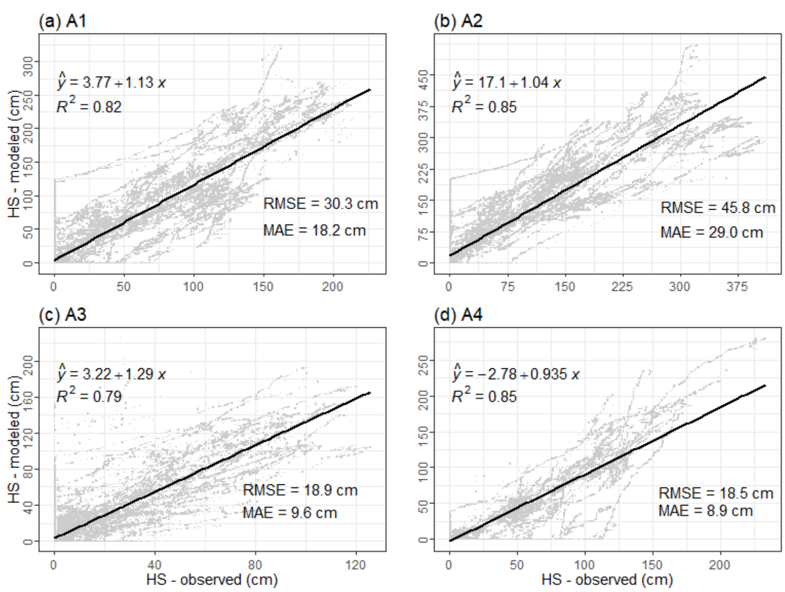

Figure 3. Regression analysis of the observed (x axis), and modelled (y axis), HS values.

4.2 Seasonal snowpack climate sensitivity analysis

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Seasonal HS profiles for each perturbed climate scenario and compound temperature and precipitation extreme season are shown in Figure 4. There is a non-lineal response between seasonal HS losses and temperature increases. When progressively warmed at 1ºC intervals, the largest seasonal HS decreases from baseline climate are found at + 1ºC, for all elevation ranges and compound temperature and precipitation extreme seasons (Figure 4). High elevation areas show lower season-to-season snow variability than low elevations for all the season types. Here, snow is significantly higher during CW seasons in comparison with the rest of the cases. All the snowpack perturbed scenarios point towards snowpack decreases in low and mid elevations under warming climate scenarios. Depending on the season type, different snowpack sensitivities are observed (Figure 5 and 6). For low elevation ranges, the seasonal HS climate sensitivity ranges from -37 % (WW) to -28 % (CD) per ºC of temperature increase. For mid elevation ranges, no significant differences are observed between season types (Table 2), and the seasonal HS losses ranges from -34 % (WW) to -30 % (CW) per ºC. Low and mid elevations show higher snowpack reductions than in high elevations. In the latter, an increase of +10 % of precipitation counterbalances an increase of ~1ºC of temperature, and no significant differences in the seasonal HS are found from the baseline scenario (Figure S2 and Figure S3). Maximum seasonal HS climate sensitivity is observed during WD seasons (-27 % per ºC), whereas the minimum is found for CW (-22 % per ºC).

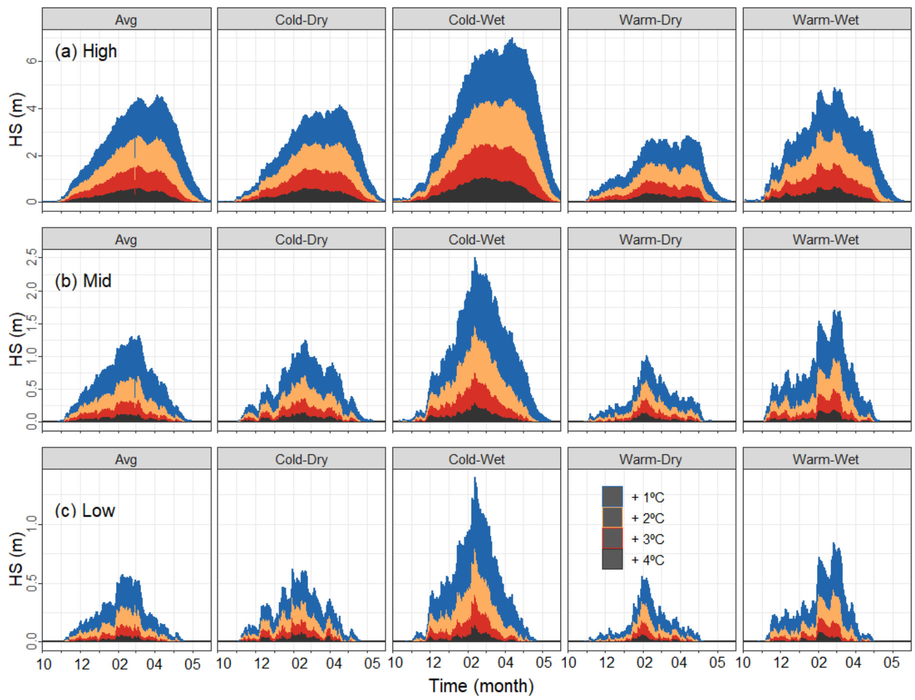

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Figure 4. Average modelled daily HS for each temperature scenario (colors) and compound temperature and precipitation extreme seasons (boxes).

Table 2. Average seasonal HS and peak HS max sensitivity grouped by compound temperature and precipitation extreme seasons and elevation range.

Compound extreme season	% HS / ºC			% peak HS max / ºC		
	Low	Mid	High	Low	Mid	High
Avg.	-33	-33	-25	-20	-20	-16
CD	-28	-30	-22	-17	-17	-14
CW	-33	-32	-22	-22	-20	-15
WD	-32	-30	-27	-19	-16	-16
WW	-37	-34	-26	-24	-24	-16

For low and mid elevation ranges, the peak HS max climate sensitivity reaches maximum values during WW seasons (-24 % per ºC, respectively) and minimums during CD and WD seasons (-17 % per ºC, for both elevation ranges). At high elevations, no significant differences are observed in the peak HS max climate sensitivity between season types. The maximum peak HS max climate sensitivity is observed at WD seasons (-16 % per ºC) and the minimum during CD seasons (-14 % per ºC).

Table 3 and Figure 6 show the average seasonal snow duration for each elevation range, season type and increase of temperature. The minimum seasonal snow duration climate sensitivities are observed during CW seasons, ranging from -13 %, -10 % to -5 % per ºC for low, mid and high elevation ranges, respectively. For low elevation ranges, the maximum seasonal snow duration climate sensitivity is observed during WW seasons (-17 % per ºC). On the contrary, at mid and high elevation ranges, the maximum seasonal snow duration sensitivities are observed during WD seasons, being -13 % (-8 %) at mid (high) per ºC.

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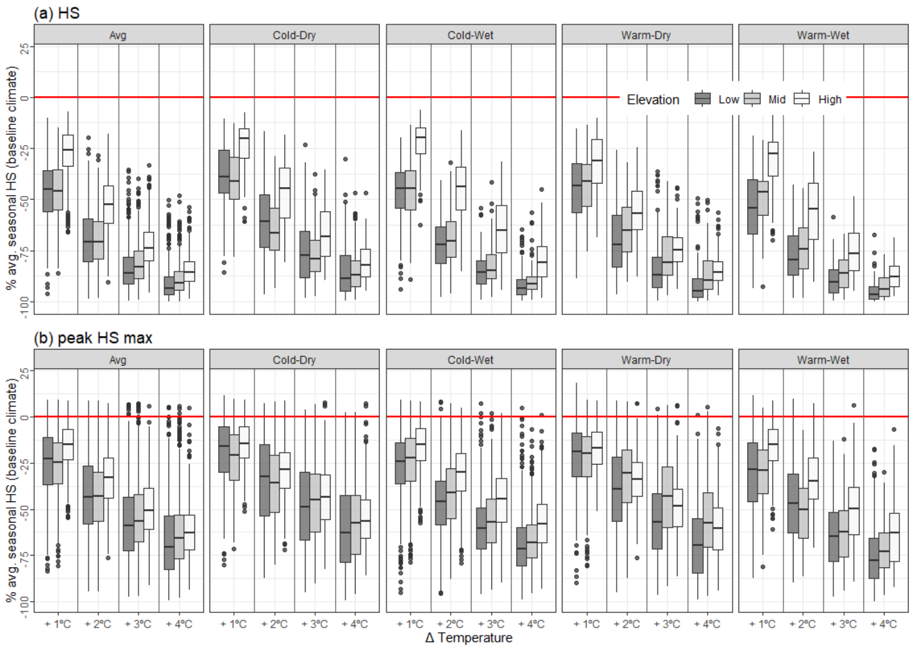

Figure 5. Average seasonal (a) HS and (b) peak HS max anomalies, grouped by increment of temperature (x axis), elevation (colors) and season type (boxes). Anomalies were calculated respect the baseline climate scenario. The boxplot represents the ± 10 % precipitation.

Table 3. Average seasonal snow duration values by degree of warming, grouped by compound temperature and precipitation extreme seasons temperature and elevation range.

Compound temperature and precipitation extreme season	**Elevation**	**Snow duration**				
		Baseline	+ 1ºC	+ 2ºC	+ 3ºC	+ 4ºC
Avg.	Low	83	57	40	25	16
CD		85	62	44	30	21
CW		116	85	60	40	25
WD		63	42	27	17	10
WW		81	53	35	22	12
Avg.	Mid	128	98	72	52	36
CD		129	101	75	54	39
CW		160	128	98	72	51
WD		102	74	52	36	25
WW		118	87	61	44	29
Avg.	High	210	189	164	135	105
CD		208	187	166	140	114
CW		231	213	191	165	135
WD		187	159	131	101	77
WW		204	179	148	117	88

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Climate warming decreases the peak HS date (Figure S4). The maximum peak HS date climate sensitivity is found during dry seasons. During WD (CD) seasons, the peak HS date will take place 9 (15), 3 (8) and 17 (1) days earlier on the season per ºC for low, mid and high elevations, respectively. The minimum peak HS date climate sensitivity is observed during WW seasons (Table 4). The peak HS date does not show any change due to warming, since the snowpack would be scarce during the season, and no defined maximum peaks would occur in any elevation range (Figure 4). In high elevation areas, if temperature increases do not exceed ~ 1ºC respect the baseline scenario, the peak HS date is not expected to drastically change (Figure S4), except during dry seasons.

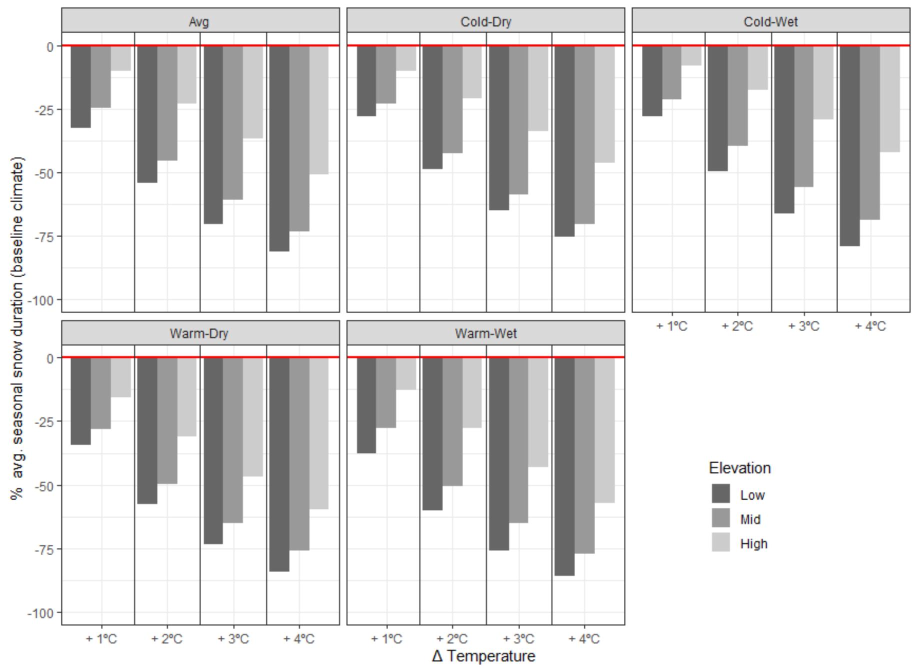

Figure 6. Average decrease of the seasonal snow duration, grouped by increments of temperature (x axis), elevation ranges (colors) and season types (boxes).

The average daily snow ablation per season grouped by temperature increments, elevation and compound extreme season type is shown in Figure 7. The data shown no differences in the average daily snow ablation in a warmer climate. For low elevation, the snow ablation between season types is the same, 12 % per ºC sensitivity (Table 4). For mid and high elevations, the maximum snow ablation sensitivities are found during dry seasons. WD seasons snow ablation sensitivity is 13 % and 10 % per ºC for mid and high elevation range, respectively. On the other hand, the minimum values for mid (high) elevations are found during WW (CW) seasons, when the snow ablation sensitivity is 8 % (5 %) per ºC.

Table 4. Seasonal snow duration, Peak HS date and snow ablation sensitivity. Data is grouped by compound temperature and precipitation extreme season and elevation range.

Compound extreme season	Snow duration (% / ºC)			Snow ablation (% / ºC)			Peak HS date (days / ºC)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
Avg	-15	-12	-6	12	11	7	-2	1	-4
CD	-13	-11	-5	12	13	8	-15	-8	-1
CW	-13	-10	-5	12	10	5	-3	-1	4
WD	-16	-13	-8	12	13	10	-9	-3	-17
WW	-17	-13	-7	12	8	7	-5	8	0

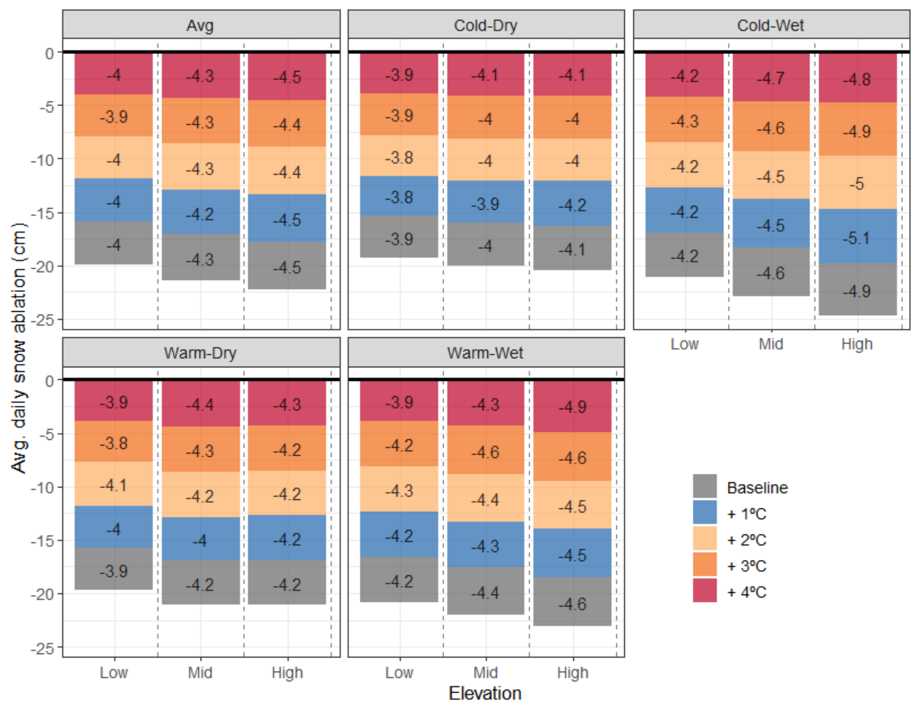

Figure 7. Average daily snow ablation by season. Data is grouped by season type (boxes), elevation (x axis) and increments of temperature (colors).

Snow climate sensitivity shows remarkable spatial contrasts. Climate sensitivity increases moving towards the eastern massifs, independently of the elevation range and season type (Figure 8 and 9). The largest sensitivities differences are observed at low elevation. Here, the

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seasonal HS sensitivity ranges from - 20% (CD) in the central area, up to - 40% (WW) per ºC in the southern slopes of the eastern Pyrenees. Similarly, the maximum peak HS max sensitivities are found in mid elevations of the latest area (> 35% per ºC; Figure 8). There is a general tendency toward higher climate sensitivities in the southern slopes in comparison to the northern ones. This pattern is accentuated at high elevation massifs for all the season types. The lowest snow duration sensitivity is observed in the northern slopes and at high elevation, specially during CD and CW seasons (-5 % per ºC; Figure 9). Snow duration sensitivity clearly increases during WW seasons; when maximum sensitivities are detected at the lowest elevations of the southern-eastern Pyrenees (-35 % per ºC).

5. Discussion

The spatial and temporal patterns of snow in the Pyrenees are highly variable and international climate reports indicate that extreme events will likely increase over the next decades (e.g., Meng et al., 2022). In this context, a better understanding of the present-day controls of the snowpack is crucial to anticipate how the future climate will affect the snow regime.

5.1 Spatial and elevation factors controlling the snow climate sensitivity

Climate sensitivity spatial patterns found in this work (Figure 8 and 9) are consistent with the snow accumulation and ablation spatial patterns reported in the range (e.g., Lopez-Moreno, 2005; Navarro-Serrano et al., 2018; Alonso-González et al., 2020a; Bonsoms et al., 2021a). Atlantic climate influence is reduced moving into the eastern massifs of the range; in the latter area, in-situ observations record almost half (<= 40 %) of the seasonal snow accumulation amounts than northern and western ones for the same elevation (>2000 m; Bonsoms et al., 2021a). The southern slopes of the eastern Pyrenees exhibit higher climate sensitivities since those massifs are exposed to higher turbulent and radiative heat fluxes (Bonsoms et al., 2022). Results show a logical upwards displacement of the snow line due to warming. The elevation climate sensitivity dependent-pattern of snow has been previously reported in specific stations of the central Pyrenees (López-Moreno et al., 2013; 2017), Iberian Peninsula mountains (Alonso-González et al., 2020a), as well as in other ranges such as the Cascades (Jefferson, 2011; Sproles et al., 2013), the Alps (Marty et al., 2017), or the western USA (Pierce et al., 2013; Musselman et al., 2017b), where snow models suggest higher (lower) snowpack reductions due to warming in subalpine (alpine belts) sites (Jennings and Molotch, 2020; Mote et al., 2018). Low elevations present a higher climate sensitivity than high lands since

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temperature is closer to the isothermal conditions (Brown and Mote, 2009; Lopez-Moreno et al., 2017).

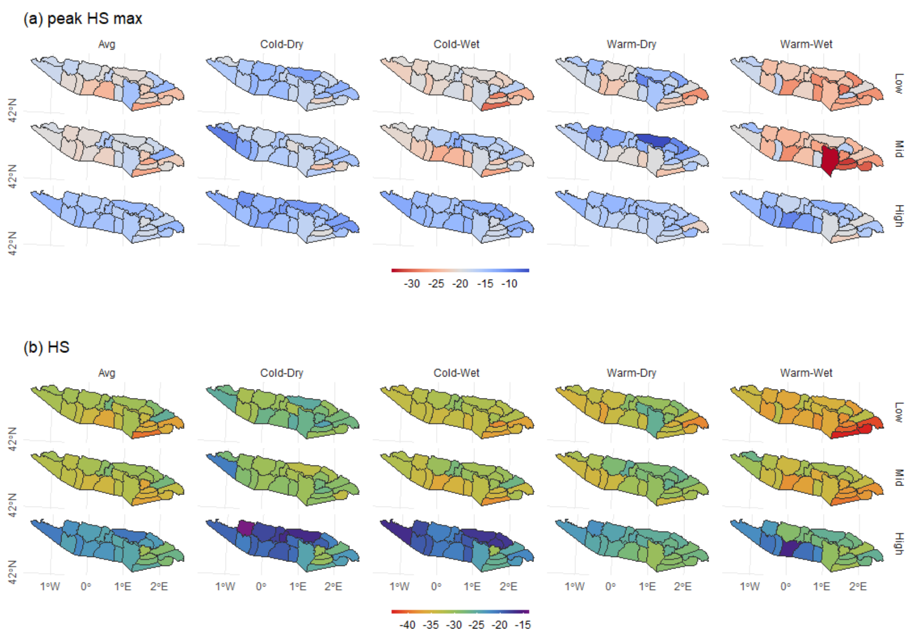

Figure 8. Spatial distribution of the climate sensitivity (percentage of variation from the baseline climate per ºC) for (a) seasonal peak HS max and (b) HS, during average and compound temperature and precipitation extreme seasons.

5.2 Snow climate sensitivity and its relation with historical and future snow trends

5.2.1 Snow accumulation phase

Snow losses by warming reported in this work are mainly associated with increases in the rain/snowfall ratio, changes in the snow onset and offset dates and increases in the energy available for snow ablation (e.g., Pomeroy et al., 2015; Lynn et al., 2020; Jennings and Molotch, 2020). At high elevation areas, an upward trend of precipitation (+ 10 %) could counterbalance temperature increases (< 1ºC; Figure S2 and S3), which is consistent with the results found at specific sites of the central Pyrenees (Izas, 2000m; López-Moreno et al., 2008). Rasouli et al. (2014) also found that an increase of 20 % of precipitation could compensate 2ºC of warming in the subarctic Canada. Climate sensitivity analysis in the western Cascades (western USA), reveals that increases of precipitation due to warming moderates (~ 5 % per ºC) the snowpack

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accumulation losses (Minder, 2010). The results are consistent with recent snow trends at > 1000 m in the Pyrenees, where increases in the frequency of west circulation weather types since the 1980s triggered positive HS (Serrano-Notivoli et al., 2018; López-Moreno et al., 2020), snow accumulation (Bonsoms et al., 2021a) and winter snow days trends (Buisan et al., 2016). Similar trends have been found in the Alps, where during the last decades an increase of extreme snowfall (> 3000 m; Roux et al., 2021) as well as winter precipitation 100-year return levels has been detected (Rajczak and Schär, 2017).

5.2.2 Snow ablation phase

The comparison between low and high elevation reveals faster average daily snow ablation in the latter elevation range (Figure 7). The average daily snow ablation per season in deep snowpacks (high elevations) are probably explained because snow last until late spring, when there are higher rates of energy available for snow ablation (Bonsoms et al., 2022). Climate warming leads a cascade of physical changes in the SEB increasing snow ablation due to the near 0ºC isotherm. However, the average daily snow ablation shows small increases due to warming. Slower snow ablation rates in a warmer world are consistent with snow ablation trends found in the Northern Hemisphere, where snow melt rates (1980 – 2017 period) show decreasing trend (Wu et al., 2018). Data suggest that increases of temperature do not imply faster daily snow ablation rates per season, since warming decreases the snowpack magnitude (seasonal HS and peak HS max) and triggers earlier snowmelt onsets (Wu et al., 2018). The early peak HS date reported in this work (Table 4; Figure S4) implies lower rates of net shortwave radiation, since snow melting starts on winter (Pomeroy et al., 2015), coinciding with shorter days and lower solar zenith angles (Lundquist et al., 2013; Sanmiguel-Vallelado et al., 2022). Same conclusions are found for the subarctic Canada (Rasouli et al., 2014) or western USA snowpacks (Musselman et al., 2017b), but contrast with faster melt rates found in Arctic sites (Krogh and Pomeroy, 2019).

5.2.3 Climate sensitivity and snow projections

Data suggest a non-lineal snowpack reduction due to warming. The largest snow losses are found for seasonal HS under an increase of 1ºC respect the baseline scenario. At low and mid elevations, the seasonal HS would decrease on average > 40 % for all season types, with maximum climate sensitivities found during WW seasons. Previous research in the Pyrenees and in other mid-latitude mountain ranges, have found similar climate sensitivities. In the central Pyrenees, the peak of SWE climate sensitivity is 29 % per ºC, whereas snow season duration decreases by ~ 20–30 days per ºC (at ~ 2000 m; López-Moreno et al., 2013). The

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average peak HS max climate sensitivity detected at high elevations if the Pyrenees (-16 % per ºC; Figure 6 and Table 2) is slightly over the average peak SWE climate sensitivity found in Iberian Peninsula mountains at 2500 m (-15 % per ºC; Alonso-González et al., 2020a). Results are also consistent with climate projections found in the range. Under an increase of temperature (>2 ºC), the snow season is reduced 38 % in the lowest (~ 1500 m) ski-resorts located in the southern slopes of the eastern Pyrenees (Pons et al., 2015). However, high emission climate scenarios project an increase of the frequency and intensity of high snowfall in the highlands (+ 20 %; López-Moreno et al., 2011b). According to climate projections for the mid-end 21th century, climate sensitivity in the easternmost area could be reduced during winter, since an upward trend of precipitation is expected in the latest area (~ 10 %; Amblar-Francés et al., 2020). The projected changes in the Pyrenean snowpack dynamics are similar to the expected snow losses in near mountain ranges. In the Atlas Mountains, snowpack decreases are accentuated in the lowlands, and climate change projections anticipate seasonal SWE declines of 60 % (80 %) under RCP4.5 (RCP8.5) scenarios for the entire range (Tuel et al., 2022). In the Washington Cascades (western USA), snowpack climate sensitivity is -19 to -23 % per ºC (Minder, 2010), which is similar with the values found in this work for high elevation ranges. In the French Alps (Chartreuse, 1500 m), seasonal HS decreases in the order of 25 % (32 %) for 1.5 ºC (2ºC) of global temperature rise above the pre-industrial years (Verfaille et al., 2018). For the Swiss Alps, snowpack climate sensitivity is ~ -15 % per ºC (Beniston, 2003). In the latter range, seasonal HS is expected to decrease > 70 % in the massifs placed at < 1000 m for all future climate projections (Marty et al., 2017). The largest snow reductions are expected to occur in the shoulders of the seasons (Steger et al., 2013; Marty et al., 2017). Nevertheless, at high elevations, snow climate projections revealed no significant trends in the majority (80 %) of maximum HS for the mid-end 21st (> 2500 m, eastern Alps; Willibald et al., 2021), being internal climate variability the major source of uncertainty of SWE projections in the highlands (Schirmer et al., 2021).

5.3 The influence of compound temperature and precipitation extreme seasons

The maximum seasonal HS and peak HS max climate sensitivities are detected during WW (WD) seasons for low and mid (high) elevations. Brown and Mote (2008) analyzed the snow climate sensitivity of the Northern Hemisphere, finding maximum SWE sensitivities in mid-latitudinal maritime winter climate areas, and minimums in dry and continental zones, which is consistent with our results. Also, López-Moreno et al. (2017) detected higher SWE decreases in wet and temperate Mediterranean ranges than at drier ones. Further, in northern North American Cordillera, Rasouli et al. (2022) found higher snowpack sensitivities in wet basins in

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comparison with drier ones. The maximum snow ablation and peak HS date climate sensitivities are observed during dry seasons, which is in accordance with Musselman et al. (2017b), who detected higher snowmelt rate climate sensitivities during dry years for western USA. Low and mid elevations are highly sensible to WW seasons since wet conditions favours decreases in the seasonal HS through the advection of sensible heat fluxes. At high elevations, however, temperature is still cold allowing solid precipitation during WW seasons, and for this reason maximum climate sensitives are observed during WD seasons. Alpine zones snowfall reductions can be further compensated in a warmer scenario, given that warm and wet snow is less susceptible to blowing wind transport and snow sublimation losses (Pomeroy and Li, 2000; Pomeroy et al., 2015). During spring, snow runoff could be also amplified in wet climates due to rain-on-snow events (Corripio and López-Moreno, 2017), coinciding with higher rates of energy available for snow ablation.

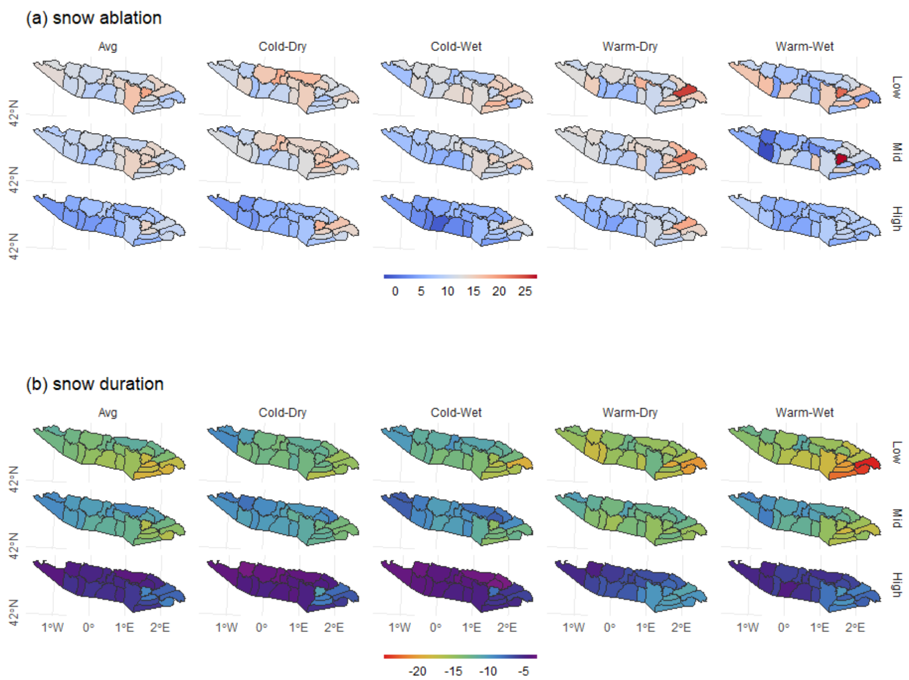

Figure 9. Spatial distribution of the climate sensitivity (percentage of variation from the baseline climate per ºC) for (a) snow ablation and (b) snow duration during average and compound temperature and precipitation extreme seasons.

5.4 Environmental and socioeconomic implications

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The results points towards an extension of snow ablation through the season, implying the disappear of the typical alternance of snow accumulation and ablation seasons. Climate warming triggers the simultaneously occurrence of snow accumulation and ablation episodes, snow droughts during winter, as well as ephemeral snowpacks in the shoulders of the season. The expected snow decreases have significant impacts in the ecosystem. Snow cover in springs acts as a cooling factor of the soil (Luetschg et al., 2008), delays active layer thickness (Hrbáček et al., 2016), soils freeze initiation (Oliva et al., 2014) and protects alpine rocks exposition to solar radiation and air temperatures (Magnin et al., 2017). Due to warming temperatures, the remaining glaciers in the range are shrinking, and they are expected to disappear before the 2050s (Vidaller et al., 2021). The shallower snowpack pointed out in this work increases the glacier vulnerability, since snow has a higher albedo than the dark ice and debris-covered glaciers and acts as a protective layer of the glaciers (e.g., Fujita and Sakai, 2014).

The early snowmelt onset suggested in this work, accentuated at low and mid elevation during WD seasons, goes in line with early streamflow's due to earlier runoff rates found in global studies (Adam et al., 2009; Stewart, 2009) and with the observed trends in the Iberian Peninsula River flows (Morán-Tejeda et al., 2014). Overall, results are consistent with the slight decrease of the river peak flows found in the southern slopes of the Pyrenees since the 1980s (Sanmiguel-Vallelado et al., 2017). The significant reductions of seasonal HS pointed out in this article, driven by increases in the rainfall ratio, suggest that snowmelt-dominated streams flows are likely to shift to rainfall dominated regimes. Whereas high elevation meltwater might increase, contributing to earlier groundwater recharges (e.g., Evans et al., 2018), the upward evapotranspiration trends in the lowlands (Bonsoms et al., 2022) could counter this effect, with no net change in the downstream areas (Stahl et al., 2010). Snow ephemerality triggers lower spring and summer flows (e.g., Barnett et al., 2005; Adam et al., 2009; Stahl et al., 2010) and have related impacts in the hydrological management strategies. The reservoirs operation strategies include hydrological resources storage during peak flows and water releases during summer; which coincides with the driest season in the lowlands, and when there are higher water and hydropower demands than in winter (Morán-Tejeda et al., 2014). Recurrent snow scarce seasons may intensify the hydrological impacts named and the water resources competition between the ecological and socioeconomical systems. The economic reliability of mountain ski-resorts in the range is dependent of the year-to-year variability of the snowpack (Gilaberte-Burdalo et al., 2014; Pons et al., 2015) which has been shown to be highly variable, especially at low and mid elevations. The expected snow scarce seasons under an increase of > 1ºC due to the high climate sensitivity pointed out in this work, is consistent with climate projections for the range, which suggest that no Pyrenean ski-resort will be reliable under high climate projections (RCP 8.5) for the end of the 21st century (2080 – 2100; Spandre et al., 2019).

6 Conclusions

This work presents an assessment of the climate change impact on the Pyrenean snowpack during compound temperature and precipitation extreme seasons, by using a physical-based snow model forced by reanalysis data. The climate sensitivity of the snowpack was analyzed through five key snow accumulation and ablation indicators. Climate sensitivity follows an elevation pattern. Snowpack losses are accentuated during WW (low and mid elevations) and WD (high elevation) seasons. The lowest snow climate sensitivity was observed in the high elevated zones of the western and northern Pyrenees, increasing towards the lowest stretches of the eastern and southern slopes. An increase of 1º C in low and mid elevation supposes a significant decrease in the seasonal HS and snow duration. However, at high elevations, precipitation plays a key role in the snowpack evolution, and temperature is far from the isothermal 0ºC during the core months of the season. During the latter, an increase of 10 % of precipitation - as suggested by many climate projections over the eastern sectors of the range -, could compensate small temperature increases (~ 1ºC warming). The impact of climate warming could be different depending on the compound temperature and precipitation extreme season. Snowpack losses are accentuated during WW (low and mid elevations) and WD (high elevation) seasons. Regarding seasonal HS, the highest (lowest) reductions are observed on WW (CD) seasons, when the seasonal HS will be reduced -37 % (- 28 %), -34 % (- 30 %), -27 % (-22 %) per ºC at low, mid and high elevation areas, respectively. For seasonal snow duration, the highest (lowest) reductions are found during WD (CW) seasons, representing the -17 % (13 %), -13 % (-10 %) and -8 % (-5 %) per ºC at low, mid and high elevation areas, respectively. The peak HS date and snow ablation show the largest climate sensitivities during dry seasons. During the latter, snow ablation increases + 10 % and the peak HS date advances ~ 10 days per ºC, for all elevations. This work provides evidence of the high climate sensitivity of the Pyrenean snowpack in comparison with global mountain ranges, suggesting the existence of similar climate sensitivities in other mid-latitude mountain areas.

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Authors contribution's

JB analyzed the data and wrote the original draft. JB, JILM and EAG contributed in the manuscript design and draft edition. JB, JILM and EAG read and approved the final manuscript.

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