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 eEarth during over the last few decades, and climate projections predict anticipate water-scarcity in the future scenarios. Mid-latitude Mediterranean mountain areas, such as the Pyrenees, play a key role in the hydrological resources for the highly intensely populated lowland areas. However, there are still large uncertainties about the impact of climate change on the snowpack in the high mountain ranges of this e Mediterranean region. Here, we describe provide a sensitivity analysis of the Pyrenean snowpack using through five key snow-climatological climate indicators. We analyzed sSnow sensitivity is analyzed to seasons with four different compound extreme weather conditions (during compound temperature and precipitation extreme seasons, namely cCold-dDry [(CD]), cCold-wWet [(CW]), Wwarm-dDry [(WD]), and wWarm-wWet [(WW]) seasons, at for low elevations (1500 m), mid-elevations (1800 m), and high elevations (2400 m) elevation sectors in of the Pyrenees. In particular, we forced To this end, a physically -based energy and mass balance snow model (FSM2), with is validation ed by ground-truth data, and subsequently applied this model to the entire range, with forcing of perturbed reanalysis climate data for the period 1980 to —2019 as the baseline scenario. The FSM2 model results have shown that FSM2 successfully reproduceds the observed snow depth (HS) values (, reaching $R^2 > 0.8$), with and relative root-mean square error and mean absolute error values less than lower than 10 % of the observed HS values. Overall, the sensitivity tosnow sensitivity -climate sensitivity decreaseds with elevation and increaseds towards the eastern Pyrenees. When the temperature increased is progressively warmed at 1ºC intervals, the largest seasonal HS decreases from the baseline climate were are found at +1ºC (, reaching values of -47 % at low elevation, -48 % at mid-elevation, and -25 % at high for low, mid and high elevations, respectively). Only aAn 10% increase of upward trend of precipitation (+10 %) could counterbalanced the temperature increases (≤<= 1ºC) at high elevations during the coldest months of the season, because since temperature was is far from the isothermal 0ºC conditions. The maximal um (minimum) seasonal

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HS and peak HS max reductions were during ~~are observed on~~ WW ~~(CD)~~ seasons, and the minimal reductions were during CD seasons. During the CD ~~latter~~ seasons, the seasonal HS decline per °C was ~~is expected to be reduced by~~ –37 % at (low elevations [–28 %]), –34 % at (–mid-elevations [30 %]), and –27 % at (high elevations [–22 %]) ~~per °C, at low, mid and high elevation areas, respectively~~. For climate indicators of snow ablation ~~climate indicators~~, the largest decreases were ~~are observed~~ during the WD seasons, when the peak HS date is anticipated 10 days and snow duration (ablation) decreases (increases) 12 % per ºC of warming. ~~The results~~ Results suggests ~~similar climate~~ snow, sensitivity ~~ies~~ will be similar at other mid-latitude mountain areas, ~~where~~ where ~~significant~~ snowpack reductions ~~are anticipated,~~ will have major ~~with relevant~~ consequences on the nearby ~~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's climate system (Armstrong and Brun, 1998)~~,~~ because ~~since~~ it cools the planet (Serreze and Barry, 2011) by ~~through~~ altering the Surface Energy Balance (SEB), decreasing ~~modifying~~ the albedo,~~,~~ and reducing surface and air temperatures (~~e.g.,~~ Hall, 2004). ~~Since the 1980s,~~ Northern-Hemispheric snowpack patterns have changed ~~are~~ rapidly during recent decades ~~changing~~ (~~e.g.,~~ Hammond et al., 2018; Hock et al., 2019; Notarnicola et al., 2020). It is crucial to improve our ~~A better~~ understanding and predictions of changes ~~shifts~~ in ~~the~~ snowpack quantity~~,~~ patterns~~,~~ ~~and~~ as well ~~of~~ as ~~in~~ the timing of snow accumulation and ablation ~~timings~~ due to changing climate conditions ~~is crucial~~, because ~~since~~ snowpack affects many ~~has relevant feedbacks in the~~ nearby social and environmental systems. From the hydrological point of view, snow melt ~~ing~~ controls ~~high~~ mountain runoff rate~~s~~ during the spring (Barnett et al., 2005; Adams et al., 2009; Stahl et al., 2010), river flow magnitude and timing~~s~~ (Morán-Tejeda et al., 2014; Sanmiguel-Vallelado et al., 2017), water infiltration and groundwater storage (Gribovszki et al., 2010; Evans et al., 2018), and ~~or~~ transpiration rate~~s~~ (~~e.g.,~~ Cooper et al., 2020). The presence and duration of ~~the~~ snowpack affects ~~strongly conditions~~ terrestrial ecosystem dynamics~~,~~ because ~~since~~ snow ablation date~~s~~ affects ~~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 thickness of the active layer ~~thickness~~ in permafrost environments (Hrbáček et al., 2016; Magnin et al., 2017). ~~Further, s~~Snowpack also has remarkable economic impacts. For example, ~~;~~ the snowpack ~~in the highlands,~~ at high elevations and ~~as well as the~~

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surrounding areas~~,~~ ~~snow~~ determines the economic success of many mountain ski-resorts (~~e.g.,~~ Scott et al., 2003; Pons et al., 2015; Gilaberte-Búrdalo et al., 2017). ~~The impact of~~ Changes in the snowpack of mountainous regions also influence associated ~~changes in the~~ lowland areas because it ~~s~~ affects the availability of ~~can be amplified, given that~~ snow meltwater that is ~~provides significant hydrological resources~~ used for water reservoirs, hydropower generation, agriculture~~al~~, industries, ~~al~~ and other applications ~~human uses~~ (e.g., Sturm et al., 2017; Beniston et al., 2018).

Mid-latitude snowpacks have among ~~are highly sensitive to climate warming, showing one~~ the highest ~~climate~~ snow sensitivities worldwide ~~across the globe~~ (~~e.g.,~~ Brown and Mote, 2009; López-Moreno et al., 2017; 2020b). In regions at high latitudes or ~~and~~ high elevations~~-sectors~~, increasing ~~positive~~ precipitation ~~trends~~ can partly ~~ould~~ counterbalance the effect of increases of temperature ~~increases to some extent in regard~~ on ~~to~~ snowpack duration (Brown and Mote, 2009). Climate warming is decreasing ~~es~~ the maximum and seasonal snow depth (HS), ~~and~~ the s~~S~~now w~~W~~ater e~~E~~quivalent (SWE) (Trujillo and Molotch, 2014; Alonso-González et al., 2020a; López-Moreno et al., 2013; 2017),~~;~~ and ~~decreases~~ the fraction ~~of snowfall of the~~ total precipitation as snowfall (snowfall ratio; e.g., Mote et al., 2005; Lynn et al., 2020; Jeenings and Molotoch, 2020; Marshall et al., 2019), and is also delaying the ~~triggers later~~ snow onset~~s~~ date~~s~~ (Beniston, 2009; Klein et al., 2016). ~~During the snow ablation phase,~~ However, warming can slow~~,~~ ~~slows~~ the early snow ablation rate on the season ~~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) because of the ~~due to~~ earlier ~~y~~ HS and SWE peak dates (Alonso-González et al., 2022), which coincide ~~ing~~ with periods of low solar radiation ~~periods~~ (~~e.g.,~~ Pomeroy et al., 2015; Musselman et al., 2017a).

The Mediterranean basin is a region that is critically affected by ~~one of the primary~~ climate change ~~Hot Spots of the Earth~~ (Giorgi, 2006)~~,~~ being densely populated (>~~-~~500 million ~~of~~ inhabitants) and affected by an intense anthropogenic activity~~iesy~~. ~~W~~Warming of ~~across~~ the Mediterranean basin ~~is projected to~~ will accelerate ~~for the mid-end~~ for the next decades ~~(202250 to 2100) 21st century~~, and ~~and~~ temperatures ~~is expected to~~ will continue to increase ~~higher than the global average~~ in this region during the warm months ~~half of the year~~ (~~e.g.,~~ Knutti and Sedlacek, 2013; Lionello and Scarascia 2018; Cramer et al., 2018; Evin et al., 2021; Cos et al., 2022), increasing atmospheric evaporative demands (Vicente-Serrano et al., 2020), drought severity (Tramblay et al., 2020), leading to ~~and implying a~~ water-scarcity ~~scenario~~ over most of this region ~~e basin~~ (García-Ruiz et al., 2011). Mediterranean mid-latitude mountains, such as the Pyrenees, where

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this research focuses, are the main runoff – generation zones of the downstream areas (Viviroli and Weingartner, 2004), and provide ing the most majority of the water resources used by for major cities located in the lowlands (Morán-Tejeda et al., 2014).

Snow patterns in the Pyrenees have high are spatial, ly highly diversity e (Alonso-González et al., 2019), due to internal climate variability of mid-latitude precipitation (e.g., Hawkins and Sutton 2010; Deser et al., 2012) and , 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 exposures of the the different mountains exposition to the main circulation weather types (Bonsoms et al., 2021a). Thus, snow accumulation per season is almost twice as much in the northern slopes as almost doubles the recorded in the southern slopes (Navarro-Serrano and López-Moreno, 2017), and there is a high interannual variability of snow in the lower regions at lower elevations stretches of the range (Alonso-González et al., 2020a), and in as well as in the southern and eastern regions 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 in the Pyrenees (Bonsoms et al., 2022), and but during the same temporal period, winter snow days and snow accumulation have non-statically significantly increased (Buisan et al., 2016; Serrano-Notivoli et al., 2018; López-Moreno et al., 2020a; Bonsoms et al., 2021a) due to the increasing frequency of positive west and south-west advections frequency trends (Buisan et al., 2016). For Projections for Pyrenees during the mid-late end 21st century, anticipate climate change scenarios over the Pyrenees anticipate a temperature increase of more than > 1°C to 4 °C, and (relative to 1986–2005) an increase of positive (negative) precipitation by trends about around (~) 10 %, (respect the 1986 – 2005 period) for the eastern regions and a decrease of precipitation by about 10% for the (western) regions sectors of the range during winter and spring (Amblar-Frances et al., 2020). Therefore, changes in snow patterns evolution in regions with the high elevationss of the range are uncertain is subject to major unknowsbecause , since winter snow accumulation is affected by ruled by precipitation (e.g., López-Moreno et al., 2008), and Mediterranean basin winter precipitation projections have 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).

Previous studies in the central Pyrenees (López-Moreno et al., 2013), Iberian Peninsula mMountain ranges (Alonso-González et al., 2020a), and mountain areas that have with Mediterranean climates (López-Moreno et al., 2017) have demonstrated that the climate sensitivity of the snowpack sensitivitys is mostly controlled by elevation. Despite the relevant

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impact~~s~~ of climate warming in mountain hydrological processes, there is limited understanding of the ~~climate~~ snow, sensitivity and seasonality of mid-latitude Mediterranean mountain snowpacks~~ as well as its seasonality is still poorly understood~~. ~~To date, s~~Some studies reported ~~pointed out~~ different snowpack ~~climate~~ sensitivities during ~~on~~ wet and ~~or~~ dry years (~~e.g.,~~ López-Moreno et al., 2017; Musselman et al., 2017b; Rasouli et al., 2022; Roche et al., 2018). However, the ~~climatic~~ sensitivity of snow during periods when there are seasonal extremes of temperature ~~(Warm-Cold seasons)~~ and precipitation ~~(Wet-Dry seasons)~~ has not yet been analyzed. The high interannual variability of the Pyrenean snowpack, which is expected to increase according to ~~snowpack~~ climate projections (López-Moreno et al., 2008), indicates a ~~shows evidence of the~~ need to examine snowpack ~~climate~~ sensitivity under conditions of high ~~ies focused on the~~ year-to-year variability, ~~;~~ especially during the warm seasons in the Mediterranean basin (~~e.g.,~~ Vogel et al., 2019; De Luca et al., 2020) because these are ~~that are~~ likely to increase in the future (e.g., Meng et al., 2022). Further, the occurrence of different HS trends at ~~for~~ mid- and high-~~-~~elevation areas of this ~~e~~ range (López-Moreno et al., 2020a)~~,~~ suggest that elevation and spatial factors ~~the~~ contribute to the ~~existence of a~~ wide variations of the sensitivity of snow to the ~~ety of~~ climate ~~sensitivities of snow depending on elevation and spatial factors~~.

Therefore, the main objective of this research ~~article~~ is to ~~better~~ understand the effect of seasons with compound temperature and precipitation extremes on ~~the sensitivity of~~ snow accumulation,~~,~~ snow ablation, and the timing of these processes in ~~patterns due to climatic changes during compound temperature and precipitation extreme seasons,~~ the Pyrenees.

2 Geographical area and climate setting

The Pyrenees is a mountain range located in the n~~N~~orth of the Iberian Peninsula (South Europe; 42ºN-43ºN to 2ºW-3ºE)~~,~~ that is aligned e~~E~~ast~~-~~to~~-~~ w~~W~~est between the Atlantic Ocean and the Mediterranean Sea. The highest elevations ~~peaks~~ are ~~found~~ in the central region ~~zone~~ (Aneto, 3~~,~~404 m~~ asl~~) and elevations ~~,~~ decrease~~ing~~ towards the w~~W~~est and e~~E~~ast (**Figure 1**). The Mediterranean basin, including the Pyrenees, is located in a transition area, and is influenced by ~~between~~ the continental climate and the subtropical temperate climate~~influences~~. Precipitation is mostly ~~ajorly~~ driven by large-scale circulation patterns (~~i.e.,~~ Zappa et al., 2015; Borgli et al., 2019), the jet-stream oscillation during winter (~~e.g.,~~ Hurell, 1995), and land-sea temperature differences (Tuel and Eltahir, 2020). During the summer, the northward movement ~~migration~~ of the Azores high pressure region brings stable weather, and precipitation is mainly convective at that time (Xercavins, 1985). Precipitation is highly variable depending on ~~the~~ mountain exposure

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~~ition~~ to the main circulation weather types~~;~~, it ranges from ~~being~~ about ~~∼~~1000 mm/year to about ~~, reaching~~ 2000 mm/year (in the mountain summits), with ~~and~~ lower levels in ~~decreas~~the east and north~~ing (increasing) from West (North) to East~~ (~~South;~~ Cuadrat et al., 2007). There is a slight~~ly~~ 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 have greater effects on snow accumulation (Bonsoms et al., 2021a). In the southern,~~;~~ western, and central massifs of the range, the Atlantic climate and the negative North Atlantic Oscillation (NAO) phases regulate 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, the positive phases of the Western Mediterranean Oscillation (WeMO), linked with NW and N advections, trigger the most episodes ~~majority~~ of ~~the~~ snow accumulation ~~episodes~~ (Navarro-Serrano and López-Moreno, 2018; Bonsoms et al., 2021a). The seasonal snow accumulation in the northern slopes is almost double~~s~~ the amount (about ~~∼~~500 cm more) ~~the recorded~~ as in the southern slopes~~,~~ at ~~for~~ an ~~the same~~ elevation of about (~~∼~~2000 m (~~;~~ Bonsoms et al., 2021a). The temperature/elevation gradient is about ~~∼~~0.55ºC/100 m (Navarro-Serrano and López-Moreno, 2018) and the annual ~~isotherm of~~ 0ºC isotherm is ~~found~~ at about ~~∼~~ 2750 to ~~—~~2950 m (López-Moreno and García-Ruiz, 2004). Net radiation governs the ~~The~~ energy available for snow ablation ~~is governed by net radiation~~, and this is greater ~~increasing~~ at high ~~with~~ elevations and in the ~~towards the e~~East (Bonsoms et al., 2022).

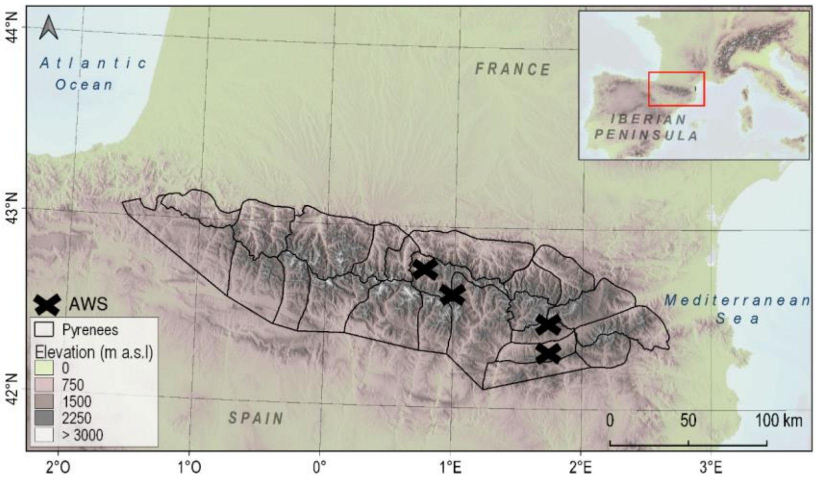

Figure 1. Locations of automatic weather stations (AWS) and geography~~ical distribution~~ of the Pyrenean massifs based on ~~included in this work. We followed~~ the spatial regionalization of the

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SAFRAN system, which groups the mountain massifs of the range according to by homogeneous topographical and meteorological characteristics 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). This model e FSM2 resolves the SEB and mass balance to simulate ing the state of the snowpack. Previous studies tested the FSM2 has been tested (Krinner et al., 2018), and its and extensively application ed in different forest environments (e.g., Mazzoti et al., 2021), and and in different hydro-climatological mountain zones, such the Andes (Urrutia et al., 2019), , the Alps (Mazzoti et al., 2020), Colorado (Smyth et al., 2022), Himalayas (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), providing confidential , among others, providing in all cases confidential results. 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}). We have evaluated different FSM2 model configurations (not shown) without significant differences in the accuracy and performance metrics. Therefore, we selected the most complex FSM2 configuration. In detail, albedo is calculated based on a prognostic function, with increases due to snowfall and decreases due to snow age. Atmospheric stability is calculated as function of the Richardson number. Snow density is calculated as a function of viscous compaction by overburden and thermal metamorphism. Snow hydrology is estimated by gravitational drainage, including internal snowpack processes, runoff, refreeze rates, and thermal conductivity. Snow cover fraction is based on a linear function of HS. Thiis model e FSM2 configuration calculates atmospheric stability as function of the Richardson number. Tthe albedo is calculated based on a prognostic function, with increases due to ing (decreasing) depending on snowfall and decreases due to (snow age). It estimates sSnow compaction rate is estimated on the basis of from overburden and thermal metamorphism,. And 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 Snow model validation

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~~The FSM2 model configuration was selected on a trial-and-error basis (not shown here).~~ FSM2 configuration~~, and~~ was validated by in-~~-~~situ snow records of four automatic weather stations (AWSs) that were ~~placed~~ at high elevations ~~areas~~ in ~~of~~ the Pyrenees. Precipitation in mountainous and windy regions ~~zones~~ is usually affected by undercatch (Kochendorfer et al., 2020). Thus, the instrumental ~~Instrumental~~ records of precipitation were ~~are~~ corrected for ~~of~~ undercatch ~~effects~~ by applying an empirical equation validated for ~~in~~ the Pyrenees (Buisan et al., 2019). Precipitation type was classified by ~~based on~~ a threshold method (~~e.g.,~~ Musselman et al., 2017b; Corripio et al., 2017):~~.~~ ~~It was quantified as~~ snow ~~fall~~ when the air temperature was below ~~<~~ 1°C and ~~as~~ rain when the air temperature was above ~~>~~ 1°C, according to previous research in the study area (Corripio et al., 2017). The LW_{inc} heat fluxes of the AWSs (**Table 1**) were estimated ~~following~~ as previously described (Corripio et al., 2017). Due to the wide instrumental data coverage (99.3 % of the total dataset), ~~no~~ gap-filling ~~method~~ was not performed. The HS records were measured each 30 min~~utes~~ using ~~with~~ an ultrasonic snow depth sensor. The meteorological data used in the validation process were ~~is open access,~~ provided and managed by the local meteorological service of Catalonia (https://www.meteo.cat/wpweb/serveis/formularis/peticio-dinformes-i-dades-meteorologiques/peticio-de-dades-meteorologiques/; data requested: 14/01/2021). Quality-checking of t~~T~~he data ~~is quality checked~~ was performed using ~~through~~ an automatic error filtering process in combination with a climatological, spatial, and internal coherency control defined by ~~at~~ the SMC (2011).

Table 1. Characteristics of the four AWSs ~~analyzed in this work~~.

~~Geographical~~ Area	Code	Lat~~itude~~/Lo~~n~~gitude °	Elevation (m)	Atlantic Ocean, Distance (km)	Mediterranean Sea, Distance (km)	Validation ~~temporal~~ period (years)	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 m~~Model accuracy was estimated based on the ~~by the~~ mean absolute error (MAE) and the root mean square error (RMSE), and ~~whereas the~~ model performance was estimated by the coefficient of determination (R^2). The MAE and the RMSE indicate ~~summarise~~ the mean differences of ~~between~~ the modelled and ~~the~~ observed values.

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3.3 Atmospheric forcing data

We forced the FSM2 with the ~~used ing the the~~ reanalysis climate dataset of Vernay et al. (2021), which ~~consists~~consists of, ~~ing in of~~ the modelled values from the SAFRAN meteorological analysis, The FSM2 was run at an hourly resolution for each massif, ~~and~~ each elevation range, and each climate perturbation scenario from ~~or the historical period (~~1980-to –2019~~) and for each climate perturbed scenario~~. The SAFRAN system provides data for ~~by~~ homogeneous meteorological and topographical mountain massifs every 300 m, from 0 to 3600 m (Durand et al., 1999; Vernay et al., 2021). There were three elevation bands: l~~L~~ow (1500 m), middle (1800 m), and high ~~elevation corresponds to 1500, 1800 and (~~2400 m~~, respectively, specific elevation bands~~). Precipitation type was classified using ~~following~~ the same threshold approach used for ~~the~~ model validation. Atmospheric emissivity was derived from the SAFRAN LW_{inc} and temperature. ~~The d~~Data were ~~was~~ forced using ~~with~~ numerical weather prediction models (ERA-40 reanalysis data from 1958 to 2002 and ARPEGE from 2002 to 2020). Meteorological data were ~~as~~ calibrated, homogenized, and improved by use of 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) provided .further technical details of the SAFRAN system. Previous studies used ~~and validated t~~The SAFRAN system ~~has been previously used and validated~~ for the meteorological modelling of ~~many other systems, including~~ 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~~.

3.4 Snow~~Climate~~ sensitivity analysis

~~Climate~~ Snow sensitivity was ~~is~~ analyzed using ~~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~~). In this method, t~~T~~emperature and precipitation were ~~are~~ perturbed for each massif and elevation range based the historical period (1980–2019). Temperature was increased ~~is perturbed~~ from 1 to 4ºC at ~~by~~ 1ºC intervals, assuming an increase of LW_{inc} accordingly (Jennings and Molotch, 2020). Precipitation was changed ~~is perturbed~~ from -–10 % to +10 %, at ~~by~~ 10 % intervals, in accordance with climate

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model~~s~~ uncertainties and the ~~,~~maximum and minimum precipitation projections for the Pyrenees (Amblar-Frances et al., 2020).

3.5 Definitions of ~~Compound~~ compound temperature and precipitation extreme seasons~~ al definition~~

The s~~S~~now season ~~includes~~ was from ~~all days between~~ October 1 to ~~to~~ June 30 (inclusive~~ded~~), and ~~.~~ s~~S~~now ~~season~~ duration was ~~is~~ defined by ~~according~~ the ~~with~~ snow onset and snow ablation dates (Bonsoms, 2021a) and results from the baseline scenario presented in this work. A "~~Compound~~ compound temperature and precipitation extreme season" (season type) was assessed ~~is performed~~ based on each massif~~-~~ and the elevation~~-based~~ historical climate record (1980–2019)~~,~~ using a joint quantile approach (Beniston and Goyette, 2007; Beniston, 2009; López-Moreno et al., 2011a)~~,~~. Season types were ~~are~~ defined according to ~~following~~ López-Moreno et al. (2011a), ~~, compound temperature and precipitation extreme season are defined~~ based on the seasonal 40th percentiles (T40 ~~and P40,~~ for temperature and P40 for precipitation~~, respectively~~) and the seasonal 60th percentiles (T60 and P60~~, for temperature and precipitation, respectively~~). There were ~~Seasons are classified into~~ four types of extreme seasons ~~categories~~based on seasonal temperature (Tseason) and seasonal precipitation (Pseason) data:

Cold and Dry (~~(i)~~ CD): ~~seasons, when the seasonal temperature~~ Tseason ≤ T40 and ~~precipitation~~ Pseason ≤ P40~~(Tseason and Pseason, respectevly) are <= T40 and P40~~;

Cold and Wet (~~(ii)~~ CW): ~~seasons, when~~ Tseason ≤ ~~is <=~~ T40 and Pseason ≥ ~~>=~~ P60;

Warm and ~~(iii) W~~Dry (WD): ~~seasons, when~~ Tseason ~~is~~> T40 and Pseason ≤ ~~is <=~~ P40;~~. Finally, (iv)~~

Warm and Wet (WW): ~~seasons, when~~ Tseason ~~is~~> T60 and Pseason is > P60.

All ~~The~~ remaining seasons were ~~are~~ classified as having average (Avg) ~~compound~~ temperature and precipitation~~ seasons~~. **Figure S1** shows t~~T~~he number of season~~s~~ types by elevation and massifs~~ is shown at Figure S1~~.

3.6 Snow-climatological indicators

Snowpack ~~climate~~ sensitivity was ~~is~~ analyzed using ~~through~~ five key ~~snow~~ indicators~~, including~~: (*i*) ~~the~~ seasonal average HS, (*ii*) ~~the~~ seasonal maximum absolute HS peak (peak HS max), (*iii*) ~~the~~ date of ~~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 snow ablation~~ daily average snow ablation per season ~~(per season (;~~ snow ablation). Snow ablation was ~~is~~ calculated as ~~by~~ the difference between the maximum daily HS recorded on ~~between~~ two consecutive days (Musselman et al., 2017a), and ~~. We retained~~ only ~~the~~ days with decreases of 1 cm or more ~~hen the difference was < -1~~

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~~cm~~were recorded. 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 were ~~are~~ computed according to ~~by~~ massif and elevation range.

4. Results

4.1 Snow model validation

Our s~~S~~now model validation analysis (**Figures 2 and 3**) confirmed~~s~~ that FSM2 accurately reproduced~~s~~ the observed HS values. On average, the FSM2 ~~performance~~ had an ~~reached a~~ R^2 greater than ~~>~~ 0.83 for all stations. In general, the snow model slightly overestimated~~s~~ the maximum HS values. The highest R^2 values were ~~are observed~~ at A4 and A2 (R^2 = 0.85 in both stations), and ~~whereas~~ the lowest ~~values are~~ were ~~observed~~ at A3 and A1 (R^2 = 0.79 and R^2 = 0.82, respectively). The highest accuracy was ~~obtained~~ at A4 (RMSE = 18.5 cm, MAE = 8.9 cm), and ~~whereas~~ the largest errors were ~~are measured~~ at A2 (RMSE = 45.8 cm, MAE = 29.0 cm).

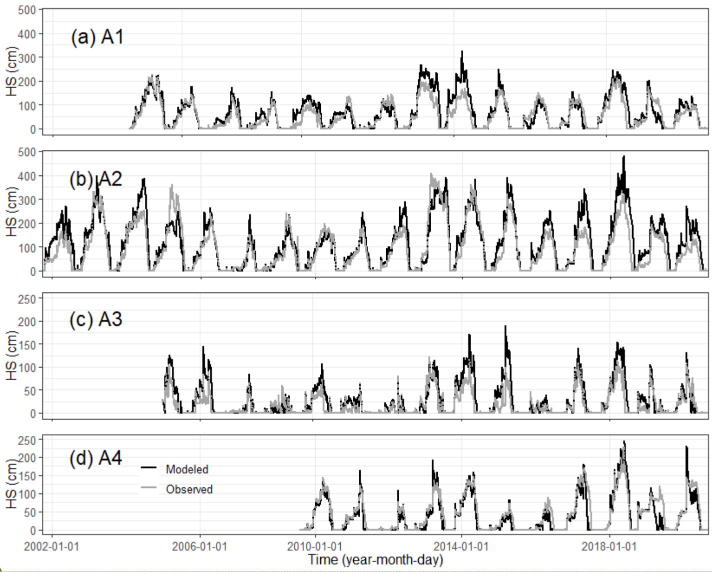

Figure 2. Time series of the observed (gray) and modelled (black) HS values at the four ~~grouped by~~ AWSs.

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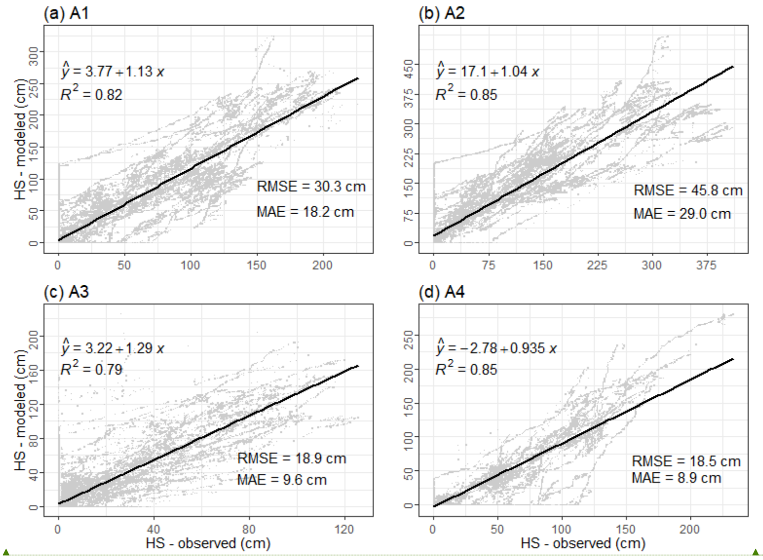

Figure 3. Regression analysis of ~~the~~ observed (x-axis) and simulated (y-axis) HS values.

4.2 ~~Seasonal snowpack cClimate~~Snow sensitivity ~~of seasonal snowpackanalysis~~

We then determined s~~S~~easonal HS profiles for each perturbed climate scenario and compound temperature and precipitation extreme season ~~are shown in~~ (**Figure 4**). The results show ~~re is~~ a non-linear response between seasonal HS loss~~es~~ and temperature increase~~s~~. When the temperature increased ~~progressively warmed~~ at 1ºC intervals, the largest relative seasonal HS decrease~~s~~ from the baseline ~~climate~~ was ~~are found~~ at + 1ºC~~,~~ for ~~for~~ all elevation~~s~~ ~~ranges~~ and all compound temperature and precipitation extreme seasons. High elevation areas had ~~show~~ lower season-to-season snow variability than low elevations for all ~~the~~ season types (**Figure 4**). At low elevations, snow was ~~is~~ significantly greater ~~higher~~ during CW seasons than other seasons~~in comparison with the rest of the cases~~. All the snowpack-perturbed scenarios indicated that ~~point towards~~ snowpack decreased~~s~~ at ~~in~~ low and mid elevations under warming climate scenarios. ~~Depending on the season type, different s~~Snowpack sensitivity depended on the season type ~~ies are observed~~ (**Figures 5 and 6**). At ~~For~~ low elevations ~~ranges~~, the seasonal changes in HS ~~climate sensitivity~~ ranged~~s~~ from -37 % (WW) to -28 % (CD) per 1ºC ~~of temperature~~ increase. For mid-elevation ranges, there were no significant differences ~~are observed between~~ among season types (**Table 2**), and the seasonal HS changes ~~losses~~ ranged~~s~~ from -34 % (WW) to -30 % (CW) per 1ºC increase. Low and mid-elevations had greater ~~show higher~~ snowpack reductions than ~~in~~ high elevations. In the latter, a ~~n increase of +~~10 % increase of precipitation counterbalanced~~s~~ a~~n~~ temperature increase of about 1ºC ~~of temperature~~, and there were no significant differences in

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the seasonal HS ~~are found~~ from the baseline scenario (**Figure S2 and Figure S3**). The m~~M~~aximum seasonal HS ~~climate sensitivity~~ was ~~is observed~~ during WD seasons ~~(~~(27 %/ ~~per~~1 ºC), and ~~whereas~~ the minimum was during ~~is found for~~ CW seasons ~~(~~(−22 %/ ~~per 1~~ ºC).

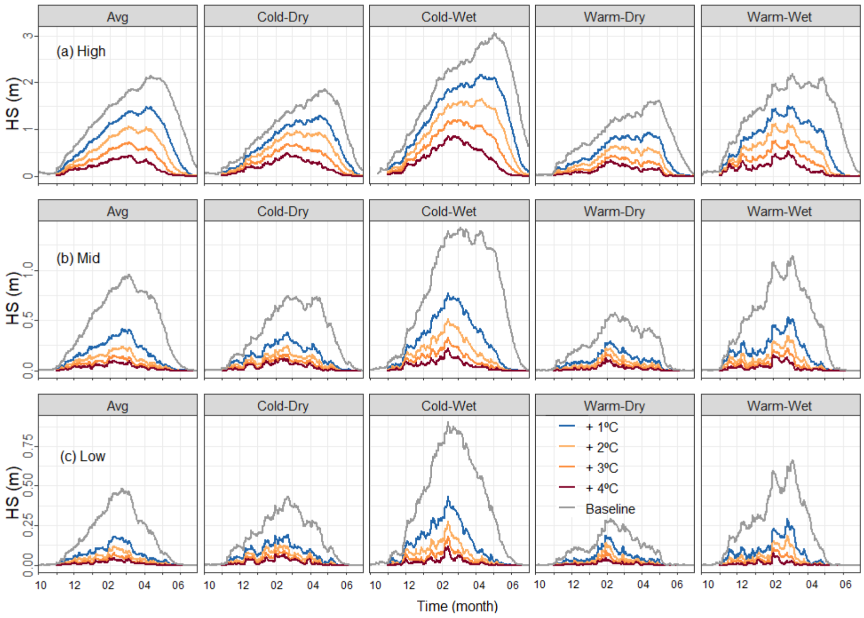

Figure 4. Average daily values for season type, baseline climate and different temperature increases at (a) high (b) mid and (c) low elevation.

~~**Figure 4.** Average seasonal s~~Sensitivity of HS ~~on average and during~~ for the four different ~~each compound temperature and precipitation extreme seasons (columns)~~ (boxes) ~~at~~ and high elevation (a), mid elevation (b), and low elevation (c) for different temperature increases relative to baseline~~elevation (rows).~~

Table 2. Average and seasonal HS and peak HS sensitivity during the four different ~~max sensitivity grouped by~~ compound temperature and precipitation extreme seasons at three ~~and~~ different elevations~~-range~~.

Compound extreme season	**% HS / °C**			**% peak HS max / °C**		
	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

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WW	–37	–34	–26	–24	–24	–16

At ~~For~~ low and mid elevations~~ ranges~~, the peak HS max ~~climate sensitivity~~ was greatest ~~reaches maximum values~~ during WW seasons ~~(~~(−24 %/~~ per 1~~ºC~~, respectively~~) and lowest ~~minimums~~ during the CD and WD seasons ~~(~~(−17 %/~~ per 1~~ºC~~,~~ for both ~~elevation ranges~~). At high elevations, there were no significant differences ~~are observed~~ in the peak HS max ~~climate sensitivity~~ for the different ~~between~~ seasons~~ types~~. The maximum peak HS max ~~max climate sensitivity~~ was during ~~is observed at~~ WD seasons ~~(~~(−16 %/~~ per 1~~ºC) and the minimum was during CD seasons ~~(~~(−14 %/~~ per 1~~ºC).

We also determined ~~Table 3 and Figure 6 show the~~ average seasonal snow duration for each elevation range~~,~~ and season type for different ~~and increase of~~ temperature increases (**Table 3 and Figure 6**). The minimum ~~seasonal~~ snow duration ~~climate sensitivities are observed~~ was during CW seasons (~~, ranging from~~ −13 %/~~1~~ºC at low elevations, −10 %/~~1~~ºC at mid-elevations, ~~−to~~ −5 %/~~1~~ºC ~~per ºC for low, mid and~~ at high elevations~~ ranges, respectively~~). At ~~For~~ low elevations~~ ranges~~, the snow duration was most ~~maximum~~ sensitive ~~seasonal snow duration sensitivities to climate change are observed~~ during WW seasons (−17 %/~~ per 1~~ºC). On the contrary, at mid-elevations and high elevations~~ ranges~~, the ~~maximum seasonal~~ snow duration was most sensitive~~ities are observed~~ during WD seasons (~~, being~~ −13 %/~~1~~ºC at mid-elevations and (−8 %/~~1~~ºC) at ~~mid (~~high elevations)~~) per ºC~~.

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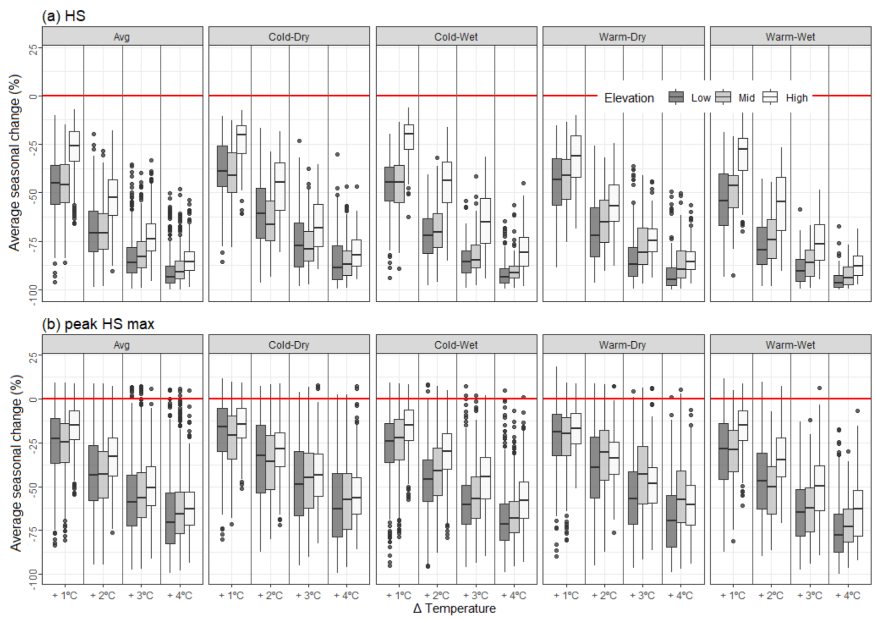

Figure 5. Anomalies of seasonal ~~(a)~~ HS (a) and ~~(b)~~ peak HS max (b) for different temperature increases relative to baseline ~~(horizontal red line)~~ at three different elevations during the four different temperature and precipitation extreme seasons~~for low, mid and high elevation, grouped by increment of temperature and season type. Anomalies were calculated respect the baseline climate scenario~~. The solid black lines within each boxplot are the average. Lower and upper hinges correspond to the 25th and 75th percentiles, respectively. The whisker is a horizontal line at 1.5 interquartile range of the upper quartile and lower quartile, respectively. Dots represent the outliers. Data is grouped by season, season type, increment of temperature, precipitation variation, elevation, and massif.

~~**Table 3.** Effect of temperature increases and elevation on Average seasonal snow duration values by degree of warming, during grouped by compound the four different compound temperature and precipitation extreme seasons temperature and elevation range.~~

~~**Compound temperature and precipitation eExtreme 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~~

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~~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~~

Overall, the peak HS date occurred~~s~~ earlier due to warming (**Figure 7~~S4~~**), independently of precipitation shifts. During WD ~~(CD)~~ seasons, the peak HS date per ~~1~~°C was ~~will take place~~ earlier by 9 days~~(15)~~ at low elevations, 3 days at mid-elevations, ~~(8)~~ and 17 ~~(1)~~ days at high elevations; during CD seasons, the peak HS date per ~~1~~°C was earlier by 15 days at low elevations, 8 days at mid-elevations, and 1 day at high elevations~~earlier in the season per °C for low, mid and high elevations, respectively~~. In high elevation areas, if the temperature increase~~s~~ was no more than ~~do not exceed~~ about ~~~~~1ºC above ~~with respect to the~~ baseline ~~scenario~~, there was little change in the peak HS date ~~is not expected to drastically change~~ (**Figure ~~S4~~7**), except during dry seasons. The maximum peak HS date ~~sensitivity~~ was ~~is found~~ during dry seasons. ~~-~~ On the contrary, the peak HS date did~~oes~~ not change ~~show~~ significantly ~~changes~~ due to warming during WW seasons (**Table 4**), and because ~~given that~~ the snowpack would be scarce at those times, and there were ~~and~~ no defined ~~maximum~~ peaks ~~would occur~~ (**Figure 4**).

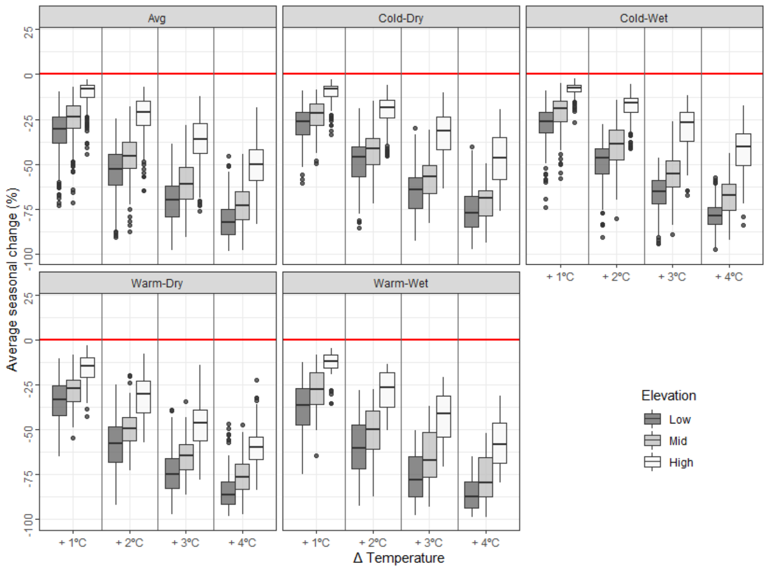

Figure 6. Average and seasonal decrease of snow duration at three different elevations, ~~increaments~~increments of temperature, and during the four different temperature and precipitation

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extreme seasons. The solid black lines within each boxplot are the average. Lower and upper hinges correspond to the 25th and 75th percentiles, respectively. The whisker is a horizontal line at 1.5 interquartile range of the upper quartile and lower quartile, respectively. Dots represent the outliers. Data is grouped by season, season type, increment of temperature, precipitation variation, elevation, and massif.

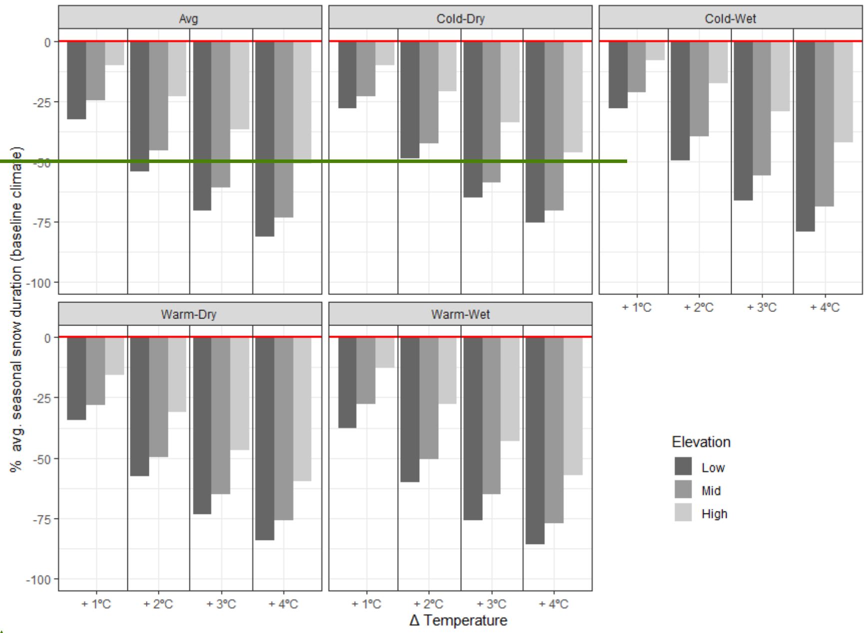

Figure 6. Average and seasonal decrease of the seasonal snow duration for at three different (a) low, (b) mid and (c) high elevations ranges, increaments of temperature and during the four different temperature and precipitation extreme seasonsgrouped by increments of temperature (columns) and elevation ranges (colors).

We determined ~~The~~ average daily snow ablation ~~per season grouped~~ in response to different ~~by~~ temperature increases~~ments,~~ at different elevations and ~~compound~~ during different extreme seasons ~~type is shown in~~ (**Figure 8**). The results ~~data~~ shown there were moderate~~no~~ differences in the average daily snow ablation in a warmer climate. At ~~For~~ low elevations, the snow ablation in all four extreme ~~between~~ seasons ~~types~~ was ~~is the same,~~ 12 %/~~1 per~~ °C ~~sensitivity~~ (**Table 4**). At ~~For~~ mid-elevations and high elevations, the maximum snow ablation ~~sensitivities~~ was ~~are found~~ during dry seasons;~~.~~ WD seasons had a snow ablation ~~sensitivity is~~ of 13 %/°C at mid-elevations and ~~and~~ 10 %/~~1 per~~ °C ~~for mid and~~ at high elevations~~range, respectively~~. On the other hand, the minimum values for mid-~~(high)~~ elevations were ~~are found~~ during WW ~~(CW)~~ seasons,

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when the snow ablation ~~sensitivity~~ was ~~is~~ 8 %/1 ~~(5 %) per~~ °C; the minimum values at high elevations were during CW seasons, when snow ablation was 5%/°C.

Figure 7. ~~Average~~ Difference (days) from baseline Peak HS d~~ays~~ate at three different elevations and during the four different temperature (colors) and precipitation shifts (columns) for each season (boxes). Error bars indicate the maximum and minimum values (mean by massifs and elevation).

Table 4. ~~Changes Sensitivity of seasonal~~ Snow duration, snow ablation, and Peak HS date sensitivity during ~~and snow ablation,~~ the four different ~~grouped by~~ compound temperature and precipitation extreme ~~compound temperature and precipitation extreme~~ seasons ~~and elevation range~~.

~~Compound~~ Extreme season	Snow duration (%/1 °C)			Snow ablation (%/1 °C)			Peak HS date (days/1 °C)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
Avg.	-15	-12	-6	12	11	7	-2	1	-4

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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

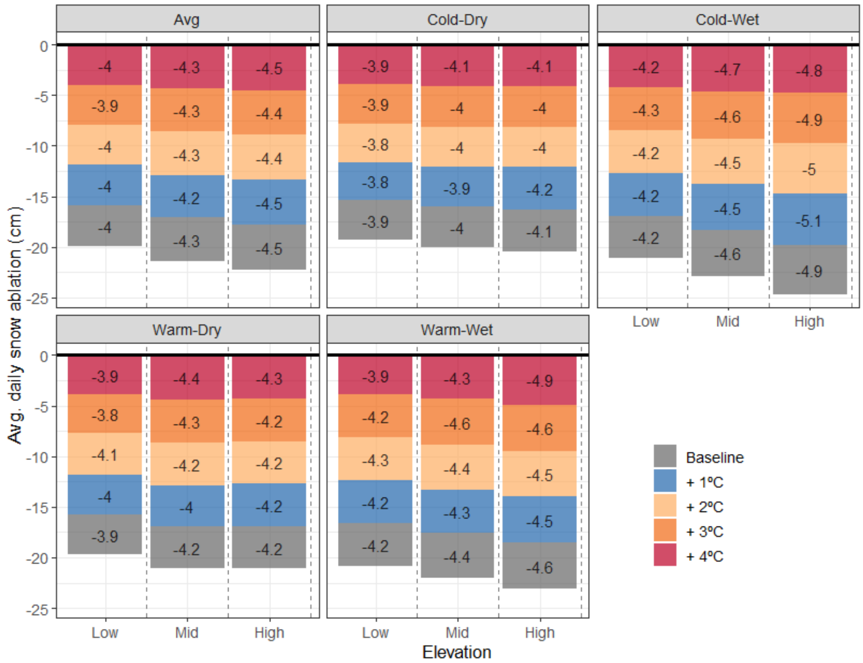

Figure 8. Average daily snow ablation ~~(y axis)~~ at three different ~~by~~ elevations ~~(x axis),~~ during four different compound temperature and precipitation extreme seasons, ~~(boxes)~~ for different temperature increases above baseline (gray) ~~and climate scenario~~.

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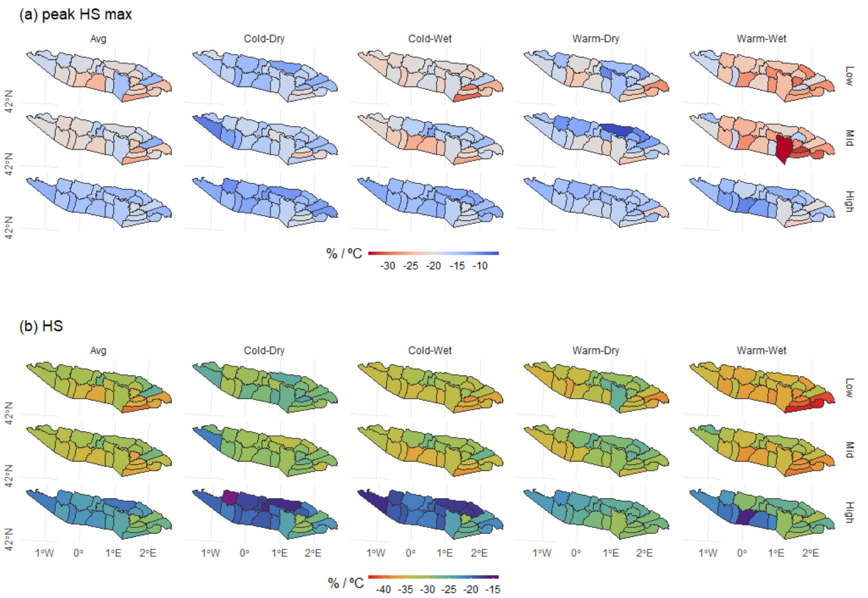

Figure 9. Geographical distribution of seasonal (a) peak HS ~~(a)~~ and (b) HS sensitivity ~~(b)~~ during the four different compound temperature and precipitation extreme seasons.

The ~~HS~~ sensitivity of HS to climate change also had ~~shows~~ remarkable spatial patterns~~contrasts~~. The s~~S~~ensitivity was greater ~~increases moving towards the~~ in the eastern massifs, independently of the elevation range and season type (**Figures 9 and 10**). The greatest ~~largest~~ sensitivities of HS ~~differences are observed~~ were at low elevations. Here, the seasonal HS ~~sensitivity~~ ranged~~s~~ from −~~-~~20%/~~1~~°C during ~~(~~CD~~)~~ in the central area~~,~~ to ~~up to —~~−40%/~~1~~°C during ~~(~~WW~~) per °C~~ in the southern slopes of the eastern Pyrenees. Similarly, the maximum sensitivity of peak HS max ~~sensitivities~~ was at ~~are found in~~ mid~~-e~~-elevations in the southern slopes of the eastern Pyrenees, and the change was less than ~~of the latest area (>~~ −35%/~~1°~~ ~~per~~ °C (~~;~~ **Figure 9**). There was ~~is~~ a general tendency for ~~toward~~ higher sensitivity~~ies to climate change~~ in the southern slopes than in ~~in comparison to~~ the northern~~-~~ slopes~~ones.~~. ~~The lowest~~ S~~s~~now duration ~~sensitivity is observed~~ in the northern slopes and at high elevations had the lowest sensitivity, especially during CD and CW seasons ~~(~~(−5~~-~~%/~~1 per~~ °C). The sensitivity of s~~S~~now duration ~~sensitivity~~ increase~~d~~s during WW seasons, and ~~; when~~ the maximum changes ~~sensitivities~~ were ~~are detected~~ at the lowest elevations of the southern-eastern Pyrenees ~~(~~(−35~~-~~%/~~1 per~~ °C; **Figure 10**).

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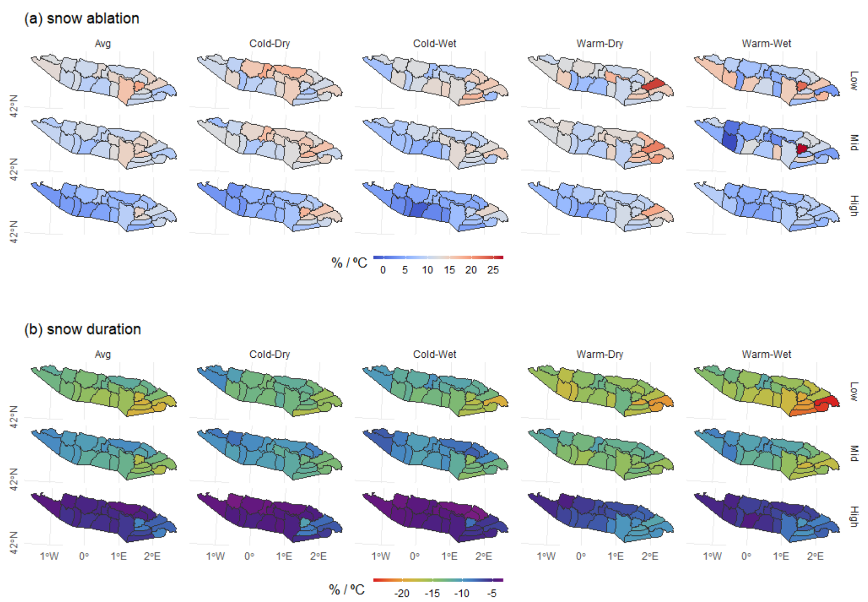

Figure 10. Geographical distribution of seasonal (a) snow ablation ~~(a)~~ and (b) snow duration ~~(b)~~sensitivity during the four different compound temperature and precipitation extreme seasons.

5. Discussion

The spatial and temporal patterns of snow in the Pyrenees are highly variable, and ~~international~~ climate data from many sources ~~reports~~ indicate that extreme events will likely increase during future ~~over the next~~ decades (~~e.g.,~~ Meng et al., 2022). Therefore, ~~In this context,~~ we analyzed ~~a better understanding~~ factors that affect the ~~of the present-day controls of the~~ snowpack sensitivity to gain insight into ~~is crucial to anticipate~~ how ~~the~~ future climate changes may ~~will~~ affect the snow regime.

5.1 Spatial and elevation factors controlling ~~the~~ snow sensitivity to climate change~~.~~

The ~~snow~~ sensitivity of snow to different ~~climate change~~ spatial patterns of climate change that we ~~found in this~~ identified here ~~work~~ (**Figures 9 and 10**) are consistent with the snow accumulation and ablation patterns previously reported in this region ~~e range~~ (~~e.g.,~~ Lopez-

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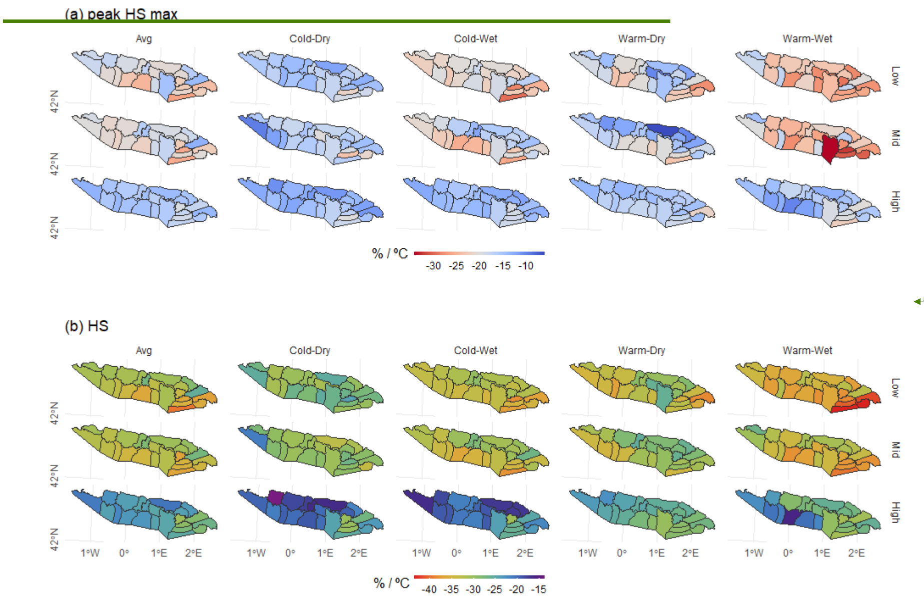
Moreno, 2005; Navarro-Serrano et al., 2018; Alonso-González et al., 2020a; Bonsoms et al., 2021a). The Atlantic climate has less of an influence ~~influence is reduced moving~~ in ~~to~~ the eastern massifs~~of the range~~; in this area~~e latter area~~, *in-situ* observations indicated there was ~~record~~ about ~~lmost~~ half ~~(<= 40 %)~~ of the seasonal snow accumulation amounts as in ~~than~~ northern and western areas at the ~~ones for the~~ same elevation (>2000 m; Bonsoms et al., 2021a). The snow in the southern slopes of the eastern Pyrenees is ~~exhibit higher snow~~ more sensitiv~~ite~~e ~~ies~~ to climate change because ~~since~~ th~~e~~ose massifs are exposed to higher turbulence~~t~~ and radiative heat fluxes (Bonsoms et al., 2022). The r~~R~~esults thus show an ~~logical~~ upward~~s~~ displacement of the snow line due to warming. Previous studies described t~~T~~he ~~elevation~~ sensitivity ~~dependent pattern~~ of the snow pattern to elevation at ~~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), and ~~as well as in~~ other ranges such as the Cascades (Jefferson, 2011; Sproles et al., 2013), the Alps (Marty et al., 2017), and ~~or the~~ western USA (Pierce et al., 2013; Musselman et al., 2017b). In these regions, the ~~where snow~~ models suggest larger ~~higher (lower)~~ snowpack reductions due to warming at ~~in~~ subalpine sites than at ~~(~~alpine ~~belts)~~ sites (Jennings and Molotch, 2020; Mote et al., 2018). Low elevations are more ~~present a higher snow~~ sensitive simply ~~ity~~ because ~~than high lands since~~ the temperatures there are ~~is~~ closer to ~~the~~ isothermal conditions (Brown and Mote, 2009; Lopez-Moreno et al., 2017).



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~~**Figure 8.** Geographical distribution of sSeasonal (b) peak HS (a) and (b) HS sensitivity (b) during average and during the four different compound temperature and precipitation extreme seasons.~~

5.2 Snow sensitivity to climate change and ~~its~~ relationship with historical and future snow trends

5.2.1 Snow accumulation phase

The s~~S~~now losses due ~~by~~ warming that we described here ~~reported in this work~~ are mainly associated with increases in the rain/snowfall ratio (Figure S4), changes in the snow onset and offset dates (Figure 4), and increases in the energy available for snow ablation during the later ~~st~~ months of the snow season, as it was previously reported by literature (~~e.g.,~~ e.g., Pomeroy et al., 2015; Lynn et al., 2020; Jennings and Molotch, 2020). At high elevations ~~areas~~, a ~~n upward~~ trend of increasing precipitation (+~~-~~10 ~~-~~%) could counterbalance temperature increases (<~~-~~1ºC; **Figure S2**), ~~which is~~ consistent with the results previously reported for ~~found at~~ specific sites of the central Pyrenees (Izas, 2000m; López-Moreno et al., 2008). Rasouli et al. (2014) also found that a ~~n increase of~~ 20 ~~-~~% increase of precipitation could compensate for 2ºC increase of temperature ~~of warming~~ in ~~the~~ subarctic Canada. A c~~C~~limate sensitivity analysis in the western Cascades (western USA)~~,~~ found ~~reveals~~ that increases of precipitation due to warming modulated ~~erates (~ 5 % per °C)~~ the snowpack accumulation losses by about 5%/1°C (Minder, 2010). These results are consistent with recent data that examined snow ~~trends at~~ above ~~>~~ 1000 m in the Pyrenees, which found that an ~~where~~ increase~~s~~ in the frequency of west circulation weather types since the 1980s increased the ~~triggered positive~~ HS (Serrano-Notivoli et al., 2018; López-Moreno et al., 2020), snow accumulation (Bonsoms et al., 2021a), and changes in winter snow days ~~trends~~ (Buisan et al., 2016). There are s~~S~~imilar trends ~~have been found~~ in the Alps, with ~~where during the last decades~~ an increase of extreme (exceeding the 100-year return level) snowfall (~~>~~ above 3000 m during recent decades (~~;~~ Roux et al., 2021) ~~as well as~~ and extreme winter precipitation ~~exceeding the 100-year return level s has been detected~~ (Rajczak and Schär, 2017).

5.2.2 Snow ablation phase

Our ~~The~~ comparison of ~~between~~ low and high elevations indicated ~~reveals~~ slightly faster ~~average daily~~ snow ablation at high elevations ~~in the latter elevation range~~ (**Figure 8**). This ~~e~~ higher rate of ~~average daily~~ snow ablation per season at ~~in~~ high elevations (which have deeper snowpacks) are probably ~~explained~~ because the snow there lasts until late spring, when ~~there are higher rates of~~ more energy is available for snow ablation (Bonsoms et al., 2022). Climate warming leads to

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a cascade of physical changes in the SEB that increase~~ing~~ snow ablation ~~due to the~~ near the 0ºC isotherm. However, on overall, the average daily snow ablation only ~~shows small~~ increased~~s~~ slightly due to warming. Our results ~~Data~~ suggest that a ~~increases of~~ temperature increase does not imply significant changes in the daily snow ablation rate per season, because ~~since~~ warming decreases the ~~snowpack~~ magnitude of the snowpack (seasonal HS and peak HS max) and triggers an earlier onset of snowmelt ~~onsets~~ (Wu et al., 2018). The earlier peak HS date at low and mid elevations (**Table 4 and ~~;~~ Figure 7~~8~~**) implies lower rates of net shortwave radiation, because ~~since~~ snow melting starts earlier ~~(i.e. in winter)~~ in ~~a~~ warmer climates (Pomeroy et al., 2015), coinciding with the shorter days and lower solar zenith angle~~s~~ (Lundquist et al., 2013; Sanmiguel-Vallelado et al., 2022). Our r~~R~~esults ~~are in agreement~~agree with the slow snow melt rates reported ~~detected~~ in the Northern Hemisphere from ~~(~~1980 to ~~–~~2017 ~~(period;~~ Wu et al., 2018). The results ~~Same conclusions~~ of previous studies were similar ~~are found~~ for ~~the~~ subarctic Canada (Rasouli et al., 2014) and ~~or~~ western USA snowpacks (Musselman et al., 2017b), but ~~contrast with faster melt rates found in~~ Arctic sites had faster melt rates (Krogh and Pomeroy, 2019).

5.2.3 Snow sensitivity and snowpack projections

Our results ~~Data~~ suggest that warming had a non-linear effect on snowpack reduction ~~due to warming~~. Our ~~The~~ largest snow losses ~~are found~~ were for seasonal HS when the temperature ~~under an~~ increased by ~~of~~ 1ºC above ~~respect the~~ baseline ~~scenario~~. At low and mid elevations, the average seasonal HS ~~would~~ decrease was more than ~~on average >~~ 40 % for all season types, and the ~~with~~ maximum ~~climate~~ sensitivity was ~~ies found~~ during WW seasons. Previous research in the Pyrenees and ~~in~~ other mid-latitude mountain ranges~~,~~ reported ~~have found~~ similar results~~climate sensitivities~~. A study i~~I~~n the central Pyrenees~~,~~ reported the peak ~~of~~ SWE ~~climate sensitivity~~ was ~~is~~ 29 %/~~ per 1~~ºC, whereas snow season duration decrease~~d~~s by about ~~~~~20 to –30 days per ~~(~~at about ~~~~~2000 m (~~;~~ López-Moreno et al., 2013). The average peak HS max ~~climate sensitivity~~ was ~~detected~~ at high elevations in the Pyrenees ~~(~~(–16 %/~~ per 1~~ºC; **Figure 6 and Table 2**), ~~is~~ similar to ~~than~~ the average peak SWE ~~climate~~ sensitivity (–15%/~~1~~ºC) reported ~~found~~ in the Iberian Peninsula mountains at 2500 m (~~–15 % per ºC;~~ Alonso-González et al., 2020a). These r~~R~~esults are also consistent with climate projections for this ~~found in the~~ mountain range. In particular, for ~~; under~~ a ~~n increase of temperature (>~~2 ºC or more increase of temperature, ~~),~~ the snow season declined by ~~is reduced~~ 38 % at ~~in~~ the lowest ski resorts (~1500 m) ~~ski resorts located~~ in the southern slopes of the eastern Pyrenees (Pons et al., 2015). However, high emission climate scenarios projected a~~n~~ 2% or more increase in the ~~of the~~ frequency and intensity of high snowfall at high elevations ~~in the highlands~~ (~~+ 20 %;~~ López-Moreno et al., 2011b). ~~According to c~~Climate projections for the mid-late ~~end~~ 21st century~~,~~ indicated that ~~climate~~ sensitivity in the easternmost areas could ~~be~~ decline ~~reduced~~ during the winter~~,~~ because of ~~since~~ a~~n~~ ~~upward~~ trend for ~~of~~ an

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increase of about 10% in precipitation is expected in this area (~ 10 %; Amblar-Francés et al., 2020). Our The projected changes in the Pyrenean snowpack dynamics are similar to the expected snow losses in in near other mountain ranges. For example, a study of In the Atlas Mountains of northern Africa, concluded that snowpack decreases were are accentuated in the greater in the lowlands, and climate change projections predicted anticipate seasonal SWE declines of 60 % (80 %) under the RCP4.5 scenario and 80% under the (RCP8.5) scenarios for the entire range (Tuel et al., 2022). A study iIn the Washington Cascades ((western USA)), found that snowpack decline climate sensitivity was is 19 to -23 % per 1ºC (Minder, 2010), which is similar to with the values found in the is present study at work for high elevations ranges. A study of In the French Alps (Chartreuse, 1500 m), found that seasonal HS decreases on in the order of 25 % (32 %) for a 1.5 ºC increase and 32% for a (2ºC increase) of global temperature rise above the pre-industrial years (Verfaille et al., 2018). A study For of the Swiss Alps, reported a snowpack decrease of about climate sensitivity is ~ 15 %/ per ºC (Beniston, 2003);. iIn the same region, latter range,another study predicted the seasonal HS will is expected to decrease by more than > 70 % in the massifs placed at < below 1000 m in for all future climate projections (Marty et al., 2017). The largest snow reductions will likely are expected to occur during in the periods between shoulders of the seasons (Steger et al., 2013; Marty et al., 2017). Nevertheless, at high elevations, snow climate projections found revealed no significant trend for maximum HS during for the mid-late end 21st century above (> 2500 m in the , eastern Alps (; Willibald et al., 2021), suggesting being that internal climate variability is a the major source of uncertainty of SWE projections at in high elevations (Schirmer et al., 2021).

5.3 The iInfluence of compound temperature and precipitation extreme seasons

We found that the mMaximum sensitivities of seasonal HS and peak HS max were are detected during WW (WD) seasons for at low and mid-elevations and during WD seasons at (high) elevations. Brown and Mote (2008) analyzed the snow climate sensitivity of snow to climate changes in of the Northern Hemisphere, and found inding maximal um SWE sensitivities in mid-latitudinal maritime winter climate areas, and minimal ums SWE sensitivities in dry and continental zones, which is consistent with our results. Also, López-Moreno et al. (2017) also found detected greater decreases of higher SWE decreases in wet and temperate Mediterranean ranges than in at drier regionsones. Furthermore, in northern North American Cordillera, Rasouli et al. (2022) studied the northern North American Cordillera and found higher snowpack sensitivities in wet basins than in comparison with dry ier basinsones. Our The maximum snow ablation and peak HS date occurred climate sensitivities are observed during dry seasons, which is in accordance with Musselman et al. (2017b), who found a detected higher snowmelt rate

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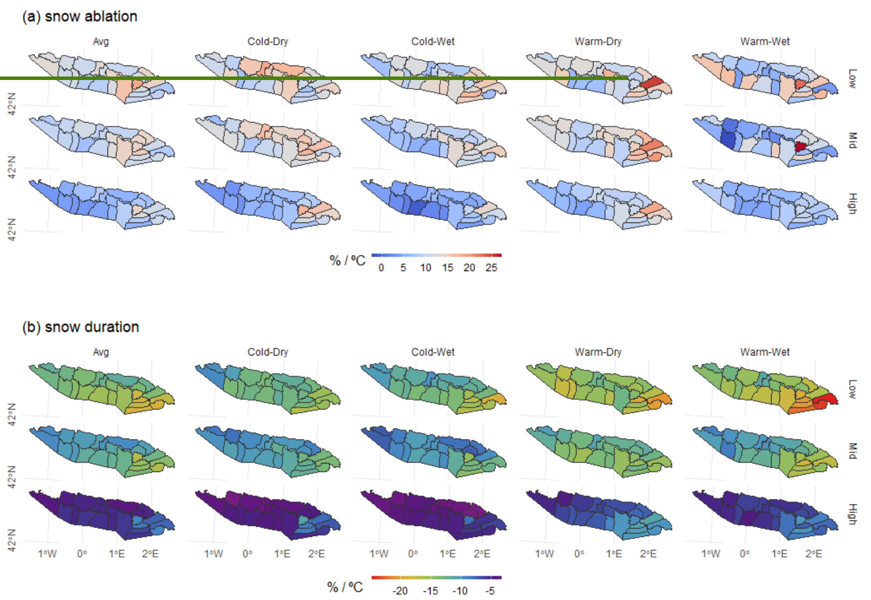
~~climate sensitivities~~ during dry years in the ~~for~~ western USA. Low and mid~~-~~elevations are highly sensitive to WW seasons because ~~since~~ wet conditions ~~favour~~favors decreases in the seasonal HS due to ~~through the~~ advection from ~~of~~ sensible heat flux~~es~~. The t~~T~~emperature in the Pyrenees is still cold enough to ~~for~~ allow ~~ing~~ snowfall at high elevations ~~snowfall~~ during WW seasons, and ~~and for this reason~~ we found maximal ~~um climate~~ sensitivities ~~es are observed~~ during WD seasons. Reductions of ~~Alpine zones~~ snowfall in alpine regions ~~reductions~~ can be ~~further~~ compensated in a warmer scenario, because ~~given that~~ warm and wet snow is less susceptible to blowing wind transport and losses from ~~snow~~ sublimation ~~losses~~ (Pomeroy and Li, 2000; Pomeroy et al., 2015). During spring, snow runoff could be also greater ~~amplified~~ in wet climates due to rain-on-snow events (Corripio et al., 2017), coinciding with the availability of more ~~higher rates of~~ energy ~~available~~ for snow ablation.



~~**Figure 9.** Geographical distribution of s~~Seasonal (a) snow ablation (a) and (b) snow duration (b) climate sensitivity during the four different compound temperature and precipitation average and compound temperature and precipitation extreme seasons.

5.4 Environmental and socioeconomic implications

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Our ~~The~~ results indicated there will be ~~point towards~~ an ~~extension~~ increase of ~~the period of~~ snow ablation days ~~through the season~~, and imply ~~ing~~ a ~~the~~ disappearance of the typical sequence of snow accumulation seasons and snow ablation seasons. Climate warming triggers the simultaneous occurrence of several periods of snow accumulation and ablation, snow droughts during the winter, and ~~as well as~~ ephemeral snowpacks between ~~in the shoulders of the~~ seasons. These expected ~~snow~~ decreases in snow will likely have ~~have~~ significant impacts on the ecosystem. During ~~In~~ spring, a snow cover cools the soil ~~acts as a soil cooling factor~~ (Luetschg et al., 2008), delays the ~~freeze~~ initiation of freezing (Oliva et al., 2014), functions as a thick active layer ~~thickness~~ (Hrbáček et al., 2016)~~-~~, and protects alpine rocks from exposure ~~ition~~ to solar radiation and high air temperatures (Magnin et al., 2017). Due to warming temperatures, the remaining glaciers in the Pyrenees ~~range~~ are shrinking~~,~~ and ~~they~~ are expected to disappear before the 2050s (Vidaller et al., 2021). The shallower snowpack that we identified ~~pointed out~~ in this work will increase~~s~~ the ~~glacier~~ vulnerability of glaciers, because ~~since~~ snow has a higher albedo than ~~the~~ dark ice and debris-covered glaciers and functions ~~acts~~ as a protective layer for ~~of the~~ glaciers (~~e.g.,~~ Fujita and Sakai, 2014).

The earlier onset of snowmelt ~~onset~~ suggested by ~~in~~ our results ~~this work~~, which is greater ~~accentuated~~ at low and mid~~-~~-elevations during WD seasons, is ~~goes~~ in line with previous global studies that reported earlier ~~y~~ streamflow ~~'s~~ due to earlier runoff d~~r~~ates ~~found in global studies~~ (Adam et al., 2009; Stewart, 2009), and with a study of changes in ~~the observed trends in~~ the Iberian Peninsula River flows (Morán-Tejeda et al., 2014). Overall, our results are consistent with the slight decrease of the river peak flows ~~found~~ that have occurred in the southern slopes of the Pyrenees since the 1980s (Sanmiguel-Vallelado et al., 2017). The significant reductions of seasonal HS that we identified ~~pointed out in this article~~, which are driven by increases in the rainfall ratio, suggest that snowmelt-dominated stream~~s~~ flows will ~~are~~ likely to shift to rainfall dominated regimes. Although ~~Whereas~~ high elevation meltwater might increase~~,~~ and contribute ~~ing~~ to earlier groundwater recharging ~~es~~ (~~e.g.,~~ Evans et al., 2018), the increased ~~upward~~ evapotranspiration ~~trends~~ in the lowlands (Bonsoms et al., 2022) could counter this effect, so there is ~~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 has an ~~ve related~~ impact~~s~~ on ~~in~~ the hydrological management strategies. Winter snow accumulation ~~has a relevant~~ affects ~~impact on~~ hydrological availability during the months when water and hydroelectric demands are higher. This is because reservoirs ~~operating strategies consist of~~ store water ~~storage~~ during periods of peak flows (winter and spring ~~months~~), and release ~~subsequent~~ water ~~release~~ during the driest season ~~of the year~~ in the lowlands (summer) (Morán-Tejeda et al., 2014). Recurrent snow~~-~~-scarce seasons may intensify these hydrological impacts

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~~named~~ and lead to competition for ~~the~~ water resources among different ~~competition between the~~ ecological and socioeconomic~~al~~ systems. The economic viability ~~reliability~~ of mountain ski-resorts in the Pyrenees ~~range is~~ depends ~~ent~~ on a regular deep ~~enough~~ snow cover (Gilaberte-Burdalo et al., 2014; Pons et al., 2015), but this ~~which has been shown to be~~ is highly variable, especially at low and mid-~~-~~elevations. The expected increase in snow-~~-~~scarce seasons that we identified here ~~pointed out in this work~~ is consistent with climate projections for this regione ~~range~~, which suggest that no Pyrenean ski-resorts will be viable ~~reliable~~ under ~~high climate projections (~~RCP 8.5 scenario ~~)~~ by ~~for~~ the end of the 21st century (~~2080 – 2100;~~ Spandre et al., 2019).

5.5 Limitations and uncertainties

The meteorological input data that we used to model snow were estimated for flat slopes and the regionalization system we used was based on the SAFRAN system. According to this system, a mountain range is divided into massifs with homogeneous topography. The SAFRAN system has negative biases in shortwave radiation, a temperature precision of about 1 K, and biases in the accumulated monthly precipitation of about 20 kg/m^2 (Vernay et al., 2021). The snow model used in this work (FSM2) is a physics-based model of intermediate complexity, and the estimates of snow densification are simpler than those from more complex models of snowpack; however, a more complex model does not necessarily provide better performance (Magnusson et al., 2015). Biases in the SAFRAN system and biases related to the FSM2 were minimal because we quantified relative changes between a modeled snow scenario (climate baseline) and several perturbed scenarios. Finally, our estimates of snow sensitivity were based on the delta-approach, which considers changes in temperature and precipitation based on climate projections for the Pyrenees (Amblar-Francés et al., 2020), but assumes that the snow patterns of the reference climate period will be constant over time.

6 Conclusions

Our study ~~This work presents an~~ assessed ~~ment of~~ the impact of climate change ~~impact~~ on the Pyrenean snowpack during seasons with extreme compound temperature and precipitation ~~extreme seasons, by~~ using a physical-based snow model that was forced by reanalysis data. We determined t~~T~~he ~~climate sensitivity of the snowpack~~snow sensitivity ~~was analyzed through~~ using five key indicators of snow accumulation and snow ablation ~~indicators~~. Our results indicated that elevation affected the snow sensitivity ~~Climate sensitivity of the snowpack follows an elevation pattern~~. In particular, s~~S~~nowpack losses were greatest ~~are accentuated~~ during WW seasons at (low

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and mid--eelevations) and were greatest during WD seasons at (high elevations) seasons. The lowest snow climate sensitivity was at observed in the high elevationsed zones of the western and northern Pyrenees, and sensitivity increased at ing towards the lower elevations and in st stretches of the eastern and southern slopes. An increase of 1º-C at in low and mid elevation regions led to 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 middle of core months of the winter. season. In this region, During the latter, an 10% increase of 10 % of precipitation, –as suggested by many climate projections over the eastern regions sectors of thise range–, could compensate for small temperature increases on the order of about (~1ºC warming). The impact of climate warming could be different depends on ing on the combination of pound temperature and precipitation during extreme seasons.. Our analysis of Regarding seasonal HS, indicated the highest greatest declines (lowest) reductions were during are observed on WW seasons and the smallest declines were during (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. Our analysis of For seasonal snow duration, indicated the the highest (lowest) greatest declines were reductions are found during WD seasons and the smallest declines were during (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 had show slightly greater larger climate sensitivities during dry seasons, in that . During the latter, snow ablation increasedds by about + 10-% and the peak HS date occurreds about ~10 days earlier per ºC, at for all elevations. Our findings thus This work provides evidence of the high climate sensitivity of that the Pyrenean snowpack is highly sensitive to climate, and– our findings suggest that the snowpacks of other mid-latitude mountain ranges may also show similar sensitivities.similar snow sensitivities in other mid-latitude mountain ranges.

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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~~editing. JB, JILM and EAG read and approved the final manuscript.

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