Rain on snow responses to climate warming in the Pyrenees

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Introduction

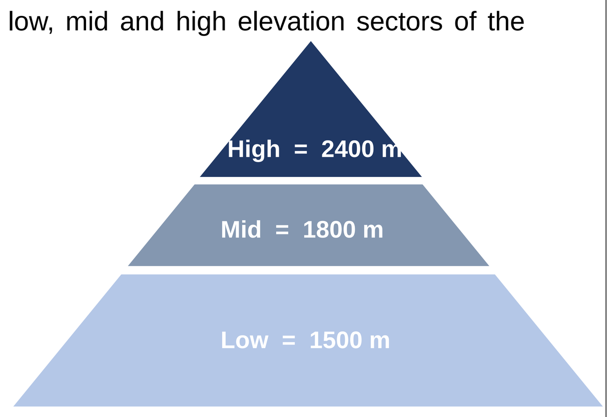
A warmer atmosphere is expected to decrease the snowfall ratio, leading to rain on snow (ROS) events, increasing the snow runoff and triggering natural hazards, such as flash flood events.

ROS is a complex phenomena, since a warmer atmosphere reduces also the snow covered season and therefore the ROS occurrence. Previous studies has shown different ROS sensitivities due to warming, depending on the elevation and the month of the season (McCabe et al 2007, Beniston and Stoffel, 2016; Morán-Tejeda et al 2016; López-Moreno et al., 2021). However, in the Pyrenees, only Corripio and López-Moreno (2017) analyzed the impact of ROS in the Surface Energy Balance for a single ROS event.

In this work we aim to analyzed the ROS sensitivity due to climate change in the Pyrenees.
ROS sensitivity to climate warming is analyzed for low, mid and high elevation sectors of the mountain range.

ROS sensitivity is analyzed through three variables:

1. ROS Frequency
2. Rainfall intensity during ROS
3. Snow ablation during ROS



Atmospheric data

Système d'Analyse Fournissant des Renseignements Adaptés à la Nivologie (SAFRAN).

Flat slopes at low, mid and high elevation ranges and Pyrenean massifs (Figure 1) at hourly resolution (Vernay et al., 2021)

Snow model

Physical-based and mass balance snow model: Flexible Snow Model (FSM2; Essery, 2015).

FSM2 resolves the SEB simulating the state of the snowpack.

FSM2 configuration includes , runoff , internal snow processes, refreeze and thermal conductivity, quantified as function of the snow density. Atmospheric stability is simulated as function of the Richardson number.

ROS detection and climate sensitivity

ROS detection : daily rainfall > 10 mm and snow depth >= 0.1 (López-Moreno et al., 2021)

Climate sensitivity (1980 – 2019 baseline climate) analyzed through a delta-change methodology:

Precipitation variation from -10 to 10 % and increments of temperature from +1 to + 4ºC, according to climate change projections (Amblar-Francés et al., 2020).

Geographical setting

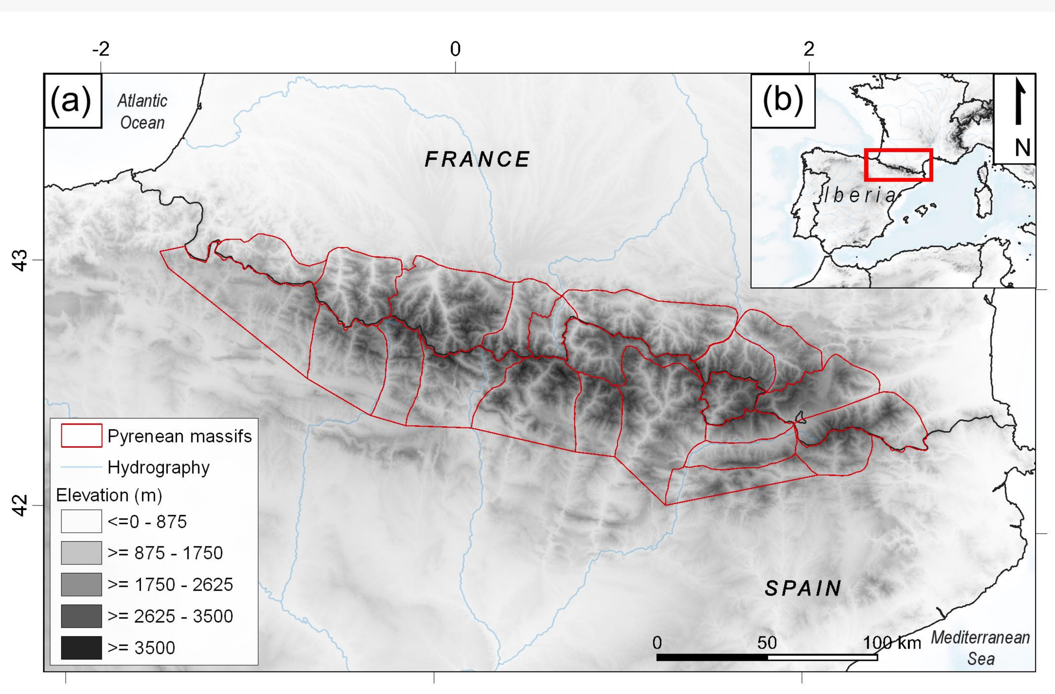


Figure 1. Geographical area analyzed in this work.

Location

The Pyrenees is located in the South of Europe (42ºN-43ºN to 2ºW-3ºE), between the Atlantic Ocean (West) and the Mediterranean Sea (East).

Elevation increases towards the central area, where the highest peak is found (Aneto, 3. 404 m asl).

Climatology

Transition belt between continental and subtropical climate.

Precipitation

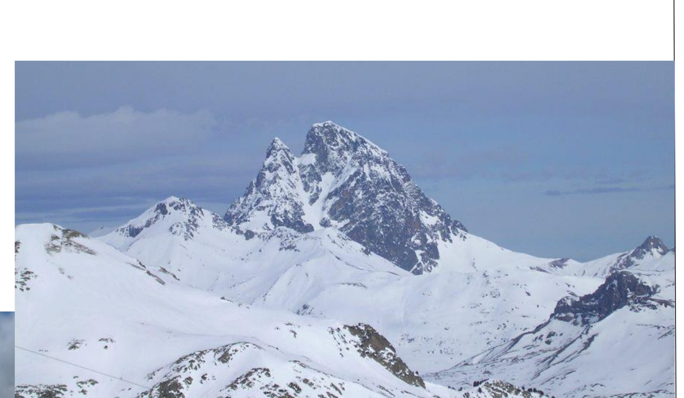
High spatial variability, ~ 1000 mm/year. Maximum (~ 2000 mm/year) is found in the central mountain summits. Increases(decreases) from West (North) to East (South)

Temperature

Adiabatic rate: ~ 0.55ºC/100 m (Navarro-Serrano and López-Moreno, 2018).

Annual isotherm of 0ºC ~ 2750 – 2950 m (López-Moreno and García-Ruiz, 2004).

Snow ablation Net radiation (55 %), latent (32 %) and sensible heat flux (13 %) (Bonsoms et al., 2022).



Credits: UB and CESBIO

Results

Figure 2. Sensitivity of ROS frequency and rainfall quantity

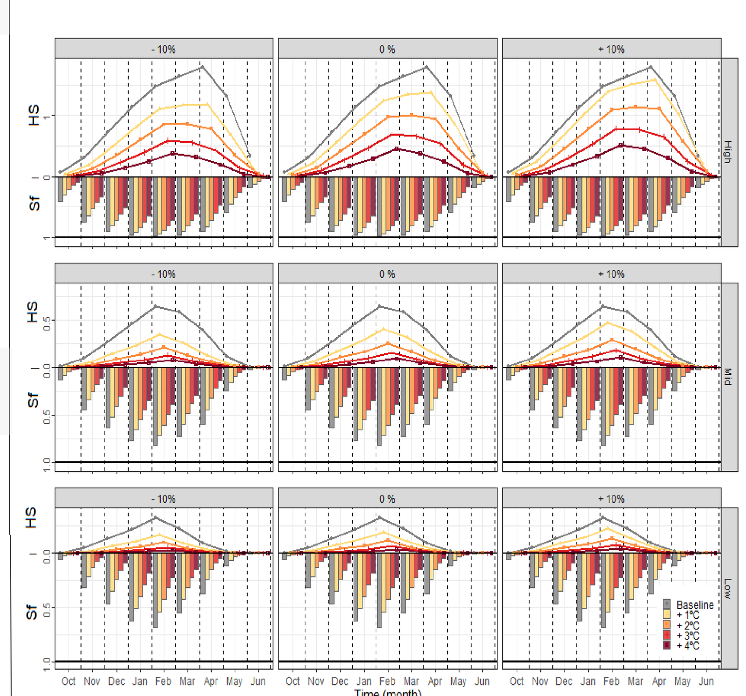


Figure 3. Snow depth and snowfall fraction evolution.

Spatial differences

Western Pyrenees:

> ROS per year
> Average daily snow ablation
> rainfall quantity during ROS events

ROS frequency

For all elevation aras: general increase in Winter.

At low and mid elevation: ROS frequency generally decreases (increases) during Autumn (Spring) for > + 2ºC.

At high elevation: large increases during Spring (western area). Decreases for + 2ºC during Summer.

Rainfall quantity during ROS

For all elevation zones: general increase in Winter.

At low and mid elevation: decreases during Spring.

At high elevation: general increases specially during Summer and Spring.

Snow ablation

Higher average daily snow ablation during ROS events than during average snow ablation episodes.

Small variation in the average daily snow ablation due to climate warming.

No spatial differences found with respect to baseline climate.

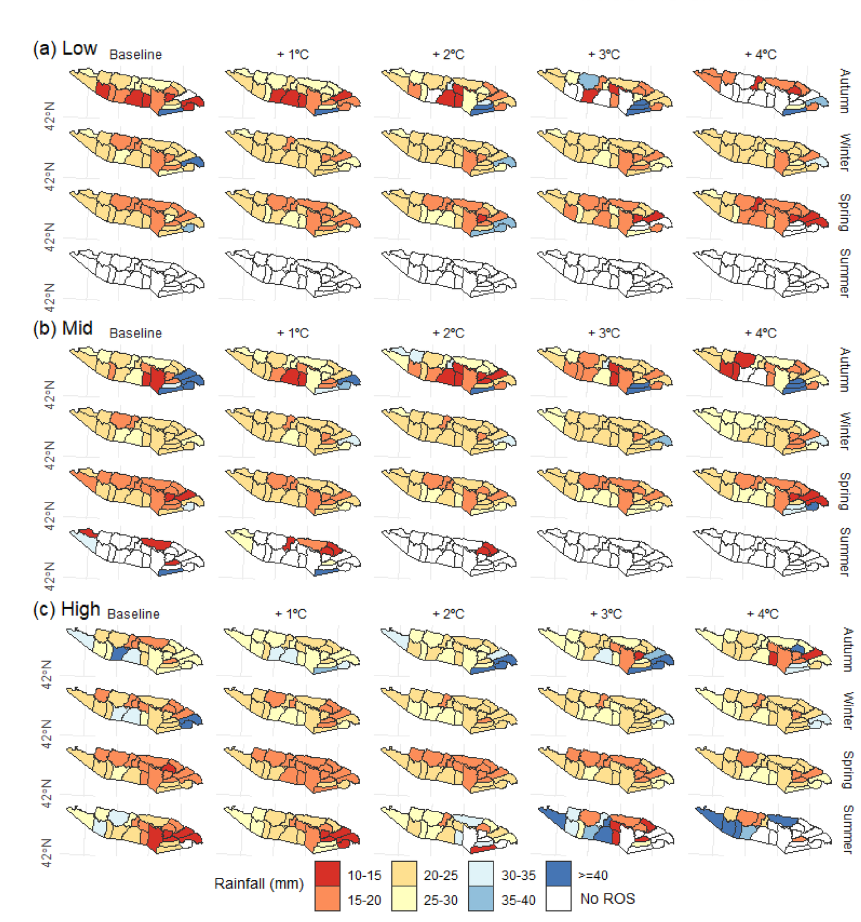


Figure 4. Spatial distribution of the rainfall intensity during ROS events

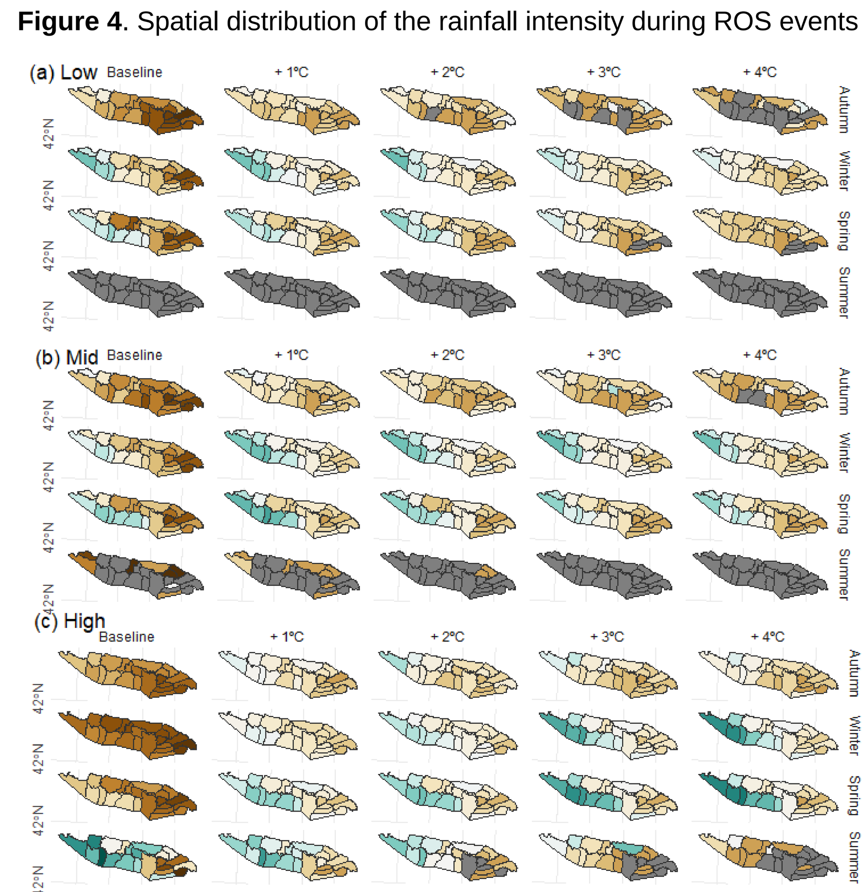


Figure 5. ROS frequency spatial distribution

Table 1. Increase of the rainfall intensity during ROS events

Elevation	Season	Baseline	+ 1ºC	+ 2ºC	+ 3ºC	+ 4ºC
Low	Autumn	14.6	+ 8.5	+11.6	+12.3	+11.1
	Winter	17.2	+3.9	+7	+8.3	+8.4
	Spring	16.3	+4.4	+6.7	+7.8	+7.7
	Summer	No ROS	No ROS	No ROS	No ROS	No ROS
Mid	Autumn	17	+7.4	+11	+8.4	+9
	Winter	16.7	+5.1	+6.8	+8.8	+10.6
	Spring	15.7	+4.6	+7.2	+8.8	+8.8
	Summer	10.1	+10.5	+14.7	+8.8	+10.6
High	Autumn	14.8	+8.4	+13.6	+16.1	+16
	Winter	10.4	+9.2	+14	+16	+16.7
	Spring	10.7	+6.4	+10.6	+12.8	+15.3
	Summer	25.2	-1.4	-0.1	+3.3	+16

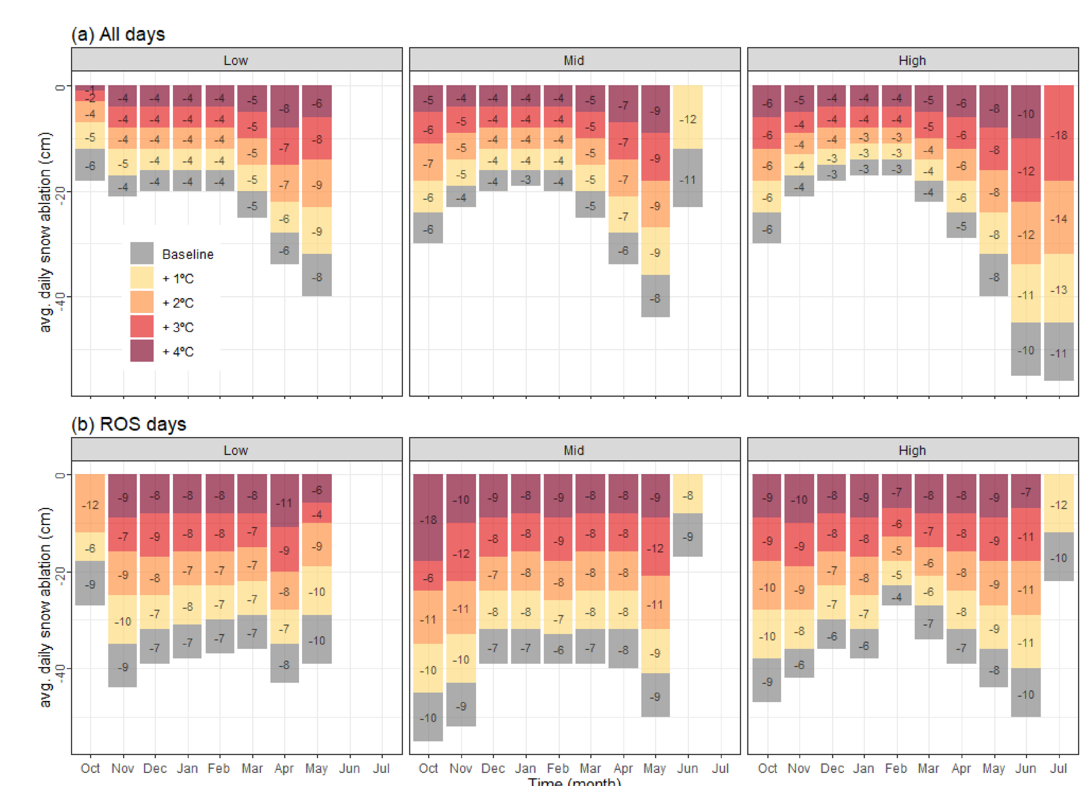


Figure 6. Average daily snow ablation during (a) all days and (b) ROS days.

ROS frequency is key controlled by snow depth duration

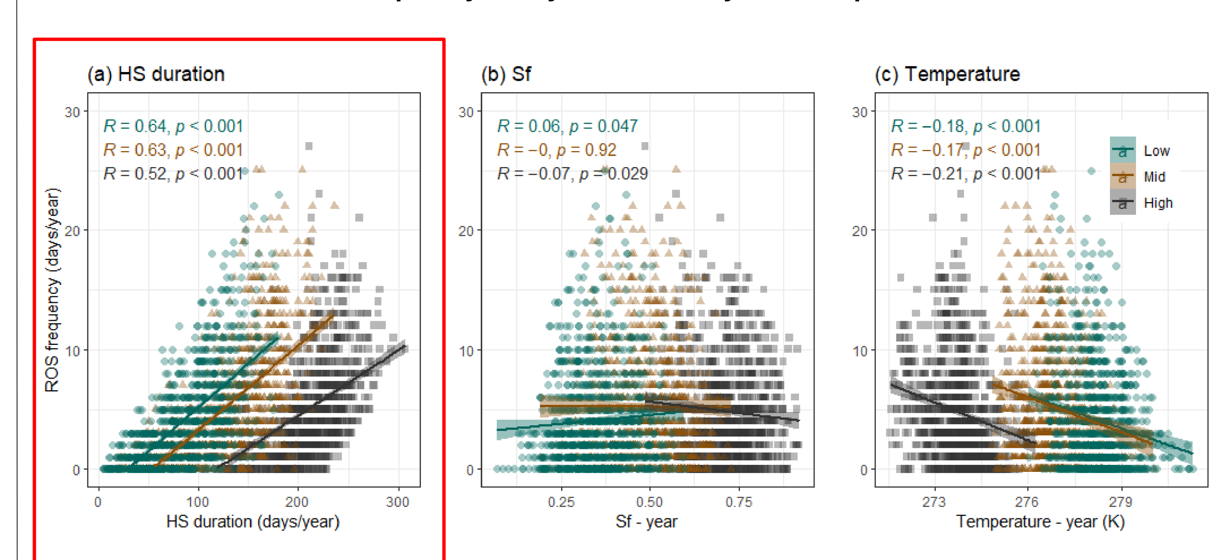


Figure 7. Pearson's correlation between ROS frequency (days/year) and yearly (a) HS duration, (b) Snowfall fraction and (c) temperature.

Conclusions

At low elevation, ROS events will decrease during Autumn and Spring.

ROS events and rainfall quantity during ROS increase in a warmer climate at high elevations.

High average daily snow ablation during ROS events.

Seasonal snow depth duration controls yearly ROS frequency

Future research

ROS interannual variability and sensitivity between extreme snow seasons

ROS physical process

Extreme events evaluation

Short term hydrological response

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