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

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Response to Reviewer 1. Comment posted on 20 September 2022.

Reviewer comments are in bold and responses in blue.

General Comments:

The submitted manuscript investigates the sensitivity of climatological snow indicators on compound temperature and precipitation changes. The analysis is based on the snow model FSM, which is forced by daily reanalysis data between 1980 and 2019 and assimilated in-situ data. The results focus on seasonal data and three elevation levels. The topic is definitely of interest for readers of TC. I liked reading the manuscript, which has a clear structure and illustrative figures. However, the language needs some proofreading by English native person. I suggest to accept the manuscript as soon as the following points, have been addressed:

The authors want to express their sincere gratitude to the reviewer comments. All the recommendations suggested by the reviewer were carefully taken into consideration and have improved the rigor and clarity to our findings presented in this paper.

Chapter 3.1 is missing a common thread and therefor hard to understand. Please restructure the entire chapter. If I got it right then the data of the 4 AWS were used to correct the reanalysis data. But how? What do you mean with "by trial and error basis"?

Sorry for the misunderstanding.

SAFRAN system data-assimilated in-situ (meteorological) records of the mountain range. We compared in-situ HS records (4 AWS) against FSM2 HS outputs (forced by meteorological AWS data) to validate the snow model. We have tried different snow model configurations (that is what we mean by "trial and error basis"), but we did not find significant differences in the performance and accuracy metrics. Therefore, we applied the most complex configuration, except for snow cover fraction estimation - we found good results with a linear function of HS-, and we forced the snow model using re-analysis data assimilated SAFRAN data.

We have rearranged the entire chapter 3.1, and we have added a new chapter “3.2 Snow model validation”.

We also added the FSM2 configuration:

“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, except for snow cover fraction that was based on a linear function of HS. 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.

The reanalysis data set of Vernay (2021) covers 1958-2020. Why do you analyze 1980 until 2019 only?

, we have performed a snow sensitivity analysis (1980-2019 temporal period as baseline), according to climate change projections for the range (Amblar-Francés et al., 2020), which are based on the average 1980s onwards temperature and precipitation used as a reference period, As we have mentioned in the 3.5 section.

According to Fig. 4 the main (average) snow cover even at high elevation last from November to Mai. This implies that extreme temperature or precipitation in October and June have no or only very marginal impact on the snow cover. However, you define the compound extremes based on October to June values. This makes not much sense!

We are sorry for the misunderstanding. The season is defined based on previous studies, and the modeled snow for the baseline climate (1980 – 2019). Previous Figure 4 included only the climate perturbed seasonal snow evolution (which are not used for the season limits definition). We have changed Figure 4 and added the baseline climate seasonal snow. We must include the months between October and June for comparison between seasons and elevation.

I don’t understand the explanation why no change in the peak HS date can be detected (L242), which is also in contradiction to your statement (L582) in conclusions?

The reference was for WW seasons. Peak HS date occurred earlier for most of the season types due to warming (Figure 7). However, for WW seasons, there are not relevant differences because maximum HS peak is significantly reduced, and the snow profile is flat (Figure 4).

We modified our statements and added Figure 7 to the main text.

We have changed: "*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 increase does not exceed ~ 1ºC 345 respect the baseline scenario, the peak HS date is not expected to drastically change (Figure S4), except during dry seasons...*" *to:*

"Overall, the peak HS date occurred earlier due to warming (Figure 7), independently of precipitation shifts. During WD seasons, the peak HS date per °C was earlier by 9 days at low elevations, 3 days at mid-elevations, and 17 days at high elevations; during CD seasons, the peak HS date per °C was earlier by 15 days at low elevations, 8 days at mid-elevations, and 1 day at high elevations. In high elevation areas, if the temperature increase was no more than about 1ºC above baseline, there was little change in the peak HS date (Figure S4), except during dry seasons. The maximum peak HS date was during dry seasons. On the contrary, the peak HS date did not change significantly due to warming during WW seasons (Table 4), because the snowpack would be scarce at those times, and there were no defined peaks (Figure 4)."

Minor points: L: 46: please rephrase

Thank you. Done

L 47: snow offset dates! You use also ablation dates and snowmelt dates. Please decide.

Thanks. We have replaced "snow offset dates" and "snowmelt dates" for "snow ablation dates".

L57: in regard to snow duration

Thank you. Added.

L82: spatially highly diverse

Thank you. Modified

L105: repetition of L57

Thank you. We have moved 103-105 to L57 paragraph.

L144: please rephrase

Thank you. Changed. We have modified:

"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)" to

“However, the sensitivity of snow during periods when there are seasonal extremes of temperature and precipitation has not yet been analyzed”

L168: Snow model and validation data

Done. We have changed the entire 3.1 order, according to comment 3.

L190: wrong reference format

Thank you. Changed.

L191: What do you mean with were excluded? If there is no data, then there is nothing to evaluate!

Thank you. We have delated our statement.

L192: ultrasonic snow depth sensor

Thanks. Changed.

L193: Please provide a reference where to get the data

Added:

“https://www.meteo.cat/wpweb/serveis/formularis/peticio-dinformes-i-dades-meteorologiques/peticio-de-dades-meteorologiques/; data requested: 14/01/2021)”

L196: I’m not able to access the pdf given in the reference

Thank you, now the reference is available (https://static-m.meteo.cat/wordpressweb/wp-content/uploads/2014/11/18120559/Les_Estacions_XEMA.pdf) .

L198: units of the 5th and 6th column is missing.

Added.

L218: LWinc and temperature

Added.

L220: Meteorological data therein…

Thank you. Changed.

L251: two times “perdentiles”

Thank you. Delated.

L253: average compound temperature and precipitation seasons.

Thank you. Changed.

L260: What did you when the same peak HS was reached at several dates?

Thank you for your suggestion. There is only one maximum peak HS for season.

L262: This makes no sense. Please rephrase.

We have changed “the average daily snow ablation per season (snow ablation)” for “daily average snow ablation per season (snow ablation)”.

L274: the best performance …

Changed for “highest R^2 values”.

L278: the better performance?

Changed for “highest accuracy”.

L279: observations are usually black...

Thank you for your suggestion. We aim to maintain the snow model values in black since it can be more visible than in grey color.

L288: non-linear (see also other occurrences)

Thank you. Changed.

L290: absolute or relative decreases

Relative. Added:

“When progressively warmed at 1ºC intervals, the largest **relative** seasonal HS decreases from baseline climate are found at + 1ºC”

L293: not surprising

We have kept our statement since we consider that the information provided is required for the results interpretation.

L306: please change temperature legend

Thank you for your suggestion, we have modified Figure 4.

L311: Average seasonal sensitivity of…

Changed.

L313: I’d suggest to replace the table with a bar plot

Thank you. We replaced the table with a figure (a boxplot, in order to be consistent with Figure 3 and following reviewer 2 suggestion).

L330: Please change the title of the y-axis to: average seasonal HS change (%)

Thank you. Done.

L331: Anomalies of…

Done.

L345: with respect to..

Changed.

L361: Sensitivity of..

Changed.

L368: Snow climate sensitivity (expressed as mean HS)

Thank you for your suggestion. We have changed “snow climate sensitivity” for “HS climate sensitivity”.

L373: “lasts area” is no English!

Changed.

L377: Where can I see that "Snow duration sensitivity clearly increases during WW seasons"?

We have added a reference to Figure 10 at L377, where it is observed that during WW seasons snow duration sensitivity increases at low elevation for the South-East.

L408: Add percentage to the legend and rephrase figure caption.

Changed.

L419: "increases in the energy available for snow ablation". This in contradiction to what you wrote earlier, because the snow offset is moving to times with lower sun angles.

We have changed the phrase for "…increases in the energy available for snow ablation **during the latest months of the seasons".**

L432: the increase in winter precipitations was mainly based on low elevation data, which is usually rain and not snow.

Thank you for your suggestion.

L437: slightly faster

Changed.

L438. This higher average …

Changed: "…This higher rate of snow ablation per season at high elevations (which have deeper snowpacks) are probably because the snow there lasts until late spring…".

L443: Therefore, slower snow ablation rate… (where is this shown?)

We have changed "slower snow ablation" for "lack of changes"

L448: The earlier peak HS date a low and mid elevation …

Thank you for your suggestion. We have changed "the earlier peak HS date" to "the earlier peak HS date at low and mid elevation".

L449: starts earlier (i.e. in winter)

Changed.

L467: mountain range

Changed.

L473L in this area

Changed.

L486: no significant trend for maximum HS

Done.

L488: in high elevations

Changed.

L493: Sensitivities of maximum seasonal HS…

Changed.

L503: highly sensitive

Changed.

L506: High elevation snowfall

Done.

L513: Add percentage to the legend and rephrase figure caption.

Done.

L521: disappearance of the typical sequence…

Done.

L522: triggers the simultaneous occurrence of several periods of…

Thank you for your suggestion. We have changed: “Climate warming triggers the simultaneously occurrence of snow accumulation and ablation episodes…” to “Our results indicated there will be an increase of snow ablation days and imply a disappearance of the typical sequence of snow accumulation seasons and snow ablation seasons.”

L524: on the ecosystem

Done.

L525: please rephrase

Done.

L533. The earlier snowmelt onset

Thank you. Changed.

L547: please rephrase

We have changed: “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” to:

“Winter snow accumulation affects hydrological availability during the months when water and hydroelectric demands are higher. This is because reservoirs store water during periods of peak flows (winter and spring), and release water during the driest season in the lowlands (summer) (Morán-Tejeda et al., 2014)”

L551 is dependent on a regular deep enough snow cover, which has been…

Done.

L553: The expected increase in snow scarce seasons pointed out in this work, is consistent with snow projections…

Changed.

L571: core month of the winter season

Changed.

L575: Repetition of L565

We have delated L575.

L581: show slightly larger sensitivities

Done

L582: increases about… and the peak HS date occurs about …

Done

L584: unclear, please rephrase

Done. We have changed “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” to

“Our findings thus provide evidence that the Pyrenean snowpack is highly sensitive to climate change, and suggest that the snowpacks of other mid-latitude mountain ranges may also show similar response to warming”

Thank you very much for your constructive comments.