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Barcelona, 2nd August 2023

Dear Dr. Haegli,

I am pleased to submit the revised version of the manuscript entitled "**Rain-on-snow responses to a warmer Pyrenees**", co-authored by myself, Dr. Juan Ignacio López-Moreno, Dr. Esteban Alonso-González, Dr. César Deschamps-Berger and Dr. Marc Oliva.

We would like to express our sincere gratitude for your valuable recommendations and feedback. All the referee's recommendations have been carefully considered and have significantly improved the manuscript, enhancing its scientific rigor.

The main manuscript modifications are summarized as follows:

1.- We have followed the reviewer's advice and updated the elevation band names. Additionally, the baseline temporal period is now clearly mentioned from the beginning of the manuscript. We have also included the relevant IPCC quotes.

2.- We have provided an extensive description of the sensitivity analysis conducted in this study and the rationale behind its use. It is important to acknowledge that sensitivity studies and climate projections are distinct types of work. In this study, we focused on evaluating the rain-on-snow sensitivity to temperature and precipitation, which allowed us to understand the non-linear spatiotemporal variations in different sectors and elevations of the Pyrenees. As mentioned by Reviewer 1, representing the results as "change per 1ºC" is advantageous, as it facilitates comparisons with other regions and seasons.

3.- Regarding our decision to use a sensitivity analysis instead of directly use GCMs models, we considered the high uncertainty associated with climate projections for the Pyrenees, particularly concerning precipitation among different models and GHGs emission scenarios presented in previous works (López-Moreno et al., 2008). To address this, we provided temperature and precipitation change values based on already established and latest climate projections for the region. While we acknowledge that this introduces some uncertainty, we consider it is still more reliable than presenting different outputs from model ensembles.

We have included a detailed point-by-point response to the reviewer's comments on the following pages.

We hope that these revisions meet your expectations, and we believe that the new version of the manuscript is now suitable for publication in **Natural Hazards and Earth System Sciences**.

Should you have any further inquiries about this work, please do not hesitate to contact us. We will be happy to answer any question you may have.

Best regards,

Mr. Josep Mª Bonsoms, on-behalf of Dr. Juan Ignacio López-Moreno, Dr. Esteban Alonso-González, Dr. César Deschamps-Berger and Dr. Marc Oliva.

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Reviewer 1: General Comments

The manuscript presents a thorough investigation of the effects of climate warming on rain-on-snow events in the Pyrenees. The manuscript is well-structured, includes a comprehensive state-of-the-art literature review, and an extensive discussion of the results. The methodology is sound, but a bit outdated with regard to the scenario approach used (delta-change method). The results show that an increase of rain-on-snow events has to be expected in mid-winter and at higher altitudes, and a decrease elsewhere. These results are innovative and relevant for various sectors, as discussed in the manuscript. The manuscript is therefore suggested for publication with minor revisions, as indicated below.

We want to express our sincere gratitude for your review and your constructive feedback.

We agree with Reviewer 1 that delta-change would be outdated if we would aim to combine observations/reanalysis with climate projections. However, it is important to note that for sensitivity analysis in snow hydrology, delta-change remains a widely used and relevant methodology.

In this manuscript version we have removed the term 'delta-change' to avoid confusion with previous works.

Specific Comments

Abstract, line 11: What do you mean with “When air temperature is increased from 1ºC to 4ºC…”? Since your study is based on spatially and temporally varying weather data from reanalysis, there is no fixed 1°C base temperature that you could raise to 4°C. Please reformulate to clarify, that 1°C is not the baseline, but already an additive constant used in the delta change approach.

Following your suggestion, we have changed:

“When air temperature is increased from 1ºC to 4ºC, ROS rain and frequency increase at a constant rate during winter and early spring for all elevation zones”

To

“When air temperature is increased from 1ºC to 4ºC with respect to the baseline climate period, ROS rain and frequency increase at a constant rate during winter and early spring for all elevation zones”

Section 3.4: Could you please motivate the value of change-factors you selected for the delta change approach? It is important to relate them at least qualitatively to more elaborated climate scenarios. E.g., how do these levels of warming relate to the +2 degree goal? Is +4K a worst case scenario, or an intermediate one? Is +/- 10% precipitation adequately spanning the expected range of change? To answer such questions would strongly increase the general impact of the study, since it could be better related to the general climate change debate going on in our society. There is very limited information on this topic in Section 5, but this needs to be extended and maybe shifted to section 3.4, where the scenario concept of this study is introduced. Section 3.4: Please clearly discuss the limitations coming along with the delta-change approach. Such a discussion is completely missing so far. E.g. a more realistic simulation of climate change would most probably include a distinct seasonality of precipitation change, which is absent in the delta change approach.

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Thanks for your comment. Reviewer is correct, the temperature and precipitation ranges we used were selected based on available climate projections for the region. To address this, we have added the following paragraph:

Section 3.4 : "A temperature increase of 1ºC can be interpreted as an optimistic projection for the region, while 2ºC and 4ºC would represent projections for mid and high emission scenarios, respectively (Pons et al., 2015). The range of +/-10% for precipitation includes the expected changes in precipitation according to the vast majority of climate models, regardless of the emission scenario (López-Moreno et al., 2008; Pons et al., 2015; Amblar-Francés et al., 2020)."

We acknowledge that climate projections and sensitivity analysis are different type of works, each with distinct objectives that complement each other. with different objectives that complements each other. As suggested by the reviewer's, we have clarified the concept of sensitivity analysis in the discussion section of the manuscript:

"5.5 Limitations

This study evaluates the sensitivity of ROS responses to climate change, enabling a better understanding of the non-linear ROS spatiotemporal variations in different sectors and elevations of the Pyrenees. Instead of presenting diverse outputs from climate model ensembles (López-Moreno et al., 2010), we provide ROS sensitivity values per 1ºC, making them comparable to other regions and seasons. The temperature and precipitation change values used in this sensitivity analysis are based on established climate projections for the region (Amblar-Francés et al., 2020). However, precipitation projections in the Pyrenees exhibit high uncertainties among different models, GHGs emission scenarios, and temporal periods (López-Moreno et al., 2008).

The SAFRAN meteorological system used in this work relies on a topographical spatial division and exhibit and accuracy of around 1 ºC in Ta and around 20 mm in the monthly cumulative precipitation, with largest uncertainities found at high elevations (Vernay et al., 2022). Precipitation phase partitioning methods are also subject to uncertainties under close-to-isothermal conditions (Harder et al., 2010). The FSM2 is a multiphysics snowpack model that has been implemented and validated previously in the Pyrenees (Bonsoms et al., 2023) and compared against different snowpack models (Krinner et al., 2018), providing evidence of its robustness."

In addition, many scientific works and doctoral thesis have been focused on snow sensitivity to climate change, including the evaluation of different snow processes and comparisons across different sites. As we state in the manuscript, the methodology applied in our work relies on previous works, some of them has been published recently (i.e., after 2020) in top scientific journals, providing evidence of the validity of the method. For instance:

Alonso-González, E., López-Moreno, J.I., Navarro-Serrano, F., Sanmiguel-Vallelado, A., Aznárez-Balta, M., Revuelto, J., and Ceballos, A.: Snowpack Sensitivity to Temperature, Precipitation, and Solar Radiation Variability over an Elevational Gradient in the Iberian Mountains, Atmos. Res., 243, 104973 https://doi.org/10.1016/j.atmosres.2020.104973, 2020.

Pomeroy J, Fang X, Ellis C. 2012. Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. Hydrological Processes 26: 1892-1905. doi:10.1002/hyp.9248.

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Pomeroy, J. W., Fang, X., and Rasouli, K.: Sensitivity of snow processes to warming in the Canadian Rockies, 72nd Eastern Snow Conference, 9–11 June 2015, Sherbrooke, Québec, Canada, 22–33, 2015.

Rasouli, K. R., Pomeroy, J. W., and Marks, D. G.: Snowpack sensitivity to perturbed climate in a cool mid-latitude mountain catchment, Hydrol. Process., 29, 3925–3940, https://doi.org/10.1002/hyp.10587, 2015.

Rasouli, K. R., Pomeroy, J. W., and Whietfiled, P. H.: The sensitivity of snow hydrology to changes in air temperature and precipitation in three North American headwater basins, J. Hydrol., 606, 127460, https://doi.org/10.1016/j.jhydrol.2022.127460, 2022.

Aygün, O.; Kinnard, C.; Campeau, S.; Krogh, S.A. Shifting Hydrological Processes in a Canadian Agroforested Catchment due to a Warmer and Wetter Climate. *Water* **2020**, *12*, 739

Spence, C., He, Z., Shook, K., Mekonnen, B., Pomeroy, J., Whitfield, C., and Wolfe, J.: Assessing hydrological sensitivity of grassland basins in the Canadian Prairies to climate using a basin classification–based virtual modelling approach, Hydrol. Earth Syst. Sci., 26, 1801-1819, https://doi.org/10.5194/hess-26-1801-2022, 2022a.

Bonsoms, J., López-Moreno, J. I., and Alonso-González, E.: Snow sensitivity to temperature and precipitation change during compound cold–hot and wet–dry seasons in the Pyrenees, The Cryosphere, 17, 1307–1326, https://doi.org/10.5194/tc-17-1307-2023, 2023.

López-Moreno, J. I., Goyette, S., Beniston, M., and Alvera, B.: Sensitivity of the snow energy balance to climate change: Implications for the evolution of snowpack in Pyrenees in the 21st century, Clim. Res. 36, 203–217, https://doi.org/10.3354/cr00747, 2008.

López-Moreno, J. I., Pomeroy, J. W., Revuelto, J., and Vicente-Serrano, S. M.: Response of snow processes to climate change: spatial variability in a small basin in the Spanish Pyrenees, Hydrol. Process., 27, 2637–2650, https://doi.org/10.1002/hyp.9408, 2013a.

Kienzle, S. W., Nemeth, M. W., Byrne, J. M. and MacDonald, R. J.: Simulating the hydrological impacts of climate change in the upper North Saskatchewan River basin, Alberta, Canada, J. Hydrol., 412–413, 76–89, doi:10.1016/j.jhydrol.2011.01.058, 2012

He, Z., Shook, K., Spence, C., Pomeroy, J. W., and Whitfield, C. J.: Modeling the sensitivity of snowmelt, soil moisture and streamflow generation to climate over the Canadian Prairies using a basin classification approach, Hydrol. Earth Syst. Sci. Discuss. https://doi.org/10.5194/hess-2023-71, 2023.

Jennings, K.S.and Molotch,N.P. Snowfall fraction,coldcontent, andenergy balance changes drive differential response to simulated warming in an alpine and subalpine snowpack, Front.Earth Sci.,8,2296–6463,https://doi.org/10.3389/feart.2020.00186, 2020.

López-Moreno, J. I., Gascoin, S., Herrero, J., Sproles, E. A., Pons, M., Alonso-González, E., Hanich, L., Boudhar, A., Musselman, K. N., Molotch, N. P., Sickman, J., and Pomeroy, J.: Different sensitivities of snowpacks to warming in Mediterranean climate mountain areas, Environ. Res. Lett., 12, 074006, https://doi.org/10.1088/1748-9326/aa70cb, 2017.

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Musselman, K. N., Molotch, N. P., and Margulis, S. A.: Snowmelt response to simulated warming across a large elevation gradient, southern Sierra Nevada, California, The Cryosphere, 11, 2847–2866, https://doi.org/10.5194/tc-11-2847-2017, 2017b.

Sanmiguel-Vallelado, A., McPhee, J., Esmeralda Ojeda Carreño, P., Morán-Tejeda, E., Julio Camarero, J., López-Moreno, J. I.: Sensitivity of forest–snow interactions to climate forcing: Local variability in a Pyrenean valley, J. Hydrol., 605, 127311, https://doi.org/10.1016/j.jhydrol.2021.127311, 2022.

Section 3.5.: The representation of the results in "change per 1K" is great, since it makes the results easily comparable to other regions/seasons/scenarios.

Thank you for your comment.

Editorial/Technical

Title: Please consider rephrasing the title. The expression "Rain-on-snow response to a warmer Pyrenees" is semantically very vague (and grammatically incorrect: Pyrenees is in plural). You describe the response of the characteristics of ROS events to warming and precipitation change in the Pyrenees in your manuscript. Something along these lines would be a much clearer title for the article manuscript.

Thank you for your recommendation.

We have changed the title : "Rain-on-snow responses to a warmer Pyrenees" to "**Rain-on-snow responses to a warmer Pyrenees: a sensitivity analysis using a physically-based hydrological model**."

Abstract: Avoid using abbreviations without introducing them in advance (line 8; "ROS fr").

Changed for "ROS frequency"

Line 470: wrong usage of singular/plural (vegetation branches intercepts)

Changed.

Generally: Some additional proofreading is advisable to remove some remaining minor language mistakes.

The manuscript has been corrected according to Reviewer 1 suggestion.