Classifying compound coastal storm and heavy rainfall events in the north-western Spanish Mediterranean" by Marc Sanuy et al.

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We thank the reviewer for the detailed review and constructive comments on the manuscript. We have performed a thorough revision to address all the comments, as detailed below.

The authors present an interesting analysis of the relatively new concepts of multivariate and spatially compounding events considering the two hazards heavy precipitation and coastal storms along the Catalan coast. Overall the analysis is sound and fits well into HESS. However, some aspects of the methodology are difficult to follow (see comments below).

This is answered in the comments below.

What is somewhat lacking is a discussion and contextualisation of the results. The current Discussion (L 425-568) can be considered as results and should be moved to the Results section (e.g. under the section headline "Case studies"). An actual discussion of the approach and results is missing. With the case studies, the manuscript is already quite extensive but maybe the authors could briefly discuss topics such as:

[R2.1] As it was mentioned in [R1.3], the Discussion section will be fully modified. Following the reviewer's recommendation, all text describing specific compound episodes will be moved to the Results section. The final Discussion section will focus on methods and results as the referee suggests while also addressing comments of the other reviewers.

- What are advantages/limitations of the approach the authors use to study compound events? How does it compare to other approaches in the literature?

[R2.2] This study can be classified as an exploratory analysis prior to a classical probabilistic approach. While being rather simple, it permitted to identify the occurrence, main characteristics and spatial distribution of different types of compound coastal events at regional level, with rainfall and waves being the considered drivers; and to identify dominant weather types during such events. The adopted approach to classify spatially compound event permits to identify the dominant type of driver and, thus, the dominant type of induced risks which clearly will condition risk management strategies. Also, to perform a sound bivariate probabilistic analysis for spatially compound events it is necessary to define the spatial domain to be considered. In this sense, this previous exploratory analysis identifies "connected" coastal sectors, and the dominant extreme contribution. Once they are identified, a more formal probability analysis can be targeted to calculate the probability of occurrence of a given type of event in a given part of the territory.

This will be introduced in the discussion section along with a deeper contextualization of some of the specific methodological choices. See, as example, answers to [R3.9] and [R3.11] copied here:

[R3.9] Events where only one variable is extreme (It exceeds the threshold to be classified as extreme) are not included in the assessment. This approach has been adopted because this is

mainly a risk-management oriented study. It is assumed that a given climatic variable (waves or rainfall) below the considered threshold is not producing a significant impact on the system by itself, neither its combination with an extreme one will substantially increase its associated risk. These events are considered as a single (univariate) extreme event. Their inclusion in the analysis would imply (in practice) to analyse all recorded univariate events and, thus, to substantially introduce noise in the analysis without providing significant information on compounding effects (which are the main target).

[R3.11] The popularity of correlation-based map-pattern classification springs from its intuitive and simple basis of automating the same task performed manually by an analyst (Yarnal, 1993 Yarnal et al., 2001). Its product is easily read and understood by the user. It also produces a good separation between weather types, i.e., a good degree of similarity among the cases within the same cluster and dissimilarity between the clusters (Huth et al., 2008). One of its main limitations is that is not as consistent as other approaches such as K-mean clustering or PCA, as it is in general sensitive to the choice of parameters that must be set a priory (such as the cutting threshold). This is also related to the fact the method tends to produce one big class followed by minor ones (snowballing effect). However, these limitations where minimized by performing a two-step comparison between classes, i.e. a first classification with low thresholds (rt=0.2) and a second classification using the preliminary classes obtained in the first and maximizing the correlation coefficient (rt), which lead to the final classes with two big groups (~40% of cases) and a follow-up one (~20% of cases). On the contrary, one of the main limitations of a clustering-based method is its tendency to produce homogeneous (equally populated) groups.

The discussion section will be completed with a paragraph describing the advantages and limitations of the chosen method and how it compares with manual, cluster-based and PCA techniques.

References:

Yarnal, B. Synoptic climatology in environmental analysis. London, UK: Belhaven Press. 1993.

Yarnal, Brent, et al. "Developments and prospects in synoptic climatology." International Journal of Climatology: A Journal of the Royal Meteorological Society 21.15 (2001): 1923-1950.

Huth, Radan, et al. "Classifications of atmospheric circulation patterns: recent advances and applications." Annals of the New York Academy of Sciences 1146.1 (2008): 105-152.

- How would climate change affect the occurrence of this type of compound events in the study area?

[R2.3] The purpose of this work is to characterize the current situation regarding the importance of analyzed compound events in the Spanish NW Mediterranean. This will be later (in a future work) used as a reference state to be compared with future scenarios to assess potential changes in probability of occurrence and/or intensity. At present, the existing information on the potential influence of climate change on compound coastal events in the area is limited to the analysis done by Bevacqua et al. 2019 at European scale. However, these authors analyzed rainfall and surge compound events (which are different drivers), they only considered multivariate co-occurring events, the scale of the work does not properly represent the regional dimension. This work is already cited in the manuscript and, now, we shall include a specific comment in the Discussion section to stress the need to study future evolution of compound

events in the area. In this sense, we shall also refer to existing studies on future projection on individual drivers such as Tramblay and Somot (2018) who report an increase in intense rains in the north of the Mediterranean basin (Tramblay and Somot, 2018); and Llasat et al (2016) reporting a possible increase in convective rains that give rise to flash-floods in the region. Also, existing studies on the evolution of coastal storminess will be included. The underlying idea is to emphasize that, although studies on the projections of individual drivers show a given trend, future compound events scenarios will not necessarily be a linear combination of them.

Tramblay, Y., Somot, S. 2018. Future evolution of extreme precipitation in the Mediterranean. Climatic Change, 151:289–302 https://doi.org/10.1007/s10584-018-2300-5.

Llasat, M.C., R. Marcos, M. Turco, J. Gilabert, M. Llasat-Botija, 2016. Trends in flash flood events versus convective precipitation in the mediterranean region: the case of catalonia. Journal of Hydrology, 541, 24-37, http://dx.doi.org/10.1016/j.jhydrol.2016.05.040 0022-1694.

Throughout the manuscript: check the usage of the word "verify". I think the word is used incorrectly and should always be replaced with "co-occur".

[R2.4] This will be addressed in the revised version of the manuscript.

Minor comments:

Abstract:

- 3.4 events per year: difficult to contextualise if the definition of events is not presented. The number depends strongly on this definition.

[R2.5] The text "(3.4 events per year)" will be removed from the abstract.

- Last sentence: On what evidence is this conclusion based? Can you add this information here, please? Further, remove either "damage" or "impact" from the sentence (both mean the same here).

[R2.6] The last sentence will be rephrased to "Overall, results obtained from evidence from specific events indicated that heavy rainfall is related to the most significant impacts despite have damages having a larger spatial reach."

Main text:

L 76: "Spatially compounding events refer to co-occurring hazards from different climate drivers within a limited time window": maybe add "spatially" between before "cooccurring"

[R2.7] This will be done in the revised version of the manuscript. *"Spatially compounding events refer to co-occurring hazards from different climate drivers at distant locations within a limited time window"*:

L 144: Is the analysis of spatially compounding events sensitive to the selection of AWS? I.e., if you include less/more stations, would this change your number of spatially compounding events?

[R2.8] The selection of AWS was made to ensure good spatial and temporal coverages within basins during the studied period (1973-2013). Although we have not performed a formal

sensitivity analysis, the spatial coverage should ensure that significant heavy rainfall events will not be excluded even in spatially-localized episodes. However, the total number of AWS within a given basin could affect the maximum P24h value recorded for each event, as this value may spatially vary. According to this, although a change in the number of AWS could slightly affect to number of compound events when they are close to threshold conditions, and/or the rainfall peak value reached within a given basin, it is not expected it will have a significant impact on obtained results for the purposes of the assessment. However, we will include a paragraph discussing the possible effects that spatial coverage of AWS within basing could have in our assessment, and in general, in any kind of assessment dealing with compounding events.

L 187: Do you analyse the correlation between driver intensity in spatially compounding events? How? In those events you typically more than two variables. Please clarify.

[R2.9] The sentence will be rephrased to "The results from (i) are used to assess the frequency of occurrence and spatial distribution of the different event types (multivariate and spatially compounding). At this stage, the correlation between driver intensity (i.e. the correlation between the maximum Hs and P24h) is also analysed for both event types."

In this study, we analyse both types of event based only on the two presented variables Hs and P24h

L 201: Usage of "significant": consider using a different word (e.g. "extreme") since significant is usually only used in the context of statistical testing. Same comment applies to L 215.

[R2.10] This will be addressed in the revised version of the manuscript

L 227: add "heavy" before the second "rainfall"

[R2.11] This will be addressed in the revised version of the manuscript

L 235: I was at first confused about the usage of "areas". I assume you mean the areas delineated in Figure 2b. If this is the case, please make this clear (e.g. by referring to the figure). In L 237 you use the word "sector". Is this the same as the areas above? I assume it's a subset and you're referring only to the coastal areas. Please clarify.

[R2.12] The words area and sector refer to the same thing, i.e. areas delineated in Figure 2.b.

The text will be rephrased as follows:

L235: "…. different characteristics along the costal basins (thereafter also named areas or sectors):"

L 237: The classification of compound events is unclear. Do you mean for each event you go through all the coastal sectors and check whether you have only rainfall or only wave extremes or both? Please make use of the word "extreme" to make clear what events you're talking about (e.g. instead of "episodes" in L 238). In particular, the phrase "where local extreme conditions correspond to. . ." is unclear. I think you mean something like "if rainfall/wave extremes occur in this sector. Also, the classes are not exclusive. An event can be multivariate, spatially compounding rain and spatially compounding waves. Which class wins?

[R2.13] Indeed, the classes are not exclusive, and therefore, there is no winning class. The classification intends to classify the event as it is experienced at each basin. Thus, given a compound event (general) there will be basins experiencing it as multivariate (both components co-occur) and basins experiencing it as spatially compounding. In the second case, the basin can

be receiving only rain (SC-rain) or only waves (SC-waves). By our definition of compound event, there will always be co-occurrence of the two analysed components at the regional scale (see next comment).

This part of the manuscript will be rephrased to avoid confusion in our definition of compound event (regional scale), multivariate event (at the basin scale) or spatially compounding event (either waves or rain at the basin scale).

L 242: See my comment higher up: what do you do when you have more then two drivers in the event?

[R2.14] Related to the former comment. By our definition of compound event, there will always be co-occurrence of the two analysed components at the regional scale (see previous comment). As an example, extreme rain at Area 1 co-occurring with extreme waves at Area 7 would be a spatially compound event. In Area 1 will be a spatially-compounding *rain*, and in Area 7 will be a spatially compounding *waves*. Another example could be extreme waves at all basins with rain in Areas 2 and 3. In this case Areas 2a and 3 would be experiencing a multivariate event, and all other areas would be under spatially compounding waves. Notably, in all cases, both components co-occur at the regional scale.

The co-occurrence of extreme waves at different sectors (without rain present at any sector) is not studied here, as it would be a regular coastal storm, and not a compound (multi-hazard) event. The same is true for rain happening at multiple sectors without any extreme waves at the coast.

This part of the manuscript will be rephrased to avoid confusion in our definition of compound event (regional scale), multivariate event (at the basin scale) or spatially compounding event (either waves or rain at the basin scale).

L 294: remove “the presence of”

[R2.15] This will be addressed in the revised version of the manuscript

L 301 and 302: usage of “location”: do you mean “area”?

[R2.16] The word location will be changed to area or sector, as these where defined following [R2.12]

L 305: it is not clear what the percentages in this paragraph refer to. Are they relative to all extreme event (i.e. 100% would mean all extreme events are compound events)? Please clarify.

[R2.18] The percentages are relative to the defined compound events. This will be specified in the revised version of the manuscript

L335: It seems that you pool all events in a given area even when they occur at different station. This should be mentioned in the methods section. It is still not clear how you deal with the case where multiple rainfall extremes in the same area co-occur with one wave extreme.

[R2.18] If an event occurs at different stations of the same area, only the maximum P24h registered within the area is retained. The subjacent idea is to correlate the maximum P24h with the maximum wave, for each sector, and for each event. This was specified in L230 (*Finally, each compound event is characterised by the maximum P24h and Hs values at the stations and nodes within each coastal area during the event duration*). However, L230 will be rephrased to avoid confusion or misunderstandings.

L 358: “statistically independent values”: please replace with “uncorrelated”. A correlation of zero doesn’t mean that the variables are statistically independent (though the reverse is true).

[R2.19] This will be addressed following reviewer’s suggestion.