***Response to Referee Comment 1 on* "Time of Emergence of compound events: contribution of univariate and dependence properties" *by* Bastien François et al.**

Jakob Zscheischler

General comments:

Comment:

François et al present a very thorough analysis of the time of emergence of compound events. The paper introduces the concept and illustrates it for two types of compound events, compound wind and precipitation extremes and false spring events. Overall this is a timely and useful study and proposes convincing ideas on how to disentangle the contribution of marginals and dependence in trends of compound event occurrence. I find it particularly interesting that in the first example changes in the dependence matter (for some models) for ToE, whereas in the second model dependence changes are irrelevant/do not occur.

Response:

We would like to thank Jakob Zscheischler for his very positive comments and the detailed questions. All the comments and our point-by-point responses are given below.

Comment:

While the paper is very thorough, it is also somewhat lengthy, so the authors might want to consider shortening some aspects to improve readability.

Response:

We agree with this comment. As suggested by Anonymous Referee #2 in the comment 2), we are relocating the application of our methodology in its "Full-version" to the supplementary material. This implies that the explanations, results, figures and appendices related to the Full-version are removed from the main body of the article, thus shortening the article and improving readability, as desired. All the modifications will be detailed in the response to the second comment of Anonymous Referee #2.

Comment:

I have a few (mostly minor) comments that should be considered before publication.

Line 65: "Recently, Abatzoglou et al. (2020) even showed, using reanalysis data, that changes in dependence properties have been more important than changes in univariate properties in the recent decades." Not sure that was really shown in that study.

Response:

We agree and propose to be more explicit in the following correction (in red and blue):

> "*Recently, Abatzoglou et al. (2020) even showed ~~, using reanalysis data, that changes in dependence properties have been more important than changes in univariate properties in the recent decades.~~**that, in the recent decades, changes in multivariate annual climatic conditions (water deficit, evapotranspiration, minimum and maximum temperature) with respect to a reference climate state have been more important than changes in univariate annual climatic conditions for a large portion of the Earth.***"

Comment:

Fig. 5: it looks like the chosen window length is a bit too small to obtain robust results (there is very high variability in the time series, leading to large uncertainties regarding the ToE). 30 years is very limited for studying compound events. I would be interested to know whether you get smoother curves if you increase the window length and thus sample size.

Response:

As mentioned by the referee, our methodology can be applied by considering a larger window length than 30 years.

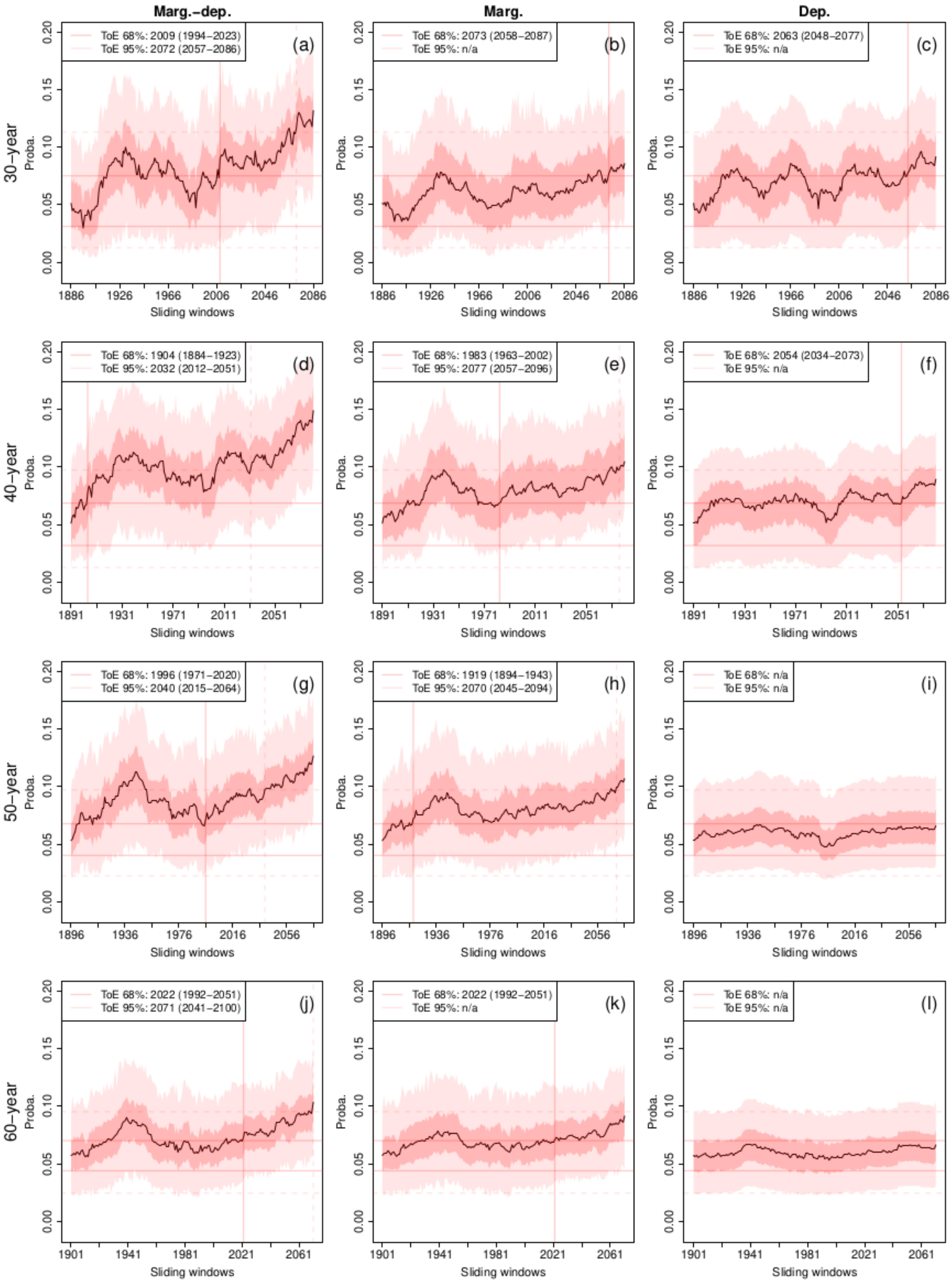
New Fig. S15 (below) shows the results we obtain by analyzing probability changes for the CNRM-CM6 simulations with:

- a 30-year sliding window (S15a-c, same results as those presented in Fig. 5a, b and c, baseline period: 1871-1900)

- a 40-year sliding window (baseline period: 1871-1910, S15d-f)

- a 50-year sliding window (baseline period: 1871-1920, S15g-i)

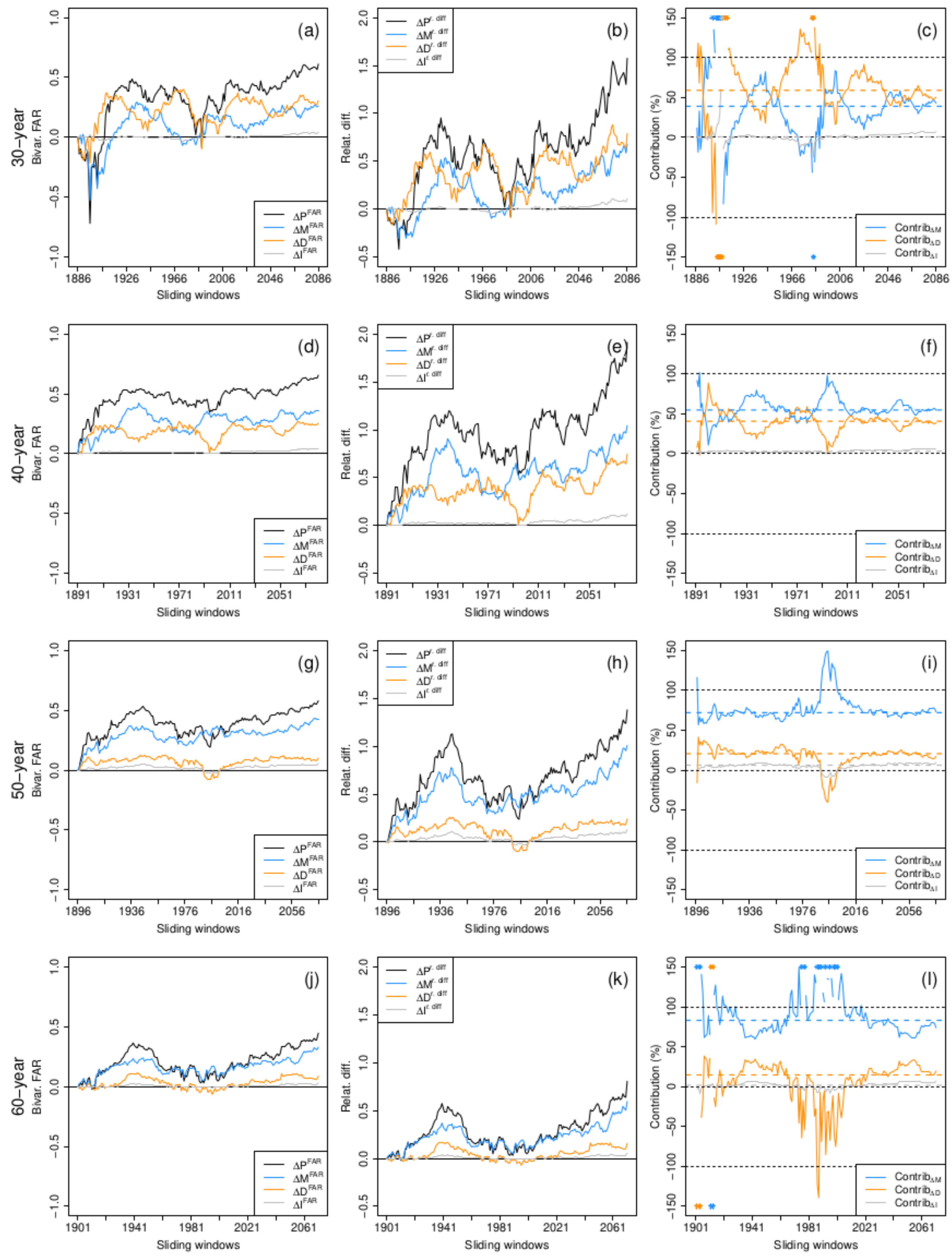
- a 60-year sliding window (baseline period: 1871-1930, S15j-l).



New Figure S15: Probability time series and time of emergence of compound wind and precipitation extremes ($P(X > x_{80|sel} \cap Y > y_{80|sel} \mid \text{CNRM-CM6}\ (X, Y) \in S^{\text{CNRM-CM6}}_{90,90})$) based on CNRM-CM6 simulations due to changes of (a, d, g, j) both marginal and dependence properties, (b, e, h, k) marginal properties only, and (c, f, i, l) dependence properties only. Results are displayed for probabilities computed by using (a-c) 30-year, (d-f) 40-year, (g-i) 50-year and (j-l) 60-year windows sliding over the period 1871-2100. In each panel, the first sliding window is considered as the baseline period. The shaded bands indicate 68% and 95% confidence intervals of the probabilities. Not-applicable (n/a) is indicated when no time of emergence is detected.

Indeed, by increasing the window length, smoother curves of probability time series are obtained, whether marginal and/or dependence changes are considered (compare Figs. S15a-c with Figs. S15d-f, g-i and j-l). ToE results are changed and will be discussed in the response to the next comment. Also, increasing the window length results in obtaining probability curves that are flatter, especially when considering the changes of dependence only (Figs. S15c, f, i and l). This can be explained by the fact that, by increasing the size of the sliding windows, more years of data are analyzed together. In a transient climate context, this results in mixing different climate conditions and, thus, different statistical properties. Changes of statistical properties between the baseline period and the sliding windows are then attenuated, which is particularly true for the dependence structure for which the climate change signal is less pronounced than for the marginal properties.

We also derived new Fig. S16 that shows the evolutions of bivariate FAR, relative differences and contribution for the CNRM-CM6 simulations with the different window lengths.



New Figure S16: Evolutions of (a, d, g, j) the bivariate fraction of attributable risk (FAR), (b, e, h, k) relative difference of probabilities with respect to the baseline periods and (c, f, i, l) contribution of the marginal, dependence and interaction terms to probability values. Median contributions computed over all sliding windows are displayed with dashed lines. Results are displayed for probabilities computed by using (a-c) 30-year, (d-f) 40-year, (g-i) 50-year and (j-l) 60-year windows sliding over the period 1871-2100. In each application of the methodology, the first sliding window is considered as the baseline period. Asterisks indicate values lying outside the plotted range.

The flattening of the probability curves when considering the changes of dependence only results in reducing the contribution of the dependence properties (Figs. S16c, f, i and l). It illustrates here that contribution results not only depend on the choice of the baseline period (as already discussed in sub-section 6.2 – Conclusion, discussion and future work / Discussion and perspectives –, L554-L564 of the initial article), but also on the choice of the window length of the baseline period.

As mentioned by the referee, 30 years can be limited to robustly study compound events and larger window length could be preferable. However, in Time of Emergence studies, i.e., in a climate change context, choosing a large window length may provide less informative results on the detection of emergence. Thus, to test and illustrate our methodology, we chose to use a 30-year sliding window, which can be seen as a trade-off between providing informative ToE results, and at the same time, having a sufficient sample size to robustly evaluate compound event probabilities.

However, in order to inform readers that ToE and contribution results can be modified by the choice of the window length, we have added the new Figures S15 and S16 in the supplementary materials, as well as the following modifications and sentences (in blue) in the sub-section 6.2 (Conclusion, discussion and future work / Discussion and perspectives) of the initially submitted article:

> "*In this study, emergence of probabilities of multivariate hazards has been investigated with respect to the* ***30-year*** *baseline period 1871-1900. This period can be considered as representative of the beginning of the industrial era (e.g., Hawkins et al., 2020) and can hence be of interest to assess if anthropogenic climate change has contributed to an emergence of probability of multivariate hazards. However, other baseline periods could have been chosen, such as more recent ones which would provide useful results for adaptation planning (e.g., Ossó et al., 2022). Of course, depending on the chosen baseline period, the estimated natural variability that serves as reference for assessing changes would be different, and thus would affect the ToE results. As an illustration, Fig. S14 shows results from a quick sensitivity experiment for the time of emergence of probabilities of compounding wind and precipitation depending on the choice of the* ***30-year*** *baseline period for the CNRM-CM6 model. It illustrates that results of emergence can vary strongly depending on the chosen baseline period. In addition to modifying the potential time of emergence, the choice of the baseline period can also influence the results of contributions from the statistical properties changes (not shown), as these statistical changes are also assessed with respect to the baseline period.* ***ToE and contribution results could also be modified by the choice of the length of the sliding windows. For example, considering a larger window length could attenuate the changes of statistical properties between the baseline period and the sliding windows, thus modifying the ToE results. Also, in a transient climate context, this results in mixing different climate conditions and, thus, different statistical properties.***

As an illustration, ToE and contribution results for the CNRM-CM6 simulations are presented in Figs. S15 and S16 of the Supplement by considering sliding windows of 40 years (baseline period: 1971-1910), 50 years (baseline period: 1971-1920) and 60 years (baseline period: 1971-1930) but are not commented on in the present study."

Comment:

Fig. 6: What is the effect of sample size on the shown patterns? More extreme values are more uncertain, and bivariate exceedances are more uncertain than univariate one, hence ToE should be shifted back in time. Interesting that one gets a generally relatively rich, non-trivial structure here.

Response:

Fig. RC1 (see below) shows the ToE results for varying exceedance thresholds for the CNRM-CM6 simulations by considering 30-year, 40-year, 50-year and 60-year sliding windows. Please note that the color scale has been changed from Fig. 6 to be consistent with the following comment. By comparing panels RC1a-c, d-f, g-i and j-l together, we can see that, depending on the window length, different results are obtained for ToE matrices. ToE values and their relationships with the sample size is not trivial. Panels RC1a-c d-f and g-i show the same patterns for ToE, with ToE being, indeed, shifted back in time for most of the bivariate thresholds. In particular, when using a 50-year sliding window, none of the bivariate thresholds present a probability emerging when considering the changes of dependence only (RC1i). ToE values being shifted back in time can be explained by a reduced estimated confidence interval for natural variability due to the increased sample size. However, increasing sample size can also lead to obtaining later ToE values: for 60-year sliding windows (panels RC1j-k), later ToE results are obtained compared to those obtained with 50-year sliding windows (RC1g-i). This is mainly due to 1) the definition of ToE we used, with ToE detection when the probability signal permanently exceeds a certain threshold, and 2) probability signals that are flattened by increasing the window length, as already explained for Fig. S15. By being flattened, probability signals could emerge later from the confidence interval even though the range of the confidence interval for natural variability is reduced.

Fig. RC2 shows median contribution matrices of the marginal, dependence and interaction terms by considering 30-year, 40-year, 50-year and 60-year sliding windows. Again, by comparing panels RC2a-c, d-f, g-i and j-l together, we can see that, depending on the window length, different contribution results are obtained. In particular, similar patterns for the contribution of marginal and dependence properties are obtained for 30-year and 40-year sliding windows (RC2a-b and d-e), with dependence changes playing an important role for the probability of high bivariate extreme events (upper-right area of the subplots). This area of exceedance thresholds for which dependence properties contribute greatly to probability changes is however smaller with 40 than with 30-year sliding windows. The decrease of the importance of the dependence properties for probability of high bivariate extreme events is then confirmed when increasing the window length (RC2h, k). It results in having marginal properties mainly driving probability changes for all pairs of thresholds (Figs. RC2g, j). Concerning the interaction term (RC2c, f, i, l), contribution values are approximately equal to 0, highlighting again the negligible role of this term in probability changes regardless of the choice of the length of the sliding window.

Although these results are interesting, including them, either in the body of the study or in the Supplement, would make the paper more cumbersome, which we think is not appropriate. Please note that, in our response to the previous comment, we have already suggested adding new sentences in the sub-section 6.2 (Conclusion, discussion and future work/ Discussion and perspectives) to discuss window length and its effect on ToE and contribution results. We thus propose not to add further details for this point. However, investigating those patterns, the importance of the dependence on the probabilities of extremes, and how they are represented by climate models, is of course an interesting perspective to explore in future research.

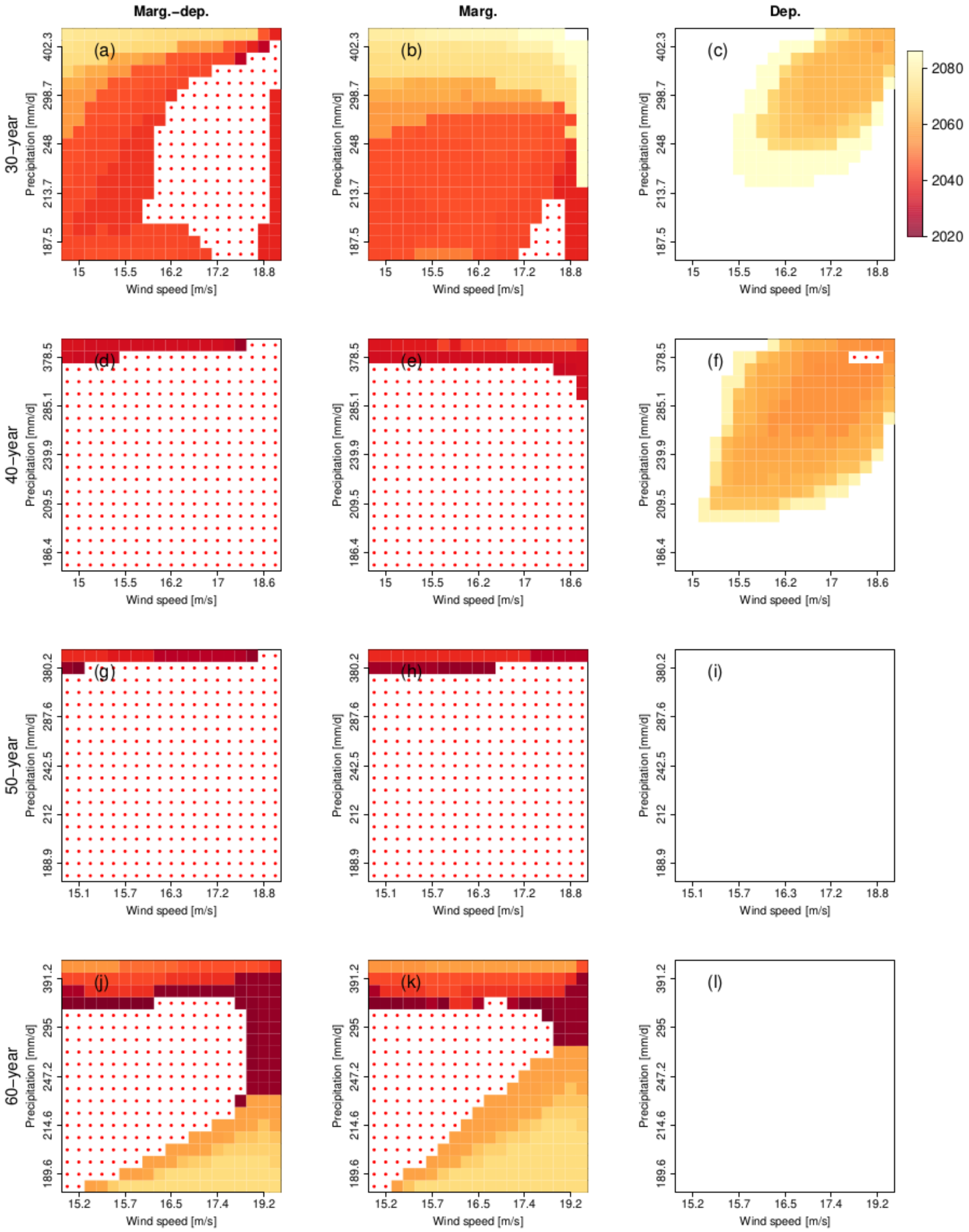


Figure RC1: CNRM-CM6 time of emergence (at 68% confidence level) for compound wind and precipitation extremes due to changes of (a, d, g, j) both marginal and dependence properties, (b, e, h, k) marginal properties only, and (c, f, i, l) dependence properties only. Results are displayed for probabilities computed by using (a-c) 30-year, (d-f) 40-year, (g-i) 50-year and (j-l) 60-year windows sliding over the period 1871-2100. In each application of the methodology, the first sliding window is considered as the baseline period. White cells indicate that no time of emergence is detected, while white cells with red points indicate ToE values before 2020. Results are presented for varying exceedance thresholds between the 5th and 95th percentile of compound wind and precipitation extremes data.

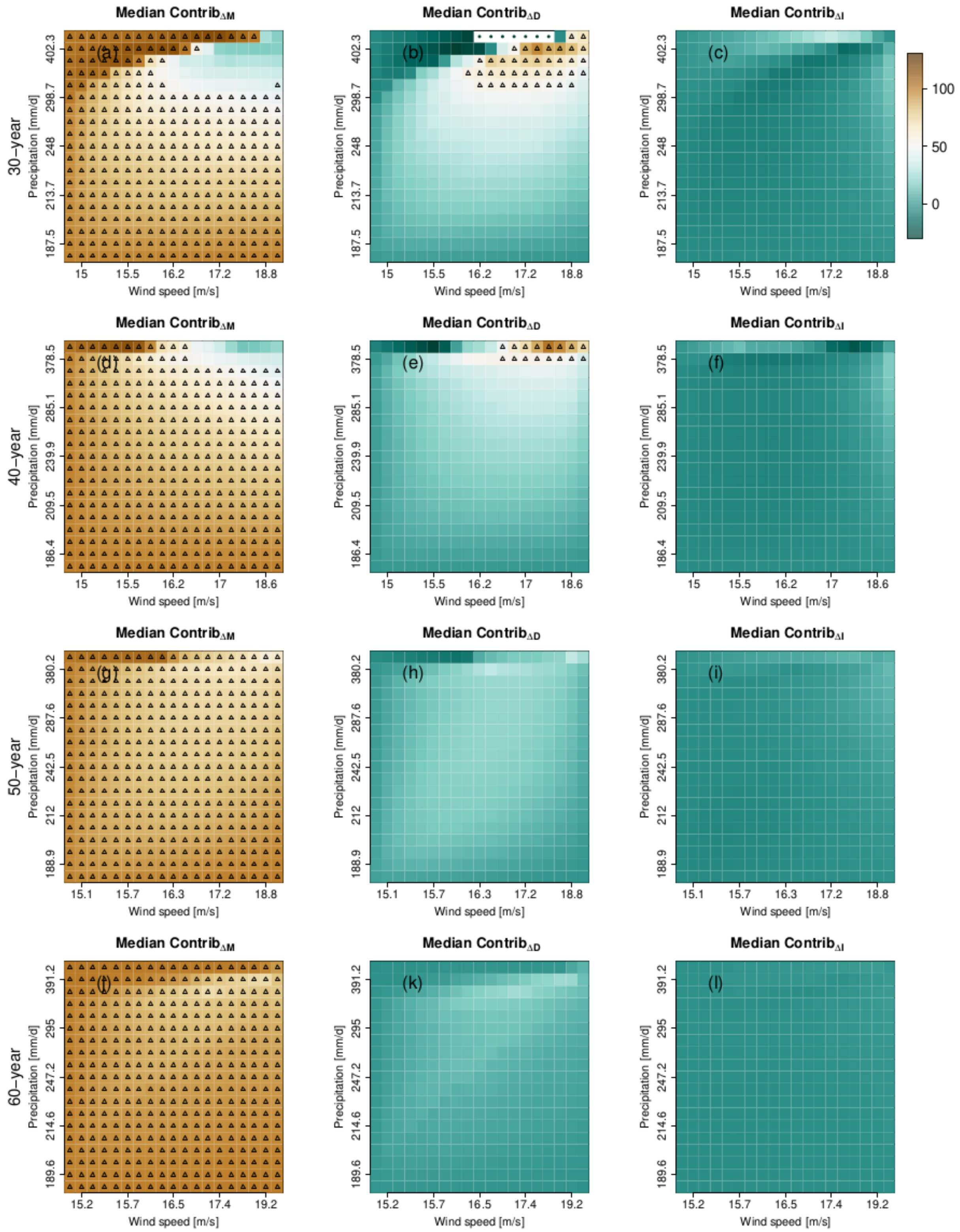


Figure RC2: Matrices of median contributions of the (a, d, g, j) marginal, (b, e, h, k) dependence and (c, f, i, l) interaction terms. Results are displayed for probabilities computed by using (a-c) 30-year, (d-f) 40-year, (g-i) 50-year and (j-l) 60-year windows sliding over the period 1871-2100. In each application of the methodology, the first sliding window is considered as the baseline period. Results are presented for varying exceedance thresholds between the 5th and 95th percentile of compound wind and precipitation extremes data. Upper triangles show a contribution ≥ 50 %.

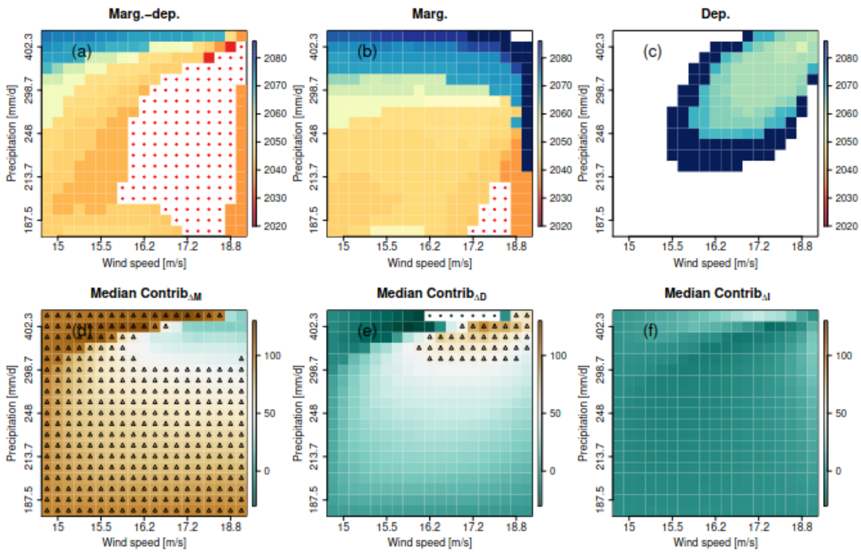
Comment:

For all figures: the colour scales for the years are not very intuitive. One continuous colour would make more sense.

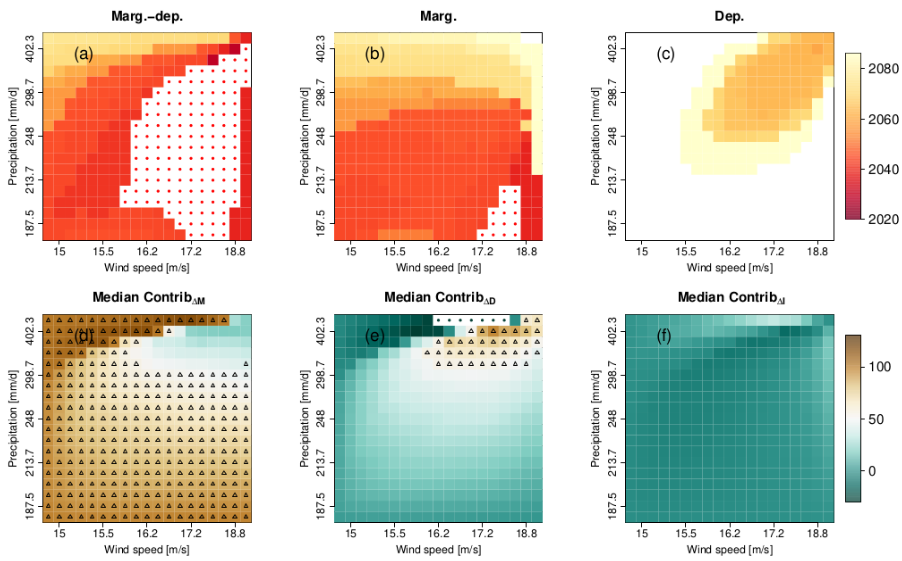
Response:

We propose to change the color scales for the years for all figures (i.e., changing the color scale “Red-Yellow-Blue” to the color scale “Red-Yellow”). Please also note that, now, we are also plotting only one color bar for each row and broadening them. As an illustration, we show here the modifications made for Fig. 6.

Previous Fig. 6:



Proposed new Fig. 6:



Comment:

Section 6 should be entitled: “Discussion and conclusion” or similar and then maybe "Summary" in Section 6.1.

Response:

We agree. Section 6 is now entitled “Summary and discussion” instead of “Conclusion, discussion and future work”. Section 6.1 is now entitled “Summary”.