Reply to Reviewer 2 for manuscript "Interannual variations in the seasonal cyle of extreme precipitation in Germany and the response to climate change"

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Reviewer 2: This work presents a non-stationary methodology to model seasonal and interannual variability of monthly maxima of daily precipitation, based on the Generalized Extreme Value distribution, applied to 519 stations in Germany. The subject is interesting, and the manuscript is very well structured, with appropriately designed analyses. Although the work is clearly presented, it follows a highly algorithmic approach which at times is difficult to follow. My remarks are mainly focused on the hydrological and practical relevance of the methodology particularly with respect to the nonstationary modelling of the interannual variations.

Major comments

- **Reviewer 2:** Although the study of seasonality through cyclo-stationary models is well established in the literature, modelling of interannual variations using nonstationary models is not as common. A possible reason might be that interannual variations do not have a well-understood physical basis, which is a theoretical requirement in order to rigorously apply nonstationary models (see e.g. Montanari and Koutsoyiannis, 2014). Rainfall interannual variations are usually irregular and linked to rainfall's natural variability, which is typically quantified and modelled with stochastic and stationary approaches (e.g. Iliopoulou et al. 2018; Iliopoulou and Koutsoyiannis, 2019). In this respect, I think it would be beneficial to expand the discussion in the Introduction on the rationale and scope of using a nonstationary approach to model interannual variability.

  Answer: In our analysis, we do not consider differences between successive years as interannual variations, but rather the trend, which could be non-linear as well. We added the sentence to the introduction: "Here, we point out that when referring to interannual variations, we are not addressing differences between successive years, but rather the trend over the entire observation period, which could be potentially non-linear." Additionally, we have added some sentences in the introduction to clarify the aim of using a nonstationary approach for these interannual changes: "Interannual variations in precipitation have been shown to be associated with its natural variability (e.g. Willems, 2013), increased air temperatures (Trenberth et al.,2003; Westra et al., 2013, 2014) and other effects influencing large-scale atmospheric circulations and precipitation characteristics (Pinto et al., 2007, 2009; Davini and d'Andrea, 2020; Detring et al., 2021). Most of these effects are highly non-linear and their roles are difficult to quantify. Here, we use time as proxy to combine those different unknown effects." Furthermore, we have included a sentence to highlight that our seasonal-interannual model is able to reflect linear changes and natural variability (higher-ordered polynomials): "Here, we use Legendre polynomials up to an order of five to describe the variations across years. This enables on the one hand the reflection of changes potentially associated with climate change and on the other hand allows for modelling of natural variability in extreme precipitation."

- **Reviewer 2:** A similar question relates to how such a method could be applied in practice. For instance, could the authors provide an example of a seasonal-interannual nonstationary EV modelling for a selected station compared to an application of their seasonal-only approach?

  Answer: A seasonal consideration of maxima in extreme value statistics provides additional information (monthly resolved return levels) and improves the quality of the return levels, as analysed in Fischer et al. (2018, 2019). An interannual consideration fosters on the one hand the knowledge about how seasonality in extreme precipitation has changed and on the other hand it enables more adabted concepts for engeneering purposes. To demonstrate the advantages, we have added the 100-year return levels for the seasonal-only model to Fig. 15 and wrote one sentence per example station to the main text. For *Rain am Lech*: "Considering the 100-year return levels of the seasonal-only model demonstrates that a non-interannual approach leads to highly underestimated values especially for the first record decades." For *Wesertal-Lippoldsberg*: "The model verification (Fig. 10) confirms that a model with a changing seasonal cycle better represents the data observed in summer for return periods of 10 to 50 years, while the 100- and 200-year return levels are strongly overestimated with respect to the observations, especially for the most recent decades. In constrast, the seasonal-interannual model is more beneficial for estimating winterly return levels with return periods longer than 30 years. These characteristics can be seen as well by comparing the 100-year return levels of the seasonal-interannual model with those of the seasonal-only model." For *Mühlhausen / Oberpfalz-Weihersdorf*: "Although differences between the 100-year return levels of the seasonal-only and the seasonal-interannual model are not very pronounced, the shift from late summer to early summer, which might be continued in future, cannot be detected with the non-interannual approach." For *Krümmel*: "For this example, the seasonal-only approach applied to the whole record might be beneficial in terms of long-term risk assessment and hydraulic design since natural variability does not play a key role for longer planning horizons. However, for short- to mid-term risk assessment, e.g. for agriculture or tourism sector, the natural variability might be of relevance."

Furthermore, we have included a section to the discussion in 8.3 pointing out a potential application of an interannual modelling approach for quantifying and communicating environmental risks in a changing world by calculating design-life levels. In addition, we added in Appendix C a brief explanation and calculation of the design-life level. We wrote in 8.3: "A possible application of the presented seasonal-interannual approach in the field of risk adaptation could be realised by calculating design-life levels. This concept has been introduced by Rootzén and Katz (2013) and widely applied in research and risk management (e.g. Thomson et al., 2015; Mondal and Daniel, 2019; Xu et al., 2019; Byun and Hamlet, 2020). The design-life level is a measure for quantifying and communicating environmental risks in a changing climate accounting for the service life of a system (design-life period, e.g. 30 years) and the time, when the system will be installed (e.g. in 2025). Due to changing extreme precipitation characteristics, the 2025-2055 1% design-life level could be different from the 2055-2085 1% design-life level. More detailed explanations and example calculations can be found in Appendix C. The seasonal-interannual modelling approach can be used to calculate future seasonal design-life levels either by extrapolating past climate trends or by an application to outputs from climate projections. Since for risk adaptation in an engineering context annual design-life levels are more beneficial then seasonal ones, the same methodological concept can be applied to obtain annual values out of a seasonal modelling approach (Maraun et al., 2009; Fischer et al., 2018)."

Appendix C has been added: "According to Rootzén and Katz (2013), the design-life level is a measure to quantify risks for engeneering design purposes in a changing climate. This measure can be regarded as a logical extention of the return level approach which can only be meaningfully interpreted in a stationary setting. For example, a 100-year return level of extreme precipitation is the value which is expected to be exceeded in mean once in hundred years. Due to changing climate, an event can occur in 2023 once every 100 years, in 2050 the same event might be exceeded on average once in 90 years. The changing return period (or exceedance probability) is an obstacle for engeneering applications. One solution is given by the design-life level, which accounts for the time when the hydraulic system will be build and the service life of the system, called the design-life period. While the design-life period should be very long for dike design (e.g. 10.000 years in Netherlands (Botzen et al., 2009)), the service life of a rain gutter is much shorter. The design-life level r_p can be obtained by numerically optimizing the equation:

$$\prod_{i=1}^{I} G_i(r_p) = p \tag{1}$$

with G_i being the Generalized Extreme Value distribution for year i, p the non-exceedance probability and I the design-life period. This approach assumes independent maxima. The design-life level is stated as T_1 - T_2 (1-p)% extreme level with T_1/T_2 indicating the start / end of the design-life period.

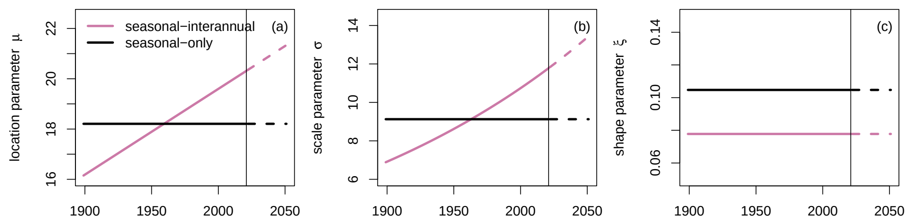

Figure 1: Estimated parameter for location μ (a), scale σ (b) and shape ξ (c) at the example station *Rain am Lech* for the month July using a seasonal-interannual model (pink) and a seasonal-only model (black). Additionally to the estimates for the observation period (solid line), extrapolated values since 2022 are also illustrated (dashed lines).

To calculate future design-life levels, we use the seasonal-interannual and the seasonal-only model to extrapolate the parameters of the GEV for the month July at the station *Rain am Lech* until 2051 (Fig. C1). With Eq. 1, the 2022-2051 1% extreme precipitation level ($I = 30$, $p = 0.99$) for the month July at *Rain am Lech* obtained with the seasonal-interannual model equals to 161.4 mm/day. In other words, there is a 1 in 100 risk that the largest daily precipitation event during 2022 - 2051 will be higher than 161.4 mm/day. The 2022-2051 1% extreme precipitation level for the seasonal-only approach is 132.5 mm/day. If the detected trend at *Rain am Lech* continues for the years 2022 - 2051, as assumed here, the seasonal-only approach will lead to underestimated risks and the designed risk adaptation system will be strained beyond its planning purpose.

- **Reviewer 2:** Regarding spatial consistency, Figure 6 suggests that stations with interannual components do not follow a specific spatial pattern, which could be potentially indicative of a physical mechanism, but rather show a large spatial variability, which might be indicative of a large uncertainty involved in the identification of these variations. How do the authors explain this spatial variability? Does the proposed nonstationary approach allow accounting for uncertainty in parameter fitting?

Answer: It is true that there is spatial variability in the selected models of neighbouring stations. There are several reasons:

1. Extreme precipitation is partly very small-scaled and one station could be affected by a heavy precipitation event while at a neibouring station it does not rain at all. A common problem in extreme value analysis is that very rare events could have large influence on the extreme value distribution especially if a short record is available.
2. The GEV parameter estimates interfere (Ribereau et al.,2011). For example, if the shape parameter is slightly increased the scale parameter will be adapted as well, such that the distribution will be fitted suitably to the data. Thus, similar distributions could be described with different parameters.
3. The model selection procedure select one suitable model. However, a different model could be even as good as the selected one. In each iteration of the stepwise-forward selection the BIC of every possible covariate is obtained and the model with the lowest BIC is selected. However, the difference in BIC between the best and the second best candidate could be negligible.

Spatial variability in the selected models is present. However, the synergy of all three GEV parameters and different covariates can model similar characteristics in extreme precipitation at neibouring stations, which can be seen for the estimated return levels. Nevertheless, common spatial characteristics in the selected interannual covariates can be detected, like described in the manuscript. We have added a sentence about the spatial variability in Section 4.1: "It can be seen that the selected interannual covariates are partly very variable in space. This can be explained by 1) a large spatial variability in extreme precipitation due to small-scaled very intense events and 2) the model selection procedure, which chooses one suitable model, even if other models are comparably appropriate. However, common characteristics can be detected:"

Uncertainty in parameter estimation can be taken into account by calculating confidence intervals, e.g. using the delta method (Coles, 2001). Since the aim of our investigation was to analyse whether interannual changes in seasonal extreme precipication in Germany can be detected with a nonstationary approach, we have refrained from integrating confidence intervals into our investigation. As we believe that uncertainty in return level estimates are crucial, we added a paragraph to the outlook section in 8.3: "In our investigation we consider return level estimates. However, analysing their uncertainties are crucial. For further investigations, confidence intervalls, e.g. calculated with the delta method (Coles, 2001), should be taken into account. A comparison of uncertainties evolved by the seasonal-interannual model and those of a seasonal-only model could deepen the investigation if interannual models are beneficial for risk assessment or if the changing return levels are rather within the uncertainty range of non-interannually varying return levels."

Minor comments

- **Reviewer 2:** Conclusions: It would also be interesting to note here the percentage of stations favoring a seasonal-only variation of the shape parameter. **Answer:** We have added a sentence in the maintext in Section 6: "Most of the stations (106 / 178, about 60 %) are represented by a model including seasonal variations, whereby many of them (92 /106 stations) do not favor an interannnually varying shape parameter at all." Additionally, we added in the conclusion: "The BIC based model selection strategy favours a flexible shape for 178 / 519 stations (about 34%), whereby about 52% (92/178) of these records prefer a seasonal-only component. For the remaining stations with variable ξ, an interannually changing seasonality occurs more often than the direct interannual variations.
- **Reviewer 2:** Please explain subscripts i, j in Equation (3). **Answer:** We have added to the text: "μ_0 denotes the constant intercept (offset), the second term the direct effects of a covariate X_i, e.g. seasonal or interannual, and the third term the intercations between different dimensions (indicated by i and j), e.g. seasonal and interannual."
- **Reviewer 2:** Line 110: typo 'interactions' **Answer:** changed