hess-2020-605

Responses to anonymous referee 4

Erwin Rottler, Axel Bronstert, Gerd Bürger and Oldrich Rakovec

January 11, 2021

Dear Anonymous Reviewer 4,

thank you very much for reviewing our manuscript. We are very grateful for your comments and suggestions. In the following, we provide detailed responses to all your comments.

On behalf of all authors,

Sincerely,

Erwin Rottler

Contents

1 General Comment

> The paper addresses a highly relevant subject on changes in flood seasonality in the Rhine basin, by analysing how climate change affects different components of the water balance and their aggregated effect on peak flows. The authors elegantly demonstrate by means of model simulations for different GCMs and climate scenarios the contributions of snow melt and rainfall-driven runoff to peak flow generation over the seasons. These analyses form a relevant contribution to earlier studies on the impacts of climate change on peak flows in the Rhine basin, provide nice insight in the underlying contributions of rainfall and snowmelt, and indicate their effects on time shifts in peak flow occurrences. The paper's title well covers the contents; the paper is well-structured, clearly presents its results in text and figures, and the interpretations, discussion and conclusions are well supported by the results. I would rate the significance and quality of the paper 'Good'.

Thank you for reviewing our manuscript. In the following, detailed responses to all your comments.

2 Specific comments

2.1 Comment 1

> Fig 1: I would suppose that the nival peak not only shifts to earlier in the season but also becomes smaller under CC - as there will be less total snow accumulation over the winter season.

You are right. We need to re-think the figure and improve the description of the hypothesis. We will improve the scheme and corresponding paragraphs in the text.

2.2 Comment 2

> Line 30: 1.5, 2 and 3 degrees warming - relative to 1970 - 2000

We investigate 1.5, 2.0 and 3.0 °C global warming levels relative to pre-industrial levels. The period 1971–2000 is assumed to be warmer by 0.46 °C compared to pre-industrial levels already. We will add another sentence on this into the method section to avoid any misunderstandings.

2.3 Comment 3

> Section 2: provide a bit more information on: which parameters did you calibrate? In particular you have a detailed representation of crops and soil types, did you use reference values in all cases, or did you do any calibration here? How did you choose LAI values for different vegetation types and seasons and latitude? How did you perform the bias correction to GCMs for future climates?

Thank you pointing this issue. We will include additional information on our multi-basin calibration, soil types, LAI values and the bias correction of the GCM data.

2.4 Comment 4

> P4, L11: assess -> assesses

Thank you, we will correct this typo.

2.5 Comment 5

> P4, L13: bases -> is based

Thank you, we will correct this typo.

2.6 Comment 6

> P6, L6-9. Do I understand here that the projection times of the periods where the 'targeted' warming was reached was different for each realisation? And with different RCPs you may reach the same warming at different moments (e.g. 1.5 degree under RCP 8.0 early in the century, and RCP2.6 only late) - but to what extent are these scenarios different in your simulations (associated P?). Can you indicate which are the according time horizons used in your simulations?

Yes, you understand correctly. Different GCM-RCP combinations reach the same warming at different moments. "A detailed description of the determination of warming levels is given in the supplementary material of Thober et al. (2018)" (Page 6, Line 9). We will extend this paragraph and add more information on the determination of warming levels.

2.7 Comment 7

> P6, L14: for the Rhine basin as a whole (e.g. Cologne) a 5 day-period for the precipitation sum seems quite short to generate extreme floods, in particular in view of saturating the soil and travel time of peaks from tributaries.

We will take a closer look into this and better explain the selection of the window widths for precipitation, snowmelt and precipitation.

2.8 Comment 8

> P6, L19: river discharge at Basel is considerably dampened by the effects of the Swiss lakes. For that reason, earlier studies focused on catchments upstream of the lakes (e.g. Murg, Thur). Can you indicate to what extent timing and maxima of small peaks - in particular after a dry period with low lake levels - are affected by this?

Yes, discharge upstream gauge Basel is considerably influenced by the large Swiss lakes. We will extend our discussion section and add more information on the dampening effect of large lakes.

2.9 Comment 9

> Figure 5: Please indicate on how many runs each histogram is based. From the methods I read how many GCMs reached each warming, with only 8 of them reaching 3 degrees, but this is not clear for the other histograms. To what extent do different numbers of realisation result in different occurrences of highest extremes, and did different GCMs result in different extremes under - in spite of bias correction?

We will try to find a way to include the number of GCM-RCP combinations reaching each warming level directly into the figure(s). Yes, you are right. Caution has to be exercised, as the different warming levels base on different numbers of realisations. We display both boxplots and histograms (probability densities) to get a comprehensive insights and try to be cautions when interpreting results. So far, we did not encounter any abnormal differences among GCMs and extremes simulated.

2.10 Comment 10

> Fig 5; P8, L9: whereas both for Basel and Cochem there is a decline in the timing of summer maxima for higher temperatures, Cologne shows a small peak emerging around DOY 250 - can you explain this? Consider using the same horizontal scale for figs 5d-f.

Yes, there seems to be a small peak emerging around DOY 250 in the histograms of gauge Cologne. However, when considering such small changes at gauge Cologne, also the tendency toward more peaks in summer at gauge Cochem might need to be considered. We will take a look into this. Changes are only small, but might still be worth discussing. Yes, a common horizontal scale is a good idea.

2.11 Comment 11

> P10, L4: is detected -> are detected

Thank you, we will correct this typo.

2.12 Comment 12

> P10, fig 6 (k,l): by displaying annual maxima distributions we indeed can see how these shift over time, but we cannot see how shifts evapotranspiration maxima link to peak flows, as the connection to the flood events is lost: we cannot see how much was the 'reduction' of the annual peak flow maxima due to evapotranspiration loss (as you do in fig 6 ab indicating the 'contribution' of snowmelt to the annual maxima). It makes sense that under a warming climate annual maximum evapotranspiration goes up - but if that happens in summer when floods never arise it is hard to judge the role of evapotranspiration in changing peak flows. In fig 9g we can see that the contribution of evapotranspiration change is small indeed.

We agree. The current analysis does not allow to directly link changes in evapotranspiration to peak flows. Yes, the investigation of monthly maxima can give a first insight, however, does not fully address this issue. We will think about this and improve our manuscript with regard to this aspect.

2.13 Comment 13

> P11: Discussions -> discussion

Thank you, we will correct this typo.

2.14 Comment 14

> P11, L4: ....diminish seasonal snow covers -> please add in a few words the key aspects of that: the total volume, the duration and the timing of melt.

Thank you for this hint. We will include additional information here to improve clarity.

2.15 Comment 15

> P11, L6: Smax14 is singular.

We refer to snowmelt sums displayed in the indivudial boxes of the months. We will rephrase this part.

2.16 Comment 16

> P11, L8: 'forward' -> in first time use, explicitly explain that you mean: 'earlier in the year'

We will rephrase this accordingly.

2.17 Comment 17

> P11, L10, 13-14: two factors may play a role: the timing of melting, and the amount of snow that has accumulated so far to be available for melting - you do not indicate the maximum amount of snow that has accumulated by the end of the season to be available for melt.

We will rephrase this sentence to avoid any misunderstandings. Yes, reduced snow accumulation also plays an important role.

2.18 Comment 18

> P11, L15. I do not see a contradiction suggested by using 'however'. Actually, you change subject here to low flow situations, as caused by disappearing glaciers and intensified evapotranspiration, which becomes different from 'lower maxima',

We agree with Reviewer that using “However” is not correct. We will rephrase this sentence.

2.19 Comment 19

> P12. l6 (and in the rest of the paper, in particular in the conclusion, P14, L32): I am not sure whether you should formulate this as 'intense rainfall events' in mm per hour and use this formulation for both summer and winter. 'High intensity' rather relates to high intensity summer storms - as you indicate in lines 12-15 here, but for the winter season I would not formulate that as intensity. Moreover, you consider in your study accumulated precipitation sums over 5 days - that is an amount, not an intensity.

Yes, you are right. We will change this and not call it “rainfall intensity”. We will find a different term that describes the variable investigated better, e.g. "rainfall totals" or "rainfall amounts".

2.20 Comment 20

> P12, L12. Here you make a relevant statement - that the summer extremes were still supported by snow melt from the Alps to produce their maxima - I presume that that has been derived from the associated historic descriptions. With reduced snow melt in late spring this would indeed reduce the risk of summer floods. Conversely, higher temperatures under future climate change may lead to more intense summer precipitation - still causing higher peak flows. Here we may encounter the questions: does the latter only hold for smaller catchments within the basin, or do these still feed large floods to Cologne? And some GCMs show a N-S difference in precipitation change (some even the signal) across the Rhine basin: is that the case in your experiments? From the histograms in fig 6g this is hard to derive. It would affect probabilities of extreme summer floods, as we experienced in early 2000s in the Elbe.

Yes, this is a very important point. For large basins, such as gauge at Cologne, local convective storms hardly play any role. Our results indicate an increase in 5-day rainfall amounts in the investigated sub-basins, also for summer. We will take a closer look into this and extend our manuscript accordingly.

2.21 Comment 21

> P14, L3: It is not a true 'interaction' between snow fall and precipitation, but their effects are counterbalancing - as you explain in the following lines.

We will rephrase this and avoid the term "interaction" here.

2.22 Comment 22

> P14, L9: hint -> suggest

Thank you, we will modify this.

2.23 Comment 23

> P14, L14: originate - > originates; During this period, we have experienced already over 0.5 degree of warming, so it would be interesting to know what the average for the past few decades would be.

Yes, the numbers we present from Stahl et al. (2016) refer to the historic period 1901–2006. Stahl et al. (2006) provide both long-term averages and figures with the time series of the runoff components: Fig. 4 in
https://chr-khr.org/en/file/1057/download?token=Zg6SY04i
Yes, due to rising temperatures within the 20th century, there possibly has been changes in the fraction of snowmelt contributions to runoff already. In our opinion, Fig. 4 also highlights the strong annual to decal variability of the relative fraction of the streamflow components. We will rephrase this part accordingly.

2.24 Comment 24

> P14, L33: 'intense precipitation events' (see earlier comment): would you describe the precipitation driving the Elbe floods earlier this millennium as 'high-intensity' or 'large amounts'? (actually, I think it was a combination of both....). I would avoid suggesting that more intense summer showers will cause the Rhine to flood Cologne.

Indeed. To avoid any misunderstandings, we will replace the term "intensity". We will scan through our manuscript and rephrase all corresponding sentences.

2.25 Comment 25

> Discussion point to consider: Your 30-year time slices from which you determined the flood maxima may not include the very extremes that are relevant for flood protection - in the box plot you see a few isolated extremes that occurred in your simulations. To what extent do you think this affects your overall message?

Yes, with regard to flood protection, the very high values are of great interest. In this analysis, we focused on the hypothesis of a merging of the flood regimes that might result in the creation of such extreme events. We are mostly interested in temporal shift and changes in magnitudes. In this regard, we focus on changes in underlying flood-generating processes. "Isolated extremes" do not influence our results and overall message. However, we will include this point of singly very strong extremes and their significance into our discussion.

2.26 Comment 26

> P15, L10. Under recommendations: Would calibration on observed extent of snow cover using RS support calibration of snow melt modules to support these analyses? To what extent would precipitation falling on a snow cover further enhance melting of a snow cover (so: not snow melt not only depends on T, but also on warm precipitation water) - and would we need to consider that in modeling? Lakes: of course these buffer flow in dry periods, but that was not the focus of your paper, it might be interesting to see their role in generating peak flows.

Yes, using a multi-variable calibration including satellite-based snow cover maps provides a very good opportunity to further improve the simulations. We will include this information into the conclusion. The snow module currently available in mHM is based on a degree-day approach. As we describe in the method section: "In order to account for snowmelt following the energy input from liquid rainfall, degree-day factors are increased depending on the amount of liquid precipitation. Degree-day factors only can increase to a certain threshold value." Hence, mHM already has a (simple) way of addressing the energy input through liquid rain. The implementation of a physically-based snow routine might improve this aspect and addresses rain-on-snow events better.

2.27 Comment 27

> For policy makers / river managers it may be relevant to see a conclusion on whether we should anticipate changes in summer floods - as the use of the river banks (agriculture, tourism) has a strong seasonality.

Yes. We will try to extend our discussion/conclusion part with regard to this aspect.