Dear reviewers,

Thank you very much for your valuable comments. We have applied the suggested revisions to the manuscript and have responded to comments, point by point, here.

General Remarks (some parts may be repeated in point-by-point responses to the comments)

Regarding the definitions of flood and drought, we agree that there are many different indices in the literature that can be used, and which may be well suited for different purposes. However, the abundant of indices also adds to the complexity of selection of appropriate indices, and we need to select one so that an analysis at this scale is practical. In case of our selection, we may note that United States Geological Survey (USGS) in its annual streamflow reports uses the 95th and 5th percentiles of streamflow as thresholds for high and low flow studies (Jian et al., 2015). Other studies also have used 5^{th} and 95^{th} percentiles to define streamflow extremes (Koirala et al., 2014). Earlier studies have used the 95th percentile of streamflow as a threshold for flood definition in gridded streamflow data (Wu et al., 2012, 2014). The 5th percentile of streamflow has also been used as a threshold for drought definition (Ellis et al., 2010; Sprague, 2005). Such a definition for flood threshold is being used in daily flood monitoring maps produced by the USGS (https://water.usgs.gov/floods/) (please refer to the map's legend: 95^{th}-98^{th} percentile and 99^{th} percentile categorization) and in the NASA-funded gridded $1/8^{th}$ degree resolution Global Flood Monitoring System (GFMS) (http://flood.umd.edu/) (please refer to General Description). We have added these references to percentile-based streamflow thresholds to the revised manuscript.

However, in response to the comments made by the reviewers, we have omitted the words flood and drought from the revised title and use "streamflow extremes" instead. Accordingly, we study changes in 95^{th} and 5^{th} percentiles of streamflow and only refer to changes in those extremes as increase in potential for flood and drought hazards. We edited the manuscript accordingly.

We see in the comments that the referees show interest in the joint analysis of high and low flow extremes, but also recommend to better describe the novelty of this study in the manuscript. Accordingly, we have added paragraphs to the introduction to emphasize on the knowledge gap that we are aiming to fill. To summarize a few, Giuntoli et al. 2015 studies changes in *frequency* of *un-routed* runoff (dimension $[L.T^{-1}]$) extremes under *one* warming scenario, while we study changes in *magnitude/intensity* of *routed* runoff (streamflow, dimension $[L^3.T^{-1}]$) extremes under *two* different warming scenarios. Un-routed runoff may not be directly used for flooding study, but routed runoff (streamflow) has been used for this purpose in the literature instead (for instance: Koirala et al., 2014 and Hirabayashi et al. 2013). So although Giuntoli et al. 2015 is closest to ours in some respects, there are critical differences. Prudhomme et al 2014 also studies un-routed runoff, not streamflow. Koirala et al. 2014 studies 5th and 95th percentiles of streamflow, but routed by only one state-of-the-art GHM, and hence, does not account for GHM uncertainties. Hirabayashi et al. 2013 also uses a single state-of-the-art GHM, to study the *frequency* of extremes.

We study the change in the *magnitude/intensity* of the high and low extremes to understand the projected changes in the distribution of streamflow over the next century, while earlier studies (Giuntoli et al. 2015 for instance, and the others referred in the comments by reviewers) study changes in the *frequency* of streamflow passing the high and low extreme threshold. However, the thresholds used in those studies are defined based on the historical (20th century) distribution of streamflow. We find that the distribution of the streamflow is projected to change in the 21st century, and hence, the 95th/10th/5th percentiles used by these studies will not hold over the next century. Therefore, studying the changes in the *magnitude* of streamflow extremes can provide better interpretability of projected changes in the streamflow distribution compared to the *frequency*. Also, in the current work we study changes in flood and drought risks (both high and low flow extremes) together to understand the changes in streamflow distribution and simultaneous vulnerability profiles to different types of hydrological risk in different regions.

We also study the changes under two emission scenarios (RCP2.6 and RCP8.5) to compare the impact of different levels of warming on streamflow distribution and consequently flood and drought risks (Giuntoli et al. 2015 uses only one (RCP8.5) warming scenario). We also calculate the number people affected by changes in different regions to understand whether the areas of increased risk coincide with highly populated regions.

Thank you.

Author Response References:

Ellis, A. W., Goodrich, G. B. and Garfin, G. M.: A hydroclimatic index for examining patterns of drought in the Colorado River Basin, Int. J. Climatol., 30(2), 236–255, doi:10.1002/joc.1882, 2010.

Giuntoli, I., Vidal, J. P., Prudhomme, C. and Hannah, D. M.: Future hydrological extremes: The uncertainty from multiple global climate and global hydrological models, Earth Syst. Dyn., 6(1), 267–285, doi:10.5194/esd-6-267-2015, 2015.

Jian, X., Wolock, D. M., Lins, H. F. and Brady, S.: Streamflow of 2015—Water year national summary, U.S. Geological Survey Fact Sheet 2016–3055, 6 p., doi:10.3133/fs20163055. [online] Available from: https://waterwatch.usgs.gov/2015summary/, 2015.

Koirala, S., Hirabayashi, Y., Mahendran, R. and Kanae, S.: Global assessment of agreement among streamflow projections using CMIP5 model outputs, Environ. Res. Lett., 9(6), 64017, doi:10.1088/1748-9326/9/6/064017, 2014.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H. and Kanae, S.: Global flood risk under climate change, Nat. Clim. Chang., 3(9), 816–821, doi:10.1038/nclimate1911, 2013.

Sprague, L. A.: Drought Effects on Water Quality in the South Platte River Basin, Colorado, J. Am. Water Resour. Assoc., 41(1), 11–24, doi:10.1111/j.1752-1688.2005.tb03713.x, 2005.

Wu, H., Adler, R. F., Hong, Y., Tian, Y. and Policelli, F.: Evaluation of Global Flood Detection Using Satellite-

Based Rainfall and a Hydrologic Model, J. Hydrometeorol., 13(4), 1268–1284, doi:10.1175/JHM-D-11-087.1, 2012.

Wu, H., Adler, R. F., Tian, Y., Huffman, G. J., Li, H. and Wang, J.: Real-time global flood estimation using satellite-based precipitation and a coupled land surface and routing model, Water Resour. Res., 50(3), 2693–2717, doi:10.1002/2013WR014710, 2014.

Anonymous Referee #1

Received and published: 27 June 2017

Review of "Global change in flood and drought intensities under climate change in the 21st century".

This paper aims at understanding how climate change will manifest in changes in flood and drought conditions globally. To pursue this, the authors collected ISI-MIP streamflow projections (which are based on bias corrected output of five global climate models (CMIP5), and five hydrological models) at a 0.5x0.5 spatial scale. Climate scenario's that are explored include RCP8.5 (which assumes emissions continue to rise throughout the 21st century) and RCP2.6 (which assumes emissions peak between 2010-2020, with emissions declining substantially thereafter).

To quantify changes in flood and drought conditions, the authors calculated the "normalized change" which they defined as the difference between mean percentiles (5th for low flows and 95th or high flows) of 20th century flow conditions compared to 21st century flow (normalized by the sum of 20th and 21st flow percentiles). Calculations are performed for areas where streamflow >0.01 mm/d, and exclude Greenland. Global maps of changes are provided.

The results suggest that: (i) Globally, both floods and drought are expected to intensify. (ii) in some regions (especially several highly-populated areas), both flood and drought intensity will intensify (iii) Especially, in northern high latitudes flood intensities will increase. (iv) RCP8.5 leads to nearly 2 times higher impact on changes in flood and drought intensities compared to RCP2.6. (v) Hydrological models have a larger contribution to uncertainty in the projections, compared to the effect of different climate models.

General comments

Understanding the nature of future floods and drought, and the effect of changing climate conditions on these hydrological extremes is very relevant for HESS. The analysis is rather straightforward and reasonably well-explained.

However, I do have several (major) concerns that need to be addressed before I recommend publication of this manuscript in HESS:

1) What makes the metric you define to characterize changes in flood and low intensities appropriate for the problem that you address? While the 5th and 95th flow percentiles are surely representing higher and lower flow conditions, they are not real hydrologic extremes. For example, if the 95th percentile represents flood conditions, every grid cell would experience _18 flood days per year. Would it not be much more useful to quantify changes in the more extreme conditions (e.g. 99th percentile?). It seems that this choice arises from Giuntoli el al (2015) *(except that they use the 10th percentile for low flow), but does that warrant that it actually is an appropriate metric to use?*

We agree that there are many different indices in the literature for flood and drought definitions that can be used. However, the abundant of indices also adds to the complexity of selection of appropriate indices, and we need to select only one of those so that an analysis in this scale is practical. In case of our selection, we may note that United States Geological Survey (USGS) in its annual streamflow reports uses the 95th and 5th percentiles of streamflow as thresholds for high and low flow studies (Jian et al., 2015). Other studies also have used 5th and 95th percentiles to define streamflow extremes (Koirala et al., 2014). Earlier studies have used the 95th percentile of streamflow as a threshold for flood definition in gridded streamflow data (Wu et al., 2012, 2014). The 5th percentile of streamflow has also been used as a threshold for drought definition (Ellis et al., 2010; Sprague, 2005). Such a definition for flood threshold is being used in daily flood monitoring maps produced by the USGS (https://water.usgs.gov/floods/) (please refer to the map's legend: 95th-98th percentile and 99th percentile categorization) and in the NASA-funded gridded 1/8th degree resolution Global Flood Monitoring System (GFMS) (http://flood.umd.edu/) (please refer to General Description). We have added these references to percentile-based streamflow thresholds to the revised manuscript.

2) A lot of literature is already available on the topic of projected flood and drought (/low flow) changes. While you cite several papers in the introduction, it remains unclear to me which knowledge gap your paper fills compared to earlier work. I made a list of detailed suggestions in the comments below, which may help to address this issue.
However, right now when I read the abstract I do not see understand knowledge gap you address, when I read the introduction no I get some idea of what has been done before but still no clear niche is identified that you fill. Any discussion is a description of the results rather than how we better understand global flood and drought changes, and in the conclusions, you summarize findings, but still I have difficulty how this relates to the vast amount of literature on previous flood changes (also what's new compared to Arnell et al. 2016, Alfieri et al. 2015, 2017, Giuntoli el al. 2015?). While I do not doubt that are new things in your paper, they need to be clearly identified.

We have added more paragraphs to the introduction to emphasize on the knowledge gap that we are aiming to fill. To summarize a few, Giuntoli et al. 2015 studies changes in *frequency* of *un-routed* runoff (dimension [L.T^{-1}]) extremes under *one* warming scenario, while we study changes in *magnitude/intensity* of *routed* runoff (streamflow, dimension [L^{3}.T^{-1}]) extremes under *two* different warming scenarios. Un-routed runoff may not be directly used for flooding study, but the routed runoff (streamflow) has been used for this purpose in the literature instead (for instance: Koirala et al. 2014 and Hirabayashi et al. 2013). So although Giuntoli et al. 2015 is closest to ours in some respects, there are critical differences. Prudhomme et al 2014 also studies un-routed runoff, not streamflow. Koirala et al. 2014 studies 5th and 95th percentiles of streamflow, but routed by only one state-of-the-art GHM, and hence, does not account for GHM uncertainties. Hirabayashi et al. 2013 also uses a single state-of-the-art GHM, to study the *frequency* of extremes. We study the change in the *magnitude/intensity* of the high and low extremes to understand the projected changes in the distribution of streamflow over the next century, while earlier studies (Giuntoli et al. 2015 for instance, and the others referred in the comments by reviewers) study changes in the *frequency* of streamflow passing the high and low extreme threshold. However, the thresholds used in those studies are defined based on the historical (20th century) distribution of streamflow. We find that the distribution of the streamflow is projected to change in the 21st century, and hence, the 95th/10th/5th percentiles used by these studies will not hold over the next century. Therefore, studying the changes in the *magnitude* of streamflow extremes can provide better interpretability of projected changes in the streamflow distribution compared to the *frequency*. Also, in the current work we study changes in flood and drought risks (both high and low flow extremes) together to understand the changes in streamflow distribution and simultaneous vulnerability profiles to different types of hydrological risk in different regions. We also study the changes under two emission scenarios (RCP2.6 and RCP8.5) to compare the impact of different levels of warming on streamflow distribution and consequently flood and drought risks (Giuntoli et al. 2015 uses only one (RCP8.5) warming scenario). We also calculate the number people affected by changes in different regions to understand whether the areas of increased risk coincide with highly populated regions.

3) Related to the previous points: the rationale behind some choices in the analysis is missing. Can you answer: (i) why we would be interested in flood and drought changes simultaneously.

Flood and drought risks are studied using the high and low extremes. Studying the change in magnitude of the high and low extremes together shows the change in the distribution of the streamflow.

(ii) why the metric you choose are appropriate to characterize what you do

We explained our choice of indices earlier here.

(iii) why correlating population density and change in flood hazard is meaningful.

We are interested to know whether the areas of increased risk coincide with highly populated regions (and hence, how many people are at risk).

(iv) why looking at "intensity" is novel and important compared to "frequency (which is already available using a similar approach).

We study the change in the *magnitude* of the high and low extremes to understand the projected changes in the distribution of streamflow over the next century, while earlier studies

(Giuntoli et al. 2015 for instance, and the others referred in the comments by reviewers) study changes in the *frequency* of streamflow passing the high and low extreme threshold. However, the thresholds used in those studies are defined based on the historical (20th century) distribution of streamflow. We find that the distribution of the streamflow is projected to change in the 21st century, and hence, the 95th/10th/5th percentiles used by these studies will not hold over the next century. We argue that studying the changes in the magnitude of streamflow extremes provides us with better understanding of projected changes in the streamflow distribution compared to the frequency.

(v) why do we also need to look at changes in median flow (when the purpose seems extreme flows) I do not try to imply that these choices are not well thought out and relevant. However, I do think you need to take the reader by the hand in why such choices are made

One goal of our work is to also study changes in the distribution of streamflow time series. Studying mean flow along with high and low extremes enables us achieve that goal better. We have reflected this in the revision.

4) 0.5 x 0.5 degrees and daily forcing seems like very large spatial and temporal scales to resolve the hydrology of flood processes. I understand it is "the best you can work with" right now if you want to understand flood changes globally for the entire 21st century.
However, can you better reflect on how this actually affect the degree to which you can resolve flood changes? Many different flood generating processes cannot be represented at these scales. For example, flash floods (e.g. I expect you need subdaily P for this?) or snowmelt driven floods (e.g. I expect that you need to parametrize the sub-grid heterogeneity of snow conditions) seem challenging, while in many places these processes are very important (e.g. see Berghuijs et al., 2016). Since there essentially is very little science in the paper (basically there are no rejectable hypotheses you test, and the paper provides a summary of available data), I think you need to say a few useful things on this topic, such that it still meets the standards of a journal like HESS.

We actually do not investigate hydrology of flood processes, but change in streamflow extremes under climate change that results in change in flood risks. As you said, it may not be feasible to study flood process in such coarse resolution, and in global scale. For that purpose, one may resort to Reginal Climate Models and limit the study to basin scale. It may not be feasible to study flash floods in global scale, since these analyses depend on the local land cover and soil type (and in shorter time scales), which are not accurately modeled in Global Climate Models. This is one of the reasons that we use multiple GHMs that use different routing schemes for streamflow generation to at least address those types of uncertainties to some degree. However, by understanding the projected changes in streamflow extremes in large scale over a region, one may use this knowledge to better calibrate the regional models to study flash floods in finer spatial and temporal scale. Our study is more similar to that of Koirala et al. 2014 and/or Hirabayashi et al. 2013. As we stated earlier, we added paragraphs to the Introduction section of the manuscript to explain better why we are interested in this type of analysis and what knowledge gap we are aiming to fill.

5) I suggest to be careful with the using low flows and drought interchangeably. Low flows and droughts are not the same. You quantify changes in low flow conditions, not in drought conditions (which reflect some deviation compared to the normal flow conditions of a catchment during a particular time of the year). These two different concepts should not be mixed. (e.g. see Van Loon, 2015). To some degree the same applies for high flows and floods. However, this difference seems less important, since those two concepts are more closely related.

We have changed the terminology in the revision, and link the change in low flow to drought *risk*, instead of direct change in drought *intensity*.

6) The changes in flood and drought indices per latitude intrigue me (Fig 2). How can they virtually be the inverse of another (when organized per latitude)? Is this the physical reality or an artifact of how this study quantifies changes in these aspects?
Surely, floods and drought within one area can be connected (since they are part of the same climate and landscape system). However, (in my opinion) this almost oneon-one inverse pattern seems to require some attention.

This is actually expected. We define the increased flood indicator as *increase* in P95 and increased drought indicator as *decrease* in P5, so by increase in all percentiles of flow the flood and drought indicators should show the opposite direction of change (same for decrease in all percentiles of flow). If all percentiles of flow increase in a grid cell, it means that the flood indicator would increase (P95 increase) but drought indicator decrease (P5 increase). However, there are regions that the flood and drought indicators both increase or both decrease or have different rate of change, due to change in the distribution of the streamflow; such grid cells are located in this study.

7) You quantify the percentage of land area that undergoes significant streamflow change. However, the two-sample t-test that you use for this (as explained in the supplementary material) seems inappropriately used. Why would scaling this relationship by the streamflow time series variances be appropriate here? Should they not be scaled by some measure of (e.g. between year) variability in the hydrologic extremes flow?

This is actually what we have done. We do the calculations directly on the extremes times series, not the mean time series. We edited the Supplementary Materials' text to clarify this.

8) By presenting only mean values of results (e.g. the mean magnitude of flood and drought changes) the reader has no idea from what distribution of changes these mean values are derived. This seems rather basic information that can easily be presented in will provide valuable insight for the reader. Right now, some of the numbers you use in key points of your *paper are difficult to interpret because we have no idea if they represent many small changes and a few extreme ones, or because they represent consist medium size changes.*

We report mean value of the results in the abstract to summarize the global findings, and in the text to discuss the changes in a broader scale. However, we do provide the global maps of changes in each indicator, which show the magnitude of changes (represented by color saturation) in each grid cell and under each warming scenario. The scatter plots in Figure 2c&d also show the distribution of small and large changes under each scenario. We also show the results averaged by latitude to show the averaged changes over different climate boundaries (high latitudes, mid latitudes, tropics and subtropics, etc). We also provide the global maps for each of the models individually in the Supplementary Materials.

9) Please address the list of comments I provide below. (Several of these comments go beyond small technical details.)
detailled comments
Page 1 Line 11-12. Consistent with my main comments above, it would be very useful to have a transition sentence that actually introduces the knowledge gap in flood and drought risk projections that the paper aims to fill. Preferable reflect on that goal in the end of the abstract.

As we stated earlier, we added paragraphs to the Introduction section and revised the manuscript to explain better what knowledge gap we are aiming to fill.

Line 16: without a definition of what aspects of these hydrological extremes you actually look at (e.g. duration, or magnitude, or both)) these precise percentages not very useful. Being more specific in line 12 may resolve this issue. The same problem applies to all other percentages provided in the abstract. (or the statement in lines 22-24)

As answered in other comments, we have revised the manuscript and the terminology to clarify our findings.

Line 17-19: "the averaged rates of increase" (can) suggest that you exclude places where it reduced? Or is this the average of all increases and decreases globally?

Yes, this is the average of change in those areas that experience increase. Average rates of increase and decrease are reported separately, as also shown in Table 1.

Line 19: "potential risk" or "are projected" (since I guess all areas are under the "potential risk"?)

We edited it to "projected risk".

Line 20: "rate" or "change" (or "increase")?

We edited to "average rates of changes".

Line 21. Semi-column or just start a new sentence?

Since it is referring to the regions experiencing simultaneous increase in flood and drought, as reported in the previous sentence, a semi-colon is used.

Line 26-29: It seems odd to me that the paper suddenly talks about changes in streamflow (I guess that means mean runoff?) while the rest of the paper is about extremes?

We are talking about streamflow, not runoff (one may define streamflow as routed runoff though). We use streamflow here in general, since both low and high extremes as well as mean flow (whole streamflow spectrum) show the reported changes in the reported areas.

Page 2

Line 15-18: Sure: more extreme P can lead to more extreme runoff. However, there is so much more going on that dictates runoff response (e.g. antecedent moisture conditions in floods etc). Would it be worth to say one or two things about other mechanisms that underlie floods? In many places, there is a disparity between extreme rainfall and flooding, or between lowest P and lowest Q, since so many other factors are also important (e.g. seasonal moisture conditions). Emphasizing which other processes are important may help to understand the reader what the added value is of adding the GHM's to the game (since they at least theoretically should represent all these processes that go beyond extreme P). Nor can I logically connect more extreme high P to more extreme drought (without some extra information about changes in dry spells, or hydrologic partitioning)

We do not specifically describe how more extreme P results in more extreme runoff because it this is not the main focus of our study and we do not want to lengthen our paper unnecessarily. Our focus is mainly on how the streamflow distribution and extremes change. We provide references for these statements to support the claim, and refer the readers to appropriate papers should they be interested in reading more about this topic. However, we do describe the impact of GHMs in the flow outing process and their implications for uncertainties in streamflow simulation, in the Introduction section.

Line 19-29: I do not see why the paper needs to talk about changes in "mean streamflow conditions" since it distracts from what you're really interested in (which are the hydrologic extremes).

Since in majority of areas, high and low extremes and mean flow show similar directions of change, an introduction in general change in streamflow as projected by GCMs would be useful. However, some regions show opposite direction of change in high and low extremes, which can translate as increase in both flood and drought risks. Simultaneous study of high and low extremes, as done in our study, helps to locate such regions.

Line 31-33: Sure, that a decrease in P can decrease runoff. However (like you give with the following example) you can also think of conditions where this does not apply.

This is exactly our point: to show that mean runoff may not be an appropriate indicator of change in water stress (and hence, drought), but changes in distribution of runoff should be studied.

Page 3
Line 1-5: Ok, I understand that there may not be many studies that use ensembles. However, still that does not answer the question of what knowledge gap you can fill with your approach. What do we not understand because we haven't run particular ensemble projections yet?)

As we stated earlier, we added paragraphs to the Introduction section and revised the manuscript to explain better what knowledge gap we are aiming to fill.

Line 4-5: The detection of areas that are expected to experience both more floods and drought sounds interesting at first, but what is again the knowledge gap that the paper fills compared to earlier work, and what is the merit in identifying these at the same time (there are reasons why this can be valuable, but they need to be presented to the reader).

Studying floods and droughts (change in magnitude of high and low extremes) together enables us to better understand changes in distribution of streamflow time series in different regions, which was not achievable through studying only one tail of the extremes. Also, as we explained earlier here, the previous studies have investigated changes in frequency of extremes, which as we argued earlier, change in distribution is better achieved through studying changes in the magnitude/intensity. We have explained this more in detail in the revision.

Lines 5-17: put these findings into context of the novel thing you're going to expose/test. Right now, it reads like a random list of previously reported streamflow changes, which are unclear why they're directly relevant to the paper.

We have edited the text in the revision.

Lines 18-20: Maybe a reference (or two) can help to support this statement?

References added.

Line 20: remove "trend" (since there may not be one)

Done.

Page 4
Line 13-14: Be very explicit to the reader what the difference between "frequency" and "intensity" is, and emphasize why this difference is relevant.

Earlier studies investigate changes in frequency, instead of magnitude/intensity. Thresholds used in those studies for extremes are defined based on the historical (20th century) distribution of streamflow. We find that the distribution of the streamflow is projected to change in the 21st century, and hence, the 95th/10th/5th percentiles used by these studies will not hold over the next century. We argue that studying the changes in the *magnitude* of streamflow extremes provides us with better understanding of projected changes in the streamflow distribution compared to the *frequency*. We have explained this more in detail in the revision.

Line 13: "this study" may be unclear because it can refer to your own work or the work of Giuntoli

We edited it to "the aforementioned study".

Line 15: It may be worth to start state "Here we" and then list the "goal", rather than directly go into the "methods". This will make the list of subsequent steps outlined in the rest of the introduction much more logical. For example, right now it sounds fun that you also investigate the link with human populations, but I have no idea (or at least it's up to my own guess!) why you'll be doing this.

We rearranged the paragraph.

Page 5
Line 13: why are these five GHM's selected? (after line 15-17 that question still stands)

We had initially selected five GHMs to have equal number of GCMs and GHMs so they contribute equally to the uncertainties. However, we removed this justification from the manuscript in response to the reviewers' comments. These GHMs have been selected by earlier studies as well, for flood change investigations.

Line 18-19: do you have any references that show this, or did this only appear in your own work?

This is problem that we faced during our calculations (and mathematics dictates that other similar studies may face this issue as well, since the GCMs show very large changes in northern latitudes). We used the normalized change to solve the issue.

Lines 19-21: consider rewriting this sentence

The sentence is rewritten for better clarity and flow.

Lines 18-27: it seems a bit confusing to justify normalization before you define the metric that you adopted.

We moved the paragraph to after definition of the metric.

Line 28 – Line 2: Is "no change" also an option?

The four categories only show the grid cells with increase or decrease in the indicators.

Page 6

Line 3- 14: Why did you choose the 5th and 95th percentile and not "real extremes" (see earlier comment above)

Answered earlier.

Line 16: 200?

2000 (edited).

Lines 26- 29: And what about any places where there are insignificant changes?

Percentage of grid cells with statistically significant change at 95% confidence level is reported in the results section.

Lines 30-3: why don't you use the absolute value (and then you don't need to separate by quadrant).

As explained in the Methods section, using absolute values would result in a large positive global trend (due to the large relative changes in high latitudes) indicating a significant increase in flood in global average, which is not realistic according to normalized averages.

Page 7
Line 3-7: Why would you even bother to try that method? It seems like this method is just less logical at the start (because it is very sensitive to absolute runoff changes between models), and hence should not be considered at all?

But as we stated there, that method also yields very similar results, proving that the final results are not sensitive to the order of averaging.

Lines 8-13: Your results suggest that 95% of the projected flood changes are significant, but what does that really mean? Does that imply that for 95% of the grid cells you are very certain about the projections? Or does it mean that model projections may show a significant change, but all other biases and uncertainties not accounted for may lead to much lower certainties of projected change?

Statistical significance at 95% confidence level does not actually mean that 95% of the changes are significant. We calculate the statistical significance of change for all of the grid cells, and if the statistical significance of change in a grid cell is over 95% we say "we are very certain about the projections". Some cells might show 80% or 10% of confidence. We have reported the percentage of grid cells that show over 95% confidence level in the projected change.

Also (in the supplementary material), why would "streamflow time series variances" be a relevant scale of variance here (rather than something like the variance of annual maxima or Q95).

The variances are actually calculated for the P5 and P95 time series (over the 20th century and 21st century). We edited the Supplementary Materials to reflect this clarification.

Line 16-18: you need to show the distribution of changes, rather than just the mean value. Right now I have no idea if the mean results from consist small changes, or a few very big changes.

The distribution of changes is shown in Figures 2 and 5.

Line 19: why bother with median flows? I thought this paper was about the extremes?

One goal of our work is to also study changes in the distribution of streamflow time series. Studying mean flow along with high and low extremes enables us achieve that goal better.

Page 8

Figure 2: The changes in flood and drought indices per latitude intrigue me. How can they virtually be the inverse of another (when organized per latitude)? Is this a physical reality or an artifact of how this study quantifies changes in these aspects?

This is actually expected. We define the increased flood indicator as <u>*increase*</u> in P95 and increased drought indicator as <u>*decrease*</u> in P5, so by increase in all percentiles of flow the flood and drought indicators should show the opposite direction of change (same for decrease in all percentiles of flow). If all percentiles of flow increase in a grid cell, it means that the flood indicator would increase (P95 increase) but drought indicator decrease (P5 increase). However, there are regions that the flood and drought indicators both increase or both decrease or have different rate of change, due to change in the distribution of the streamflow; such grid cells are located in this study.

Figure 5: it is impossible to read the scale bar in the far bottom left (on a printed page).

We enlarged the text in the revision.

Page 10

Line 30: you were not interested in decreases?

Such regions are not under threat (they are shown in the maps though).

Line 31 because people live in a grid cells where floods increase does not mean they are affected. That depends on many other factors. Correct?

We can say they are affected, but it is correct that the effect may not be serious for some regions.

Page 11

While I appreciate, you repeat all the main results of the paper, I think the paper really needs to reflect on what we learned compared to earlier work, rather than list what came out of some modeling exercises.

We revised the Conclusion Section to reflect our findings better.

Table 1: without information on the distribution of changes, I have no idea about what these mean values of change represent.

The scatter plots in Figure 2c&d also show the distribution of small and large changes under each scenario. We also provide the global maps of changes in each indicator, which show the magnitude of changes (represented by color saturation) in each grid cell and under each warming scenario.

Reference list: what does :"(80-.)" do in several references?

It was an error caused by the references management software. Fixed.

References

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. Climatic Change, 134(3), 387-401.

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. Hydrology and Earth System Sciences, 19(5), 2247-2260.

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., Roo, A., Salamon, P., ... & Feyen, L. (2017). Global projections of river flood risk in a warmer world. Earth's Future, 5(2), 171-182.

Van Loon, A. F. (2015). Hydrological drought explained. Wiley Interdisciplinary Reviews: Water, 2(4), 359-392.

Giuntoli, I., Vidal, J. P., Prudhomme, C., & Hannah, D. M. (2015). Future hydrological extremes: the uncertainty from multiple global climate and global hydrological models. Earth System Dynamics, 6(1), 267.

Berghuijs, W. R., Woods, R. A., Hutton, C. J., & Sivapalan, M. (2016). Dominant flood generating mechanisms across the United States. Geophysical Research Letters, 43(9), 4382-4390.

Trigg, M. A., Birch, C. E., Neal, J. C., Bates, P. D., Smith, A., Sampson, C. C., ... & Ward, P. J. (2016). The credibility challenge

Anonymous Referee #2

Received and published: 11 July 2017

The article by Asadieh and Krakauer investigates the very topical issue of flood and drought changes under future climate conditions. The topic has been subject to a large number of studies in the past few years, many of them based on the same set of GCM-GHM combinations from the ISI-MIP initiative, so it is difficult to find some unexplored topic of research in this area. However, this work is based on an interesting idea of comparing together increases in droughts and flood intensity and frequency under future climate, and I think it has potential for being *published. The writing style is up to international standards and the article is compact, hence I don't see room for shortening.*

My main concern is the misleading use of the terms "floods" and "droughts" throughout the article, for indicating high and low streamflow quantiles which are not really extremes, and certainly not linked to actual flood or drought events. Floods are normally linked to much higher quantiles, and in addition, they depend on the local vulnerability.

Streamflow droughts (which by the way should be specified in the article, as meteorological and agricultural droughts are calculated differently) are also not as simple as a connection to the streamflow quantile, but they depend on the duration and intensity of the droughts. My suggestion is to clarify well through the article (e.g., p4 l18-21, p5 l22-25, p6, and in general in the results) and in the title that the aim is to "high and low streamflows" rather than floods and droughts. Interestingly, only in the caption of Fig 1 did the authors write a warning about linking those streamflow quantiles to actual floods and droughts.

We agree that there are many different indices in the literature for flood and drought definitions that can be used. However, the abundant of indices also adds to the complexity of selection of appropriate indices, and we need to select only one of those so that an analysis in this scale is practical. In case of our selection, we may note that United States Geological Survey (USGS) in its annual streamflow reports uses the 95th and 5th percentiles of streamflow as thresholds for high and low flow studies (Jian et al., 2015). Other studies also have used 5th and 95th percentiles to define streamflow extremes (Koirala et al., 2014). Earlier studies have used the 95th percentile of streamflow as a threshold for flood definition in gridded streamflow data (Wu et al., 2012, 2014). The 5th percentile of streamflow has also been used as a threshold for drought definition (Ellis et al., 2010; Sprague, 2005). Such a definition for flood threshold is being used in daily flood monitoring maps produced by the USGS (https://water.usgs.gov/floods/) (please refer to the map's legend: 95th-98th percentile and 99th percentile categorization) and in the NASA-funded gridded 1/8th degree resolution Global Flood Monitoring System (GFMS) (http://flood.umd.edu/) (please refer to General Description). We have added these references to percentile-based streamflow thresholds to the revised manuscript.

However, in response to the comments made by the reviewers, we have omitted the words flood and drought from the revised title and use "streamflow extremes" instead. Accordingly, we refer to change in 95th and 5th percentiles of streamflow as change in flood and drought "*risk*", instead of direct change in flood and drought "*intensity*". We edited the manuscript accordingly.

Specific comments

P1 l11-12: This sentence reads more like a finding rather than an introduction. I'd move it to the introduction and support it with some references.

This statement is reported in the Introduction section and corresponding references are given to support it. We have included this sentence in the abstract as well to familiarize the readers with the general topic that we are investigating.

P2 l17-18: I suggest complementing the list with the more recent studies by Alfieri et al. (2015, 2017) and Winsemius et al. (2016).

Thank you. We included those references in the revision.

P2 l30-31: "Climate-change-induced" could be removed here, to avoid speculation.

Fixed.

P5 l14-15: The sentence doesn't read well. Please reformulate.

Fixed.

P5 l19: currently-frozen should be replaced with more appropriate terminology. Also, this sentence needs a supporting reference or a reason for the wider model spread.

Fixed.

P6 l28: also the over –> also over

Fixed.

P7 l4: Is it available? Otherwise you should add "not shown"

We report the outcome of that analysis, which shows that final results are not sensitive to the order of averaging.

P8 l14: flux to the Arctic Ocean

Fixed.

P8 l26-27: "In the meantime" should be replaced with more appropriate terminology.

We changed the terminology to "also".

P11 l5-7: This sentence sounds speculative as no specific simulation was performed to support it.

We show in figure 1 that streamflow is projected to increase in the regions near and above Arctic Circle and northern rivers, and in the 2nd paragraph of the Results section we argue that this results in increased fresh water flux into the Arctic Ocean, and we provide references to infer that : "*The projected increase in meltwater flux into the Arctic Ocean may contribute to sea level rise and changes in water salinity, temperature as well as circulation in the Arctic Ocean (Peterson et al., 2002; Rawlins et al., 2010)*". We have reported this as one of the general findings of the study in the Conclusion section.

Table 1: I suggest removing "rel" in the first two columns, as that is clear from the % sign.

Agreed. We removed the "rel." from the Table.

Figure 5 is surely the most interesting one, and the main novelty of this work. I wonder if the caption could be shortened. It is currently pretty long.

This is an important Figure, as you mentioned. It carries a lot of information which needs to be described to help readers better understand the results. However, we removed some sentences to shorten the caption.

Anonymous Referee #3

Received and published: 19 July 2017

This manuscript uses ISI-MIP streamflow simulations to explore the joint future of hydrological extremes (low and high flows). This is a quite relevant topic for HESS, but I have concerns about the novelty of the study, given the wealth of already published papers on hydrological extremes derived from ISI-MIP simulations. Furthermore, the statistical analysis is not (yet) convincing in my view – and choices are not justified (enough) – to bring the paper to a level where it could be published in HESS. All comments below have been initially drawn before I read comments from the two other referees, and I then added references to these in order to highlight common assessments or suggestions.

Major Comments

1. As mentioned above, and as already noted by Referee 1, there is little novelty in the topic and dataset used compared to previously published literature (especially to Giuntoli et al., 2015), and the little amount of novelty is not pushed forward in the manuscript. In my view, there are two new contributions: (1) the comparison between two contrasted RCPs, and (2) the quantification of absolute changes in high/low flow indices and their joint analysis. I agree with Referee 1 proposal to better highlight the manuscript's contributions, but I fear there are other issues that need to be tackled first.

Thank you. Accordingly, we have added more paragraphs to the introduction to emphasize on the knowledge gap that we are aiming to fill. To summarize a few, Giuntoli et al. 2015 studies changes in *frequency* of *un-routed* runoff (dimension $[L.T^{-1}]$) extremes under *one* warming scenario, while we study changes in *magnitude/intensity* of *routed* runoff (streamflow, dimension $[L^3.T^{-1}]$) extremes under *two* different warming scenarios. Un-routed runoff may not be directly used for flooding study, but the routed runoff (streamflow) has been used for this purpose in the literature instead (for instance: Koirala et al. 2014 and Hirabayashi et al. 2013). So although Giuntoli et al. 2015 is closest to ours in some respects, there are critical differences. Prudhomme et al 2014 also studies un-routed runoff, not streamflow. Koirala et al. 2014 studies 5th and 95th percentiles of streamflow, but routed by only one state-of-the-art GHM, and hence, does not account for GHM uncertainties. Hirabayashi et al. 2013 also uses a single state-of-the-art GHM, to study the *frequency* of extremes. We study the change in the *magnitude/intensity* of the high and low extremes to understand the projected changes in the distribution of streamflow over the next century, while earlier studies (Giuntoli et al. 2015 for instance, and the others referred in the comments by reviewers) study changes in the *frequency* of streamflow passing the high and low extreme threshold. However, the thresholds used in those studies are defined based on the historical (20^{th} century) distribution of streamflow. We find that the distribution of the streamflow is projected to change in the 21^{st} century, and hence, the 95^{th}/10^{th}/5^{th} percentiles used by these studies will not hold over the next century. Therefore, studying the changes in the *magnitude* of streamflow extremes can provide better interpretability of projected changes in the streamflow distribution compared to the *frequency*. Also, in the current work we study changes in flood and drought risks (both high and low flow extremes) together to understand the changes in streamflow distribution and simultaneous vulnerability profiles to different types of hydrological risk in different regions. We also study the changes under two emission scenarios (RCP2.6 and RCP8.5) to compare the impact of different levels of warming on streamflow distribution and consequently flood and drought risks (Giuntoli et al. 2015 uses only one (RCP8.5) warming scenario). We also calculate the number people affected by changes in different regions to understand whether the areas of increased risk coincide with highly populated regions.

2. The quantification of changes is, as already noted by the two other referees, first quite questionable in terms of wordings: high and low flow indices simply cannot be identified to flood and drought indices. Changes throughout the manuscript (including title) are therefore required. Furthermore, the authors consistently use the wording of streamflow in the manuscript, but I believe that the variable used is the (unrouted) runoff, as in previous related works on ISI-MIP data (Prudhomme et al, 2014; Giuntoli et al., 2015), and on the contrary to other works on (large) river basins (see e.g. Pechlivanidis et al., 2017; Vetter et al., 2017). This has serious implications for interpreting results in terms of floods and droughts (see the recent work by Zhao et al., 2017).

Giuntoli et al. 2015 studies changes in *frequency* of *un-routed* runoff (dimension $[L.T^{-1}]$) extremes under *one* warming scenario, while we study changes in *magnitude/intensity* of *routed* runoff (streamflow, dimension $[L^3.T^{-1}]$) extremes under *two* different warming scenarios. Un-routed runoff may not be directly used for flooding study, but the routed runoff (streamflow) has been used for this purpose in the literature instead (for instance: Koirala et al. 2014 and Hirabayashi et al. 2013). So although Giuntoli et al. 2015 is closest to ours in some respects, there are critical differences. Prudhomme et al 2014 also studies un-routed runoff, not streamflow.

In response to the comment made, we have omitted the words flood and drought from the revised title and use “streamflow extremes” instead. Accordingly, we refer to change in 95^{th} and

5th percentiles of streamflow as change in flood and drought "*risk*", instead of direct change in flood and drought "*intensity*". We edited the manuscript accordingly.

3. The normalization procedure is probably interesting for positive variables like streamflow, as it makes multiplicative factors symmetrical with respect to zero. Multiplying (resp. dividing) present-day values by 3 results in a value of 1/2 (resp. -1/2). However, the lack of experience with dealing with such an index makes it rather difficult to interpret values. The way values converge towards 1 or -1 is for example not intuitive. The reader should at least be accompanied through this kind of basic examples.

Thank you for pointing this out. We added more explanations in the revision regarding how to interpret the normalized changes.

4. The joint analysis of changes in low flow and high flow indices is potentially attractive. However, I don't understand why the analysis is restricted to quadrants (cf. Figure 5) when all data are available for continuous assessments over the two indices (see Teuling et al., 2011a, b). This is in my view an oversimplification of the problem. You cannot identify with the quadrants a region with a small drought increase and a large flood increase (whatever that means). Moreover, the multimodel average is, as pointed out by Referee 1, potentially quite misleading. This is all the more problematic that there is a confusion (at least of the reader) when dealing with statistical significance. At several places in the manuscript, one may expect some tests for example on the sign of change within the multimodel ensemble (see the latest IPCC report), and not (only) the significance of changes between 30-year averages of future and present period for single models. Many detailed and interesting statistical analyses could be performed with this dataset by applying ANOVA techniques, and by for example deriving individual maps of GCMs/GHMs effects (in the ANOVA sense) on joint changes in low/high flow indices. This would avoid using latitude-averaged plots that do not convey in my view the most relevant information. For example, it is not possible on Figures 2, 3, and 4 to compare the spatial variance (along any given latitude) from the variance among GCMs/GHMs/combination of GCMs and GHMs (depending on the figure).

We do report the results for each of the indicators separately in Table 1 and Figure 1. We report mean value of the results in the abstract to summarize the global findings, and in the text to discuss the changes in a broader scale. However, we do provide the global maps of changes in each indicator, which show the magnitude of changes (represented by color saturation) in each grid cell and under each warming scenario. The scatter plots in Figure 2c&d also show the distribution of small and large changes under each scenario. We also show the results averaged by latitude to show the averaged changes over different climate boundaries (high latitudes, mid latitudes, tropics and subtropics, etc). We also provide the global maps for each of the models individually in the Supplementary Materials. We do agree that it may be more informative to add more calculations and techniques; that can be subject of another interesting study.

5. This also leads to my last major comment. I don't really understand why this study is restricted to only 5 GHMs. Statistical techniques are indeed available to take account of different sample sizes in ANOVA contexts (see for example Giuntoli et al., 2015). Furthermore, there is no justification in the manuscript on the choice of these specific 5 GHMs, and this has already been pointed out by Referee 1. This thus appears as a subjective and therefore negative choice for building confidence in results from this "ensemble of opportunity".

We removed the justification for the number of GHMs being same as the number of GCMs. We would not call the selected GHMs and GCMs only an "ensemble of opportunity" though; these models have had enough credibility to be selected to contribute to a project of the scale of the ISI-MIP, and have been used in earlier studies as well.

Specific comments

1. P1L16: percentage with respect to what period?

Over the 21st century, compared to the 20th century.

2. P2L14: Please make explicit what you mean by "impact". The hierarchy of impacts (for example in terms of monetary loss) is indeed highly dependent on the anthropogenic system under study.

Impact on the intensity. The beginning of the sentence is stating that increased amount of atmospheric water content is expected to intensify precipitation extremes, and the end of sentence is stating that the aforementioned impact (increase in intensity) is stronger for extreme precipitation than mean precipitation.

3. P2L19: I believe this is about "average runoff". Please specify.

Correct. Fixed.

4. P5L21: The normalization is announced and summarized here whereas it is described only much later on (P6 L3 ff.). Please reorganize the paragraphs.

We moved the paragraph to after definition of the metric.

5. P6L12-14: This is hardly understandable. Please consider giving the actual equations.

The conversion of relative change to normalized change is shown in Eq. 1. The conversion of normalized change to relative change however is done using numerical methods, as shown in the Supplementary Figure S1 (no equation available to report).

6. P7L15-19: These figures are redundant with Table 1. Please rephrase.

Rephrased.

7. P8L5, "with high agreement": Could you explain what you mean exactly here?

All models show large value of normalized increase in flood indicator and normalized decrease in drought indicator, as seen in Figure 2.

8. P8L19, "fluctuations": Again, what do you mean here? Fluctuations in time, latitude, other? Please specify.

Over latitude. Edited.

9. P8L23, "mean": over space, latitude? Please be more specific.

Mean over each latitudinal window. We edited the text to clarify.

10. P9L8, "statistically different": What is the test used here? Please be more specific on your statements.

It says "significantly different", not "statistically". The DBH model shows the opposite direction of change in drought indicator in the Northern Hemisphere. This is seen in the Figure 3 and the figure is referred in the text.

11. P10L11, "statistically significant": see above.

The determination of significance is based on a two-sample t-test. We say in the last paragraph of the Materials and Methods section that "*The two-sample t-test is used in this study to quantify the statistical significance level of difference between the means of the 20C and 21C streamflow time series*".

12. P11L16-17: This final sentence is rather ambiguous and wrongly suggests a 200

This comment seems to be incomplete. However, this sentence is correct, suggesting that the increase or decrease in flood and drought indicators is approximately twice as much in the RCP8.5 scenario as in the RCP2.6 scenario, as shown in Table 1 (compare the first two columns from the left).

Technical corrections

1. P2L3, "to be intensified": please rephrase

We rephrased it to "become more intense".

2. P2L8, "dictation": please rephrase

Rephrased.

3. P4L11: "increase"

Fixed.

4. P6L17, "remained": please rephrase

Rephrased.

5. P8L14, missing "in" after "flux"

Fixed.

References

Giuntoli, I., Vidal, J.-P., Prudhomme, C. Hannah, D. M.: Future hydrological extremes: the uncertainty from multiple global climate and global hydrological models, Earth System Dynamics, 6(1), 267-285, doi: 10.5194/esd-6-267-2015, 2015.

Pechlivanidis, I. G., Arheimer, B., Donnelly, C., Hundecha, Y., Huang, S., Aich, V., Samaniego, L., Eisner, S. Shi, P.: Analysis of hydrological extremes at different hydroclimatic regimes under present and future conditions, Climatic Change, 141(3), 467- 481, doi: 10.1007/s10584-016-1723-0, 2017.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y. Wisser, D.: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, Proceedings of the National Academy of Sciences, 111(9), 3262-3267, doi: 10.1073/pnas.1222473110, 2014.

Teuling, A. J., Stöckli, R. Seneviratne, S. I.: Bivariate colour maps for visualizing climate data. International Journal of Climatology, 31(9), 1408–1412, doi: 10.1002/joc.2153, 2011a.

Teuling, A. J.: Technical note: Towards a continuous classification of climate using bivariate colour mapping, Hydrology and Earth System Sciences, 15(10), 3071-3075, doi: 10.5194/hess-15-3071-2011, 2011b.

Vetter, T., Reinhardt, J., Flörke, M., van Griensven, A., Hattermann, F., Huang, S., Koch, H., Pechlivanidis, I. G., Plötner, S., Seidou, O., Su, B., Vervoort, R. W. Krysanova, V.: Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins, Climatic Change, 141(3), 419-433, doi: 10.1007/s10584-016-1794-y, 2017.

Zhao, F., Veldkamp, T. I. E., Frieler, K., Schewe, J., Ostberg, S., Willner, S., Schauberger, B., Gosling, S. N., Müller Schmied, H., Portmann, F. T., Leng, G., Huang, M., Liu, X., Tang, Q., Hanasaki, N., Biemans, H., Gerten, D., Satoh, Y., Pokhrel, Y., Stacke, T., Ciais, P., Chang, J., Ducharne, A., Guimberteau, M., Wada, Y., Kim, H. Yamazaki: The critical role of the routing scheme in simulating peak river discharge in global hydrological models, Environmental Research Letters, 12, 075003, doi: 10.1088/1748-9326/aa7250, 2017.

Global change in ~~flood and drought intensities~~streamflow extremes under climate change ~~in~~ over the 21st century

Behzad Asadieh [1],*, **Nir Y. Krakauer** [2]

[1],[2] Civil Engineering Department and NOAA-CREST, The City College of New York, the City University of New York, New York, USA; basadie00@citymail.cuny.edu; nkrakauer@ccny.cuny.edu

* Correspondence to Behzad Asadieh: basadie00@citymail.cuny.edu

Abstract

Global warming is expected to intensify the Earth's hydrological cycle and increase flood and drought risks. Changes over the 21st century under two warming scenarios in different percentiles of the probability distribution of streamflow, and particularly of ~~global~~ high and low streamflow extremes (95^{th} and 5^{th} percentiles) ~~over the 21st century under two warming scenarios~~ are analyzed ~~as indicators of hydrologic flood and drought intensity,~~ using an ensemble of bias-corrected global climate model (GCM) fields fed into different global hydrological models (GHMs), to understand the changes in streamflow distribution and simultaneous vulnerability to different types of hydrological risk in different regions~~.~~. ~~Based on~~In the multi-model mean, under RCP8.5 scenario, ~~approximately~~ 37% of global land areas experience increase in magnitude of extremely high streamflow (with an average increase of 24.5%), potentially increasing the chance of flooding in those regions. On the other hand, ~~and~~ 43% of global land areas ~~are~~ show a ~~exposed to increases in flood and drought intensities~~decrease in the magnitude of extremely low streamflow (average decrease of 51.5%), potentially increasing the chance of drought in those regions.~~respectively, by the end of the 21st century under RCP8.5 scenario. The average rates of increase in flood and drought intensities in those areas are projected to be 24.5% and 51.5%, respectively.~~ ~~Nearly~~ About 10% of the global area~~s~~ ~~are~~ is ~~under the potential~~ projected ~~risk of~~to face simultaneously ~~increase~~increasing ~~in both flood and drought intensities, with average rates of 10.1 and 19.8%, respectively~~high extreme streamflow and decreasing low extreme streamflow, reflecting potentially worsening hazard of both flood and drought; further, these regions tend to be highly populated parts of the globe, currently holding around 30% of the world's population (over 2.1 billion people). In a world more than 4 degrees warmer by the end of the

Formatted: Not Superscript/ Subscript

Formatted: Superscript

Formatted: Superscript

21st century compared to the pre-industrial era (RCP8.5 scenario), ~~increases in flood and drought intensities~~ changes in magnitude of streamflow extremes are projected to be ~~nearly~~ about twice as large as in a 2 degree warmer world (RCP2.6 scenario). Results also show that inter-GHMs ~~contribute to more uncertainties~~uncertainty in streamflow changes, due to representation of terrestrial hydrology, is greater than the inter-GCMs uncertainty due to simulation of climate change. Under both forcing scenarios, there is high model agreement for ~~significan~~t increases in streamflow of the regions near and above the Arctic Circle, and consequent increases in the freshwater inflow to the Arctic Ocean, while subtropical arid areas experience reduction in streamflow.

Formatted: Complex Script Font: Bold

1. Introduction

Floods and droughts, the natural disasters with the highest cost in human lives (Dilley, 2005; IFRC, 2002), are projected to become more intense ~~intensified~~ under anthropogenic global warming and climate change (Dai, 2011; Dankers et al., 2013; Field, 2012; Stocker et al., 2013). Observational records as well as global climate model (GCM) simulations both show that the amount of water vapor in the atmosphere increases at a rate of approximately 7% per K of increase in global mean temperature (Allen and Ingram, 2002; Held and Soden, 2006; Wentz et al., 2007), ~~similar to dictation~~as expected ~~of~~from the Clausius-Clapeyron equation conditional to stable relative humidity (Held and Soden, 2006; Pall et al., 2006). Increased amount of atmospheric water content is expected to intensify precipitation extremes (Allan and Soden, 2008; O'Gorman and Schneider, 2009; Trenberth, 2011), as evidenced by both observations and GCM simulations (Alexander et al., 2006; Asadieh and Krakauer, 2015, 2016; Kharin et al., 2013; Min et al., 2011; O'Gorman and Schneider, 2009; Stocker et al., 2013; Toreti et al., 2013; Westra et al., 2013), with relatively stronger impact than for mean precipitation (Asadieh and Krakauer, 2016; Lambert et al., 2008; Pall et al., 2006). Change in intensity and distribution of precipitation events under climate change is expected to increase the intensity and frequency of flood and drought events in many regions (Alfieri et al., 2015, 2017, Asadieh and Krakauer, 2015, 2016; Dankers et al., 2013; Ehsani et al., 2017; Field, 2012; Held and Soden, 2006; Min et al., 2011; O'Gorman and Schneider, 2009; Stocker et al., 2013).

Average ~~R~~runoff projections from 3 GCMs show strong positive trend around high latitudes and negative trend for some mid-latitude regions, by the end of the 21st century (Hagemann et al., 2013). Another study of runoff projections from a larger ensemble of GCMs also confirms such trends in runoff for the 21st century (Tang and Lettenmaier., 2012). Changes in runoff, and consequently in streamflow, under current and future climate change has strong implications for available freshwater resources (Arnell, 2004; Brekke et al., 2009; Oki and Kanae, 2006; Stocker et al., 2013; Vörösmarty et al., 2000). Climate change is projected to decrease mean runoff in land areas around Mediterranean and some parts of Europe, southern Africa and central and southern America, and consequently increase water stress in those regions (Arnell, 2004). It is also projected to ~~increase~~ worsen aridity in southern Europe and the Middle East, Australia, Southeast Asia, and large parts of Americas and Africa, in the 21st century (Dai, 2011).

~~Climate change-induced decrease in mean precipitation and consequently runoff can increase water stress in such regions.~~ Regions experiencing increase in total annual precipitation and runoff under climate change may also face increased water stress, as a result of change in precipitation and runoff distribution (Arnell, 2004; Asadieh and Krakauer, 2016; Oki and Kanae, 2006). Implications of anthropogenic climate change for flood events are widely noted in the literature; However, there are few multi-model analyses of future change in streamflow extremes at global scale (Arnell, 2004; Dankers et al., 2013; Hirabayashi et al., 2008, 2013; Koirala et al., 2014; Schewe et al., 2013)~~, or detection of regions that may experience simultaneous increases in both flood and drought intensities~~. A study of streamflow provided by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2013) projects increases for the high latitudes, eastern Africa and India, and decreases in streamflow of Mediterranean and southern Europe as well as South America and southern parts of North America, by the end of the 21st century (Schewe et al., 2013), similar to some other studies (Hagemann et al., 2013; Tang and Lettenmaier., 2012). Another study of ISI-MIP streamflow projects increases in 30 year return period of high flow in major parts of Siberia and some regions around Southeast Asia, and decreases in northern and eastern Europe and some regions around western United States, by the end of the 21st century (Dankers et al., 2013). Approximately two-thirds of global land area are projected to experience positive trend in the magnitude and frequency of 30~~-~~year return period of high flow (Dankers et al., 2013) and~~,~~ magnitude of 95th percentile of streamflow (Koirala et al., 2014), and have shown increase in magnitude of annual-maximum daily streamflow (Asadieh et al., 2016). The 95th and 5th percentiles of flow have been used as indices for analysis of streamflow extremes by United States Geological Survey (USGS) (Jian et al., 2015) and other studies (Koirala et al., 2014). Some studies have used changes in the 95th percentile of flow in gridded streamflow data to study changes in flood events (Wu et al., 2012, 2014), while the 5th percentile of streamflow

Formatted: Superscript

has been used to study changes in drought events (Ellis et al., 2010; Sprague, 2005). Although changes in high and low extremes of streamflow may not be directly interpreted as changes in flood and drought events, since the thresholds for flood and drought damage vary according to factors such as mean climate, the magnitude of water demand, and engineering works for water storage and transport , such changes affect the likelihood of occurrence of those events, and can be considered a reasonable indicator of climate impacts on large-scale flood and drought hazard respectively (Vörösmarty et al., 2000).

Accurate simulation of weather fields such as precipitation, as well as simulation of the diverse hydrological processes that lead to streamflow generation, are major sources of uncertainty in streamflow ~~trend~~ simulation (Giuntoli et al., 2015; Hagemann et al., 2013; Schewe et al., 2013). Some earlier adoptions of climate model projections for flooding studies utilized single ~~state-of-the-art~~ global hydrological models (GHMs) for flow routing and streamflow simulation under the GCM-simulated climate (Hirabayashi et al., 2013; Koirala et al., 2014). However, the process simulation in GHMs ~~are~~ is also a major source of uncertainty, as flow routings in different GHMs using the same weather fields can result in markedly different flood and drought trend predictions (Giuntoli et al., 2015; Haddeland et al., 2011; Hagemann et al., 2013). Additionally, historical simulations of weather variables from GCMs have shown discrepancies (biases) compared to the observations ~~(biases)~~ (Asadieh and Krakauer, 2015; Ehret et al., 2012; Hempel et al., 2013; Krakauer and Fekete, 2014), which may affect the climate change impact projections using the GCM outputs (Hagemann et al., 2011, 2013). This issue is often solved utilizing bias correction methods, in which the mean value of the time series is adjusted according to the observational records, while supposedly preserving the trends (Hempel et al., 2013), as done in ISI-MIP dataset (Warszawski et al., 2013).

A study of changes in frequency of 95th and 10th percentiles of un-routed runoff in the 21st century, using multiple GCMs and GHMs from ISI-MIP under RCP8.5 scenario, shows that the number of days with flow above the historical 95th percentile will significantly increases in the high latitudes and the number of days with flow below the historical 10th percentile will increase significantly in Mediterranean, southern North America, and Southern Hemisphere (Giuntoli et al., 2015). However, changes in runoff extremes do not directly correspond to floods of large water bodies, where routed runoff (streamflow) has been widely used instead for this purpose (Dankers et al., 2013; Hirabayashi et al., 2013; Koirala et al., 2014). Additionally, Giuntoli et al., 2015 studies changes in frequency of streamflow extremes, and not magnitude/intensity. Change in frequency of extremes may be studied using the historical extreme thresholds/percentiles, which may come to occupy different points in the streamflow probability distribution under future climate change. A study of change in 100-yr flood return period in the last 3 decades of the 21st century compared to the last 3 decades of the 20th century, projected by 11 GCMs under various emission scenarios, shows increased flood frequency over the South and Southeast Asia, northern Eurasia, South America, and tropical Africa (Hirabayashi et al., 2013). Another similar study ~~investigates~~ investigated changes in 5th and 95th percentiles of streamflow, projected by the same 11 GCMs (Koirala et al., 2014). However, both these studies used a single ~~state-of-the-art~~ river routing model ~~developed by the authors~~ for simulating streamflow ~~data generation~~ using the GCM inputs. ~~A study of changes in frequency of 95th and 10th percentiles of streamflow in the 21st century, using multiple GCMs and GHMs from ISI-MIP, shows that the number of days with flow above the historical 95th percentile will significantly increases in the high latitudes and the number of days with flow below the historical 10th percentile will increases significantly in Mediterranean, southern North America, and Southern Hemisphere (Giuntoli et al., 2015). However, this study investigates changes in frequency of streamflow extremes, and not intensity.~~ However, a single multi-GCM multi-GHM global analysis of projected changes in magnitude of streamflow (routed runoff) extremes under different warming scenarios over the 21st century is not yet available.

Formatted: Superscript

Here, we study changes in the magnitude of the 95th percentile of annual streamflow (P95) in 21C compared to 20C, in which an increase may indicate a greater potential for flood events. We also study the change in the magnitude of the 5th percentile (P5), in which a decrease may indicate greater potential for drought events. We study changes in both extremes to understand the changes in streamflow distribution and simultaneous vulnerability profiles to different types of hydrological risk in different regions. ~~Here, w~~We use daily streamflow simulations from 25 GCM-GHM combinations (5 bias-corrected GCMs and 5 GHMs) from the ISI-MIP. We analyze simulated streamflow at the end of the 21st century (2070-2099, 21C) in comparison with the end of the 20th century (1971-2000, 20C). ~~We study changes in the magnitude of the 95th percentile of annual streamflow (P95) in 21C compared to 20C, in which an increase would be an indication of increase in the flood intensity. We also study the change in the magnitude of the 5th percentile (P5), in which a decrease would correspond to an increase in the drought intensity.~~ GHM-generated streamflow based on GCM inputs does not well capture the ~~annual trends~~interannual variability in flow compared to observations, even where, as in ISI-MIP, the GCM outputs are bias-corrected. However, the multi-decade average of bias-corrected ISI-MIP streamflow is shown to be ~~more~~ similar to that of observation-based streamflow simulations (Asadieh et al., 2016). Other studies have also used relative changes in multi-decade average of streamflow ~~indices~~ percentiles in a future 21C time window compared to a historical 20C time window for flooding and streamflow extremes analyses (Dankers et al., 2013; Hirabayashi et al., 2013; Koirala et al., 2014; Tang and Lettenmaier., 2012). Alongside the study of the magnitude of change, we also study the percentage of global population affected by changes in high and low streamflow extremes, as an indication of the potential impact of changes in flood ~~and/~~or drought ~~intensities~~events in those regions. Limiting global warming to 2 degrees Celsius above the pre-industrial era (achievable in RCP2.6 scenario (Moss et al., 2010; Stocker et al., 2013)) has been targeted in many scientific and governmental plans, for instance the 2015 Paris Climate Agreement (UNFCCC, 2015). However, the increasing trajectory of emissions observed over the beginning on the 21st century, if continued, is more consistent with around 4 degrees Celsius of warming by the end of the century (similar to RCP 8.5 scenario (Moss et al., 2010; Stocker et al., 2013)). Hence, we study both low and high radiative forcing scenarios (RCP2.6 and RCP8.5) to investigate the impacts of 21C anthropogenic forcing on ~~flood and drought risks~~streamflow extremes.

2. Materials and Methods

We use daily streamflow data obtained from the first phase of the ISI-MIP (Warszawski et al., 2013). The ISI-MIP streamflow projections are produced by multiple GHMs, based on bias-corrected meteorological outputs of 5 GCMs from the fifth version of the Coupled Model Intercomparison Project (CMIP5) (Dankers et al., 2013), which are downscaled to 0.5 degree resolution for the period 1971-2099. The GCMs contributing to the first phase of ISI-MIP are: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M (Warszawski et al., 2013). The 5 GHMs selected for this study are WBM, MacPDM, PCR-GLOBWB, DBH and LPJmL (refer to supplementary materials for details). These models which have been used in previous studies, along with other models (Schewe et al., 2013). However, we limit the number of GHMs to 5 so the analysis in this global scale is practical. ~~ISI-MIP provides the streamflow outputs for only 5 GCMs, from more than 5 GHMs. Here, the number of GHMs is also limited to 5 so that the uncertainties arising from the GCMs and GHMs are readily comparable.~~

~~Relative changes in streamflow can be very large for individual grid cells, particularly in currently frozen high latitudes. This bias averages across models and grid cells toward a positive trend, as the decreases are limited to 100% loss of the historic flow, while the increase can be well over 100% of the historic flow. Accordingly, changes are here normalized to between -1 and +1, so the ranges of increases and decreases are comparable. Normalized increase in the magnitude of P95 indicates increase in flood intensity, and is called the flood indicator. Since increased drought intensity corresponds to decrease in the magnitude of P5, the normalized changes in P5 are multiplied by -1 to form the drought indicator. We refer to positive/negative change in flood (drought) indicator as increased/decreased flood (drought) intensities, respectively.~~

~~Increase~~Increasing~~ and ~~/decreasinge extreme ~~in flood~~ high/~~and drought~~ low streamflow can form four combinations, which are categorized as the following four quadrants: 1. Increased ~~flood~~ high extreme and decreased low extreme~~and drought~~, 2. Increased ~~flood~~ high and ~~decreased drought~~low extreme, 3. ~~Increased drought~~Decreased high and ~~decreased flood~~low extreme, and 4. Decreased ~~flood~~ high extreme and ~~drought~~increased low extreme. Results obtained are averaged for each of these quadrants and the comparison of results between different scenarios is made for each quadrant individually. Assignment of each grid cell to the specified quadrant is based on the averaged change across GCMs and GHMs.

In order to calculate the normalized change in ~~flood~~ high extreme~~intensity~~ of a grid cell, the magnitude of the 95th percentile of daily streamflow (P95) is calculated for each year, and then averaged for 20C (called Q_{20C}) and 21C (called Q_{21C}). The normalized change is calculated as:

$$\Delta Q = \frac{Q_{21C} - Q_{20C}}{Q_{21C} + Q_{20C}} \qquad \text{Eq.1}$$

The ΔQ value ranges between -1 and +1, where a normalized change equal to -1 indicates total loss of the 20C flow in the 21C and a normalized change equal to +1 indicates that all of the 21C flow is resultant of the change and the flow in 20C was zero. As mentioned in the Introduction, an increase in P95 suggests the potential for an increase in flooding hazards. For normalized change in ~~drought intensity~~ low extreme of a grid cell, the same calculations are performed on the magnitude of the 5th percentile of annual streamflow (P5). A decrease in P5 indicates the potential for worse drought hazards, and hence,~~ and~~ the ΔQ for P5 is multiplied by -1 when shown in the plots, so that ~~a~~ a positive ~~number~~ value ~~would indicate~~ corresponds directly to increase in potential for hydrological drought~~ intensity (decrease in low flow)~~.

Formatted: Font: Not Italic, Complex Scrip
Font: Not Italic

Multi-model ensemble averages of changes are calculated based on the normalized change values. However, averaged normalized changes are then reverted to relative changes, and results are shown in both normalized change and relative percentages (cf. Figure S1). Normalized change is symmetrical with respect to zero, meaning that multiplying flow by a factor of m and dividing flow by m over the 21C both yield normalized change values with same magnitude but opposite sign. For instance, tripling the flow over the 21C will yield a normalized change of 0.5, while dividing flow by 3 yields a normalized change value of -0.5. Relative changes in streamflow can be very large for individual grid cells, particularly in high latitudes that are currently ice-covered. This biases the averaging across models and grid cells towards a positive value, as the decreases are limited to 100% loss of the historic flow, while the increase can be well over 100% of the historic flow. Normalizing changes to between -1 and +1 is adopted here so the ranges of increases and decreases are comparable.

We exclude ~~the~~ grid cells that have average daily flow below 0.01 mm over the period of 1971-2000 (Hirabayashi et al., 2013). Greenland ~~ice sheets~~and Antarctica are also excluded from the analysis. The remaining ~~G~~grid cells ~~remained to be studied,~~ cover 75.9% of global land area, but include 95.9% of global population as of the year 2015. The grid cells with very low streamflow volume are excluded from the calculations, because such regions are very sensitive to changes projected by models and small increases in streamflow result in large relative changes in flood index, which may not meaningfully ~~correspond~~ indicate to flooding risk for such dry regions. To identify the dry grid cells, the streamflow simulation of the WBM-plus model driven by reanalysis climate fields of WATCH Forcing Data (WFD) is used (Asadieh et al., 2016), as the ISI-MIP uses the WFD dataset for bias-correction of the GCM output (Hempel et al., 2013).

Calculation of normalized change in streamflow in 21C compared to 20C is performed on each of the 25 GCM-GHM combination datasets individually. The results are averaged over the models for each grid cell. The multi-model averages are then averaged over the grid cells that show increase in the indicator and also separately ~~the~~ over the grid cells that show decreases in the indicator (two separate values for each indicator). The multi-model averages are also averaged for each quadrant. This averaging gives a better sense of the projected magnitudes of ~~flood and drought intensity~~ changes in the high and low streamflow extremes for each warming scenario in affected regions than averaging over all land areas, because the positive and negative trends cancel each other out in a global averaging due to the semi-symmetric behavior of changes (Figures 2.c and d). In a supplementary analysis, the

Formatted: Font: Italic, Complex Script Fo
Italic

Formatted: Font: Italic, Complex Script Fo
Italic

streamflow data of all the model combinations were averaged first and the normalized change was calculated on the multimodel-averaged streamflow data. Both approaches yielded very similar results, indicating that the analyses are not sensitive to the method of averaging.

The two-sample t-test (Snedecor and Cochran, 1989) is used in this study to quantify the statistical significance level of difference between the means of the 20C and 21C streamflow time series (refer to supplementary materials). The percentage of land area with statistically significant change (at 95% confidence level) is reported. The affected population is calculated using the Gridded Population of the World (GPW) data from the Center for International Earth Science Information Network (CIESIN) (Doxsey-Whitfield et al., 2015).

3. Results and Discussion

Based on multi-model mean results under RCP8.5 scenario, 36.7% of global land area shows an increase in ~~flood indicator~~high extreme (95th percentile) of streamflow (whose magnitude averages 24.55%), potentially increasing the chance of flooding in those regions, and 39.2% of land area shows an average ~~of~~ 21.10% decrease in P95. On the other hand, 43.2% of global land area shows an average 51.40% ~~increase in drought indicator~~decrease in low extreme (5th percentile), potentially increasing the chance of drought in those regions, and 32.7% of land area shows an average 30.30% decrease in P5 (Table 1). Compared to RCP8.5, RCP2.6 shows a higher percentage of land area with increasing P95, a lower percentage with decreasing P5, and much smaller magnitudes of mean changes (Table 1).

Figure 1 shows global maps of normalized change in median, P5, and P95 of streamflow in 21C compared to 20C under two different warming scenarios, obtained from the ensemble mean of all 25 GCM-GHM combination datasets. Under RCP8.5 scenario, the high latitudes show an increase in all percentiles of flow, while the Mediterranean shores, Middle East, southern North America and the Southern Hemisphere show a decrease in all percentiles. The United Kingdom, some parts of Indonesia, India and southern Asia show an increase in the magnitude of P95 while experiencing a decrease in the magnitude of P5. Median flow shows a general pattern of change similar to P5. As shown in the figure, changes are more intense in RCP8.5 scenario (representative of 4 degrees warmer world in 21C compared to pre-industrial era) than in RCP2.6 scenario (representative of 2 degrees warmer world in 21C compared to pre-industrial era). However, unlike the RCP8.5 scenario, the RCP2.6 scenario projects increase in P95 for eastern United States as well as southern and western Europe. Global maps

Formatted: Superscript

Formatted: Superscript

Formatted: Indent: First line: 0.29" of change in median, P5, and P95 of streamflow for each individual model, are shown in supplemental Figures S2-7.

Figure 2 depicts the multi-model mean changes in high and low ~~flood and drought indicators~~extremes of streamflow averaged by latitude, as well as the scatter of the grid cells over the defined quadrants, under each RCP scenario. ~~–~~Results show ~~increased~~ increasing ~~flood~~P95 (and thus increased potential for flooding) and ~~decreas~~increasing~~ed~~ ~~drought~~P5 (and thus decreasing potential for drought) in high latitudes, especially in the regions near and above the Arctic Circle, in both warming scenarios. The changes are projected with high agreement among the models in both scenarios, with greater change in RCP8.5 compared to RCP2.6 (Figure 2). This indicates future increase in the flow volume of the Arctic rivers and increased freshwater inflow into the Arctic Ocean, continuing the trend observed over the last decades (Peterson et al., 2002; Rawlins et al., 2010), which can be attributed to the thaw of permafrost and increased precipitation in a warmer climate. Rivers play a critical role in the Arctic freshwater system (Carmack et al., 2016; Lique et al., 2016), as river runoff is the major component of freshwater flux into the Arctic Ocean (Carmack et al., 2016). Arctic rivers' inflow to the Arctic Ocean accounts for around 10% of global annual water flux into the oceans (Haine et al., 2015; Lique et al., 2016). The projected increase in meltwater flux into the Arctic Ocean may contribute to sea level rise and changes in water salinity, temperature as well as circulation in the Arctic Ocean (Peterson et al., 2002; Rawlins et al., 2010). The Southern Hemisphere shows a general ~~increasing~~ decreasing trend in ~~drought~~ both P5 and P95~~and decrease in flood~~, indicating a negative trend in flow volume. The Northern Hemisphere tropics however show a mixed trend, as ~~flood and drought mean~~ changes averaged over latitude show fluctuations between latitudes within the tropics (Figure 2).

Figures 3 and 4 depict multi-model changes in ~~flood and drought indicators~~streamflow extremes under different warming scenarios, averaged over different latitudinal windows. Figure 3 shows the results from streamflow routings of each GHM based on inputs from multiple GCM simulations, where the thick lines in the plots denote the mean of change in the indicator and the shades denote ±1 st. dev. For each single GHM (shown by distinct colors), the thick line in the plots show the average of GCMs and the shading denotes the standard deviation of GCMs. Hence, the shadings in this figure are representative of uncertainties arising from GCMs. ~~In the meantime~~Also, different average values (thick lines) means that different GHMs have produced different streamflow routings and different change values in the indicators, even though the routings are based on inputs from the same ensemble of GCMs.

Figure 4, on the other hand, shows streamflow routings of multiple GHMs based on inputs from each of the GCMs, where the thick lines in the plots denote the mean of change in the indicator and the shades denote ±1 st. dev. For each single GCM (shown by distinct colors), the shading denotes the standard deviation of GHMs and hence, is representative of uncertainties arising from GHMs. The RCP8.5 scenario show higher normalized change values and larger uncertainties, compared to the RCP2.6 scenario. The uncertainties are proportionally greater for ~~drought~~ P5 trend projection than for ~~flooding~~ P95 (Figure 3 and 4).

The shadings in ~~the~~ Figure 4 (inter-GHM uncertainty ~~representative~~) is ~~wider~~ broader than in ~~the~~ Figure 3 (inter-GCM uncertainty ~~representative~~), which shows that the GHMs contribute to higher rate of uncertainties in ~~flood and drought~~streamflow change projections than GCMs. As seen in Figure 3 (c-d), for instance, ~~drought~~ the P5 predictions of the DBH hydrological model for Northern Hemisphere are significantly different from the other 4 hydrological models considered here, even though the streamflow routings are based on the same GCM inputs. Such inconsistency between DBH models and other models' results may not be detectable, if, as ~~the results are averaged as they are~~ in the Figure 4, only the mean and standard deviation across GHMs is shown. ~~Wide shadings~~High uncertainties in Northern Hemisphere ~~drought~~ low extreme trends in Figure 4 (c-d) ~~shows high uncertainties~~reflects large disagreements among the GHMs for that region, while ~~the~~ Figure 3 (c-d) reveals the major cause of such uncertainties to be the DBH model.

Figure 5 illustrates the global maps of combined change in ~~flood~~ high and ~~drought indicators~~low streamflow extremes under each RCP scenarios, obtained from the multi-model mean results ~~of~~ across all 25 GCM-GHM combination datasets. Grid cells falling in each of the defined quadrants are shown with different colors, saturation of which is representative of the intensity of changes. As shown in the Figure, northern high latitudes, especially north Eurasia, northern Canada and Alaska, as well as eastern Africa and parts of South and Southeast Asia and Eastern Oceania show increase in ~~flood intensity~~ the magnitude of high streamflow extremes (P95) in both scenarios, similar to findings of earlier studies and reflecting a potential for increasing flood hazard (Dankers et al., 2013; Hirabayashi et al., 2013; Schewe et al., 2013). Central America, Southern Africa, Middle East, Southern Europe, Mediterranean and major parts of South America and Australia show ~~increase in drought intensity~~ decrease in the magnitude of low streamflow extrem (P5) in both scenarios, comparable to findings of earlier studies and reflecting a potential for increasing drought hazard (Arnell, 2004; Dai, 2011; Hagemann et al., 2013; Schewe et al., 2013). The United

Kingdom and the shores of the North Sea as well as large parts of Tibetan, South Asia and Western Oceania show increase in potential for both flood and drought ~~intensities~~hazards (increase in P95 and decrease in P5). In these cases, while preserving the direction of change, the RCP8.5 scenario projects stronger magnitude change compared to the RCP2.6 scenario. Southern and Western Europe and southern parts of the United States show small-magnitude, mixed-sign ~~increases in flood and drought~~ changes in P95 and P5~~intensities~~ in the RCP2.6 scenario. However, projections under RCP8.5 scenario are for strong ~~increase in drought~~decrease in P5 in those regions, suggesting increasing potential for drought hazard. Some parts of eastern Russia and northern United States show decreases in P95 and increases in P5, suggesting the potential for reduction in both flood and drought hazards~~intensities~~ (Figure 5). ~~Compared to RCP2.6, the RCP8.5 scenario shows more expansion in drought intensity and less expansion in flood intensity (Figure 5 and Table 2).~~

Under the low radiative forcing scenario (RCP2.6), 45.4% of global land area shows increase in ~~flood intensity~~ high extreme in the multi-model mean and 36.4% shows ~~increase in drought~~decrease in low extreme, indicating more land area ~~exposure~~ exposed to increasing flood ~~intensity~~ hazard compared to~~than~~ to drought hazard. The high radiative forcing scenario (RCP8.5) projections show the opposite outcome, with~~projects~~ increased ~~flood intensity~~ high extreme streamflow in 36.6% of global land area and ~~increased drought~~decreased low extreme in 43.2%. Unlike the RCP2.6 scenario, the RCP8.5 scenario projects more land area ~~exposure~~ exposed to increasing drought ~~intensity~~ hazard compared~~than~~ to flood. Moreover, ~~flood and drought events~~changes in streamflow extremes are ~~more intense~~larger in magnitude in RCP8.5 compared to RCP2.6, as the relative change values for 21C are ~~nearly~~ approximately double; for instance, comparing the relative increases in ~~flood indicator~~high extreme in Quad.2 (30.2% vs. 15.1%), and relative ~~increases in drought indicator~~decrease in low extreme in Quad.3 (62.2% vs. 28.1%) (Table 3). Under RCP8.5 scenario, change in ~~flood and drought indicators~~high and low extremes in 54.0 and 64.9%, respectively, of the global land area is statistically significant. The significance fraction is lower for the RCP2.6 scenario (38.4 and 53.8% of global land area in ~~flood and drought indicators~~high and low, respectively). The significance percentage is calculated for the multimodel-averaged streamflow time series in 21C compared to 20C, and the percentages for each individual model may be different~~.~~.

Under RCP8.5 scenario (and similarly in RCP2.6), nearly 9.6% of global land areas show increasing potential exposure to both increase ~~in~~ flood and drought hazards (increasing P95 combined with decreasing P5)~~intensities~~. Unfortunately, these regions are dominantly highly populated parts of the globe, the residence of around 29.6% of the world's current population, or more than 2.1 billion people (Table 2). The 2015 Paris Climate Agreement, adopted at the 21st meeting of the Conference of Parties (COP21), targets to limit the global temperature rise "well below" 2°C above the pre-industrial levels (UNFCCC, 2015). Even though seeming to be ambitious, such an agreement in intergovernmental level is a start to motivate the developed countries producing the majority of greenhouse gases to limit emissions and finance the climate-resilient development in lower income economies, and, based on the projections analyzed here, would limit changes in streamflow extremes that correspond to the potential for increasing flood and drought hazards in many densely populated areas.

4. Conclusion

Global daily streamflow simulations of 25 GCM-GHM combination datasets are analyzed to study the implications of increased GHG emissions and consequent atmospheric temperature rise for global streamflow extremes. The projected changes in high and low streamflow percentiles in the 21C compared to the 20C were studied, under both low and high radiative forcing scenarios, to investigate ~~the regions projected to face increases in flood and/or drought~~ the changes in streamflow distribution and simultaneous vulnerability to different types of hydrological risk in different regions~~events' intensities~~, and study the number of people affected by such changes. Multiple GHMs and GCMs are used to account for uncertainties arising from the hydrological models and flow routing process on the flood and drought studies, additional to the weather field simulation uncertainties~~.~~.

Results suggest that northern high latitudes, especially north Eurasia, northern Canada and Alaska, as well as Tibet Plateau~~an~~ and ~~Southern~~ southern India will face strong increases in ~~flood intensities~~ high extreme of streamflow over the 21st century, with the potential for increasing flood hazard in those regions.~~, while~~ ~~t~~The Mediterranean shores, Middle East, southern North America and the Southern Hemisphere are projected to see strong ~~increases in drought intensities~~decrease in low extreme of streamflow, with the potential for increasing drought hazard for those areas. The projected increase in meltwater flux from the pan-Arctic watershed into the Arctic Ocean may contribute to sea level rise, and changes in salinity, temperature and circulation in the Arctic Ocean. The United Kingdom and the shores of the North Sea as well as large parts of Tibetan, South Asia and Western Oceania show increase in potential for both flood and drought hazards~~intensities~~. Regions projected to experience simultaneous increases in both flood and drought chances~~event intensities~~ as a result of change

Formatted: Indent: First line: 0.29" in streamflow distribution, are highly populated parts of the globe, even though covering a small fraction of global land area. A world 2°C warmer than the pre-industrial era will still face increases in flood and drought in most regions. However, the GCM and GHM ensemble projects that 4°C of warming will bring nearly twice as much increase in the magnitude of high and low streamflow extremes that, in many densely populated areas, are likely to correspond to high-impact flood and droughts.

Similar to previous studies (Giuntoli et al., 2015; Hagemann et al., 2013), our r~~R~~esults show that GHMs contribute to more uncertainty~~ies~~ in streamflow changes than the GCMs, where different GHMs have produced different streamflow routings and different change values in the ~~indicators~~extremes, even though the routings are based on inputs from the same ensemble of GCMs. Our findings suggest that in addition to inclusion of ensembles of GCMs for hydrological impact assessments in lieu of a single model, inclusion of ensembles of GHMs, as done in projects like ISI-MIP, may further improve accuracy of projections. The bias-corrections applied on GCM outputs in ISI-MIP may help reduce the uncertainties of climate models in hydrological impact assessments. However, high inter-GHM uncertainties suggest that more focus is needed on improving the process representation and calibration of hydrological models, so that the next generations of climate-hydrological model intercomparison projects yield higher agreement on future hydrological hazard assessments.~~A world 2°C warmer than the pre-industrial era will still face increases in flood and drought in most regions. However, the GCM and GHM ensemble projects that 4°C of warming will bring nearly twice as much increase in the intensity of those events.~~

Author Contribution

B. Asadieh and N.Y. Krakauer conceived and designed the experiment. B. Asadieh carried out the analyses and wrote the initial manuscript. B. Asadieh and N.Y. Krakauer analyzed the results, and wrote the manuscript~~, and made the conclusions~~.

Acknowledgments

The authors gratefully acknowledge support from NOAA under grants NA11SEC4810004, NA12OAR4310084~~ and~~, NA15OAR4310080 and NA16SEC4810008, and from PSC-CUNY Award # 68346-00 46. All statements made are the views of the authors and not the opinions of the funding agency or the U.S. government.

Conflict of interest

The authors declare that they have no conflict of interest.

References

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D. B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M. and Vazquez-Aguirre, J. L.: Global observed changes in daily climate extremes of temperature and precipitation, J. Geophys. Res., 111(D5), D05109, doi:10.1029/2005JD006290, 2006.

Alfieri, L., Burek, P., Feyen, L. and Forzieri, G.: Global warming increases the frequency of river floods in Europe, Hydrol. Earth Syst. Sci., 19(5), 2247–2260, doi:10.5194/hess-19-2247-2015, 2015.

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., Wyser, K., Feyen, L. and Roo, A. De: Earth ' s Future Global projections of river flood risk in a warmer world Earth ' s Future, Earth's Futur. Res., 5, 171–182, doi:10.1002/eft2.183, 2017.

Allan, R. P. and Soden, B. J.: Atmospheric warming and the amplification of precipitation extremes, Science~~ (80-.)~~., 321(5895), 1481–484, doi:10.1126/science.1160787, 2008.

Allen, M. R. and Ingram, W. J.: Constraints on future changes in climate and the hydrologic cycle, Nature, 419(6903), 224–232, doi:10.1038/nature01092, 2002.

Arnell, N. W.: Climate change and global water resources: SRES emissions and socio-economic scenarios, Glob. Environ. Chang., 14(1), 31–52, doi:10.1016/j.gloenvcha.2003.10.006, 2004.

Asadieh, B. and Krakauer, N. Y.: Global trends in extreme precipitation: climate models versus observations, Hydrol. Earth Syst. Sci., 19(2), 877–891, doi:10.5194/hess-19-877-2015, 2015.

Asadieh, B. and Krakauer, N. Y.: Impacts of changes in precipitation amount and distribution on water resources studied using a model rainwater harvesting system, JAWRA J. Am. Water Resour. Assoc., 1–22, doi:10.1111/1752-1688.12472, 2016.

Asadieh, B., Krakauer, N. Y. and Fekete, B. M.: Historical trends in mean and extreme runoff and streamflow based on observations and climate models, Water, 8(5), 189, doi:10.3390/w8050189, 2016.

Brekke, L. D., Maurer, E. P., Anderson, J. D., Dettinger, M. D., Townsley, E. S., Harrison, A. and Pruitt, T.: Assessing reservoir operations risk under climate change, Water Resour. Res., 45(4), 1–16, doi:10.1029/2008WR006941, 2009.

Carmack, E. C., Yamamoto-Kawai, M., Haine, T. W. N., Bacon, S., Bluhm, B. A., Lique, C., Melling, H., Polyakov, I. V., Straneo, F., Timmermans, M. L. and Williams, W. J.: Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans, J. Geophys. Res. G Biogeosciences, 121(3), 675–717, doi:10.1002/2015JG003140, 2016.

Dai, A.: Drought under global warming: A review, Wiley Interdiscip. Rev. Clim. Chang., 2(1), 45–65, doi:10.1002/wcc.81, 2011.

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., Heinke, J., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y. and Wisser, D.: First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble, Proc. Natl. Acad. Sci., 111(9), 3257–3261, doi:10.1073/pnas.1302078110, 2013.

Dilley, M.: Natural disaster hotspots: a global risk analysis (Vol. 5), World Bank Publications., 2005.

Doxsey-Whitfield, E., MacManus, K., Adamo, S. B., Pistolesi, L., Squires, J., Borkovska, O. and Baptista, S. R.: Taking advantage of the improved availability of census data: a first look at the gridded population of the world, version 4 (GPWv4), Pap. Appl. Geogr., 1(3), 226–234, doi:10.1080/23754931.2015.1014272, 2015.

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K. and Liebert, J.: HESS Opinions "should we apply bias correction to global and regional climate model data?," Hydrol. Earth Syst. Sci., 16(9), 3391–3404, doi:10.5194/hess-16-3391-2012, 2012.

Ehsani, N., Vörösmarty, C. J., Fekete, B. M. and Stakhiv, E. Z.: Reservoir Operations Under Climate Change: Storage Capacity Options to Mitigate Risk, J. Hydrol., doi:10.1016/j.jhydrol.2017.09.008, 2017.

Ellis, A. W., Goodrich, G. B. and Garfin, G. M.: A hydroclimatic index for examining patterns of drought in the Colorado River Basin, Int. J. Climatol., 30(2), 236–255, doi:10.1002/joc.1882, 2010.

Field, C. B.: Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge, UK., 2012.

Giuntoli, I., Vidal, J. P., Prudhomme, C. and Hannah, D. M.: Future hydrological extremes: The uncertainty from multiple global climate and global hydrological models, Earth Syst. Dyn., 6(1), 267–285, doi:10.5194/esd-6-267-2015, 2015.

Haddeland, I., Clark, D. B., Franssen, W., Ludwig, F., Voß, F., Arnell, N. W., Bertrand, N., Best, M., Folwell, S., Gerten, D., Gomes, S., Gosling, S. N., Hagemann, S., Hanasaki, N., Harding, R., Heinke, J., Kabat, P., Koirala, S., Oki, T., Polcher, J., Stacke, T., Viterbo, P., Weedon, G. P. and Yeh, P.: Multimodel estimate of the global terrestrial water balance: setup and first results, J. Hydrometeorol., 12, 869–884, doi:10.1175/2011JHM1324.1, 2011.

Hagemann, S., Chen, C., Haerter, J. O., Heinke, J., Gerten, D. and Piani, C.: Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models, J. Hydrometeorol., 12(4), 556–578, doi:10.1175/2011JHM1336.1, 2011.

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., Hanasaki, N., Heinke, J., Ludwig, F., Voss, F. and Wiltshire, A. J.: Climate change impact on available water resources obtained using multiple global climate and hydrology models, Earth Syst. Dyn., 4(1), 129–144, doi:10.5194/esd-4-129-2013, 2013.

Haine, T. W. N., Curry, B., Gerdes, R., Hansen, E., Karcher, M., Lee, C., Rudels, B., Spreen, G., de Steur, L., Stewart, K. D. and Woodgate, R.: Arctic freshwater export: Status, mechanisms, and prospects, Glob. Planet. Change, 125, 13–35, doi:10.1016/j.gloplacha.2014.11.013, 2015.

Held, I. M. and Soden, B. J.: Robust responses of the hydrological cycle to global warming, J. Clim., 19(21), 5686–5699, doi:10.1175/JCLI3990.1, 2006.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J. and Piontek, F.: A trend-preserving bias correction – the ISI-MIP approach, Earth Syst. Dyn., 4(2), 219–236, doi:10.5194/esd-4-219-2013, 2013.

Hirabayashi, Y., Kanae, S., Emori, S., Oki, T. and Kimoto, M.: Global projections of changing risks of floods and droughts in a changing climate, Hydrol. Sci. J., 53(4), 754–772, doi:10.1623/hysj.53.4.754, 2008.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H. and Kanae, S.: Global flood risk under climate change, Nat. Clim. Chang., 3(9), 816–821, doi:10.1038/nclimate1911, 2013.

IFRC: World disaster report, focus on reducing risk, edited by J. Walter, International Federation of Red Cross and Red Crescent Societies, Geneva, Switzerland. [online] Available from: https://www.ifrc.org/PageFiles/89755/2002/32600-WDR2002.pdf, 2002.

Jian, X., Wolock, D. M., Lins, H. F. and Brady, S.: Streamflow of 2015—Water year national summary, U.S. Geological Survey Fact Sheet 2016–3055, 6 p., doi:10.3133/fs20163055. [online] Available from: https://waterwatch.usgs.gov/2015summary/, 2015.

Kharin, V. V., Zwiers, F. W., Zhang, X. and Wehner, M.: Changes in temperature and precipitation extremes in the CMIP5 ensemble, Clim. Change, 119(2), 345–357, doi:10.1007/s10584-013-0705-8, 2013.

Koirala, S., Hirabayashi, Y., Mahendran, R. and Kanae, S.: Global assessment of agreement among streamflow projections using CMIP5 model outputs, Environ. Res. Lett., 9(6), 64017, doi:10.1088/1748-9326/9/6/064017, 2014.

Krakauer, N. Y. and Fekete, B. M.: Are climate model simulations useful for forecasting precipitation trends? Hindcast and synthetic-data experiments, Environ. Res. Lett., 9(2), 24009, doi:10.1088/1748-9326/9/2/024009, 2014.

Lambert, F. H., Stine, A. R., Krakauer, N. Y. and Chiang, J. C. H.: How much will precipitation increase with global warming?, Eos, Trans. Am. Geophys. Union, 89(21), 193–194, doi:10.1029/2008EO210001, 2008.

Lique, C., Holland, M. M., Dibike, Y. B., Lawrence, D. M. and Screen, J. A.: Modeling the Arctic freshwater system and its integration in the global system: Lessons learned and future challenges, J. Geophys. Res. G Biogeosciences, 121(3), 540–566, doi:10.1002/2015JG003120, 2016.

Min, S.-K., Zhang, X., Zwiers, F. W. and Hegerl, G. C.: Human contribution to more-intense precipitation extremes, Nature, 470(7334), 378–81, doi:10.1038/nature09763, 2011.

Moss, R. H., Edmonds, J. a, Hibbard, K. a, Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. a, Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P. and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463(7282), 747–756, doi:10.1038/nature08823, 2010.

O'Gorman, P. A. and Schneider, T.: The physical basis for increases in precipitation extremes in simulations of 21st-century climate change, Proc. Natl. Acad. Sci., 106(16), 14773–14777, doi:10.1073/pnas.0907610106, 2009.

Oki, T. and Kanae, S.: Global hydrological cycles and world water resources, Science~~ (80-.)~~., 313(5790), 1068–1072, doi:10.1126/science.1128845, 2006.

Pall, P., Allen, M. R. and Stone, D. A.: Testing the Clausius–Clapeyron constraint on changes in extreme precipitation under CO2 warming, Clim. Dyn., 28(4), 351–363, doi:10.1007/s00382-006-0180-2, 2006.

Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. a and Rahmstorf, S.: Increasing river discharge to the Arctic Ocean, Science~~ (80-.)~~., 298(5601), 2171–2173, doi:10.1126/science.1077445, 2002.

Rawlins, M. A., Steele, M., Holland, M. M., Adam, J. C., Cherry, J. E., Francis, J. A., Groisman, P. Y., Hinzman, L. D., Huntington, T. G., Kane, D. L., Kimball, J. S., Kwok, R., Lammers, R. B., Lee, C. M., Lettenmaier, D. P., Mcdonald, K. C., Podest, E., Pundsack, J. W., Rudels, B., Serreze, M. C., Shiklomanov, A., Skagseth, O., Troy, T. J., Vorosmarty, C. J., Wensnahan, M., Wood, E. F., Woodgate, R., Yang, D., Zhang, K. and Zhang, T.: Analysis of the Arctic system for freshwater cycle intensification: Observations and expectations, J. Clim., 23(21), 5715–5737, doi:10.1175/2010JCLI3421.1, 2010.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L. and Kabat, P.: Multimodel assessment of water scarcity under climate change, Proc. Natl. Acad. Sci., 111(9), 3245–3250, doi:10.1073/pnas.1222460110, 2013.

Snedecor, G. W. and Cochran, W. G.: Statistical methods, 8thEdn, Iowa State University Press, Iowa., 1989.

Sprague, L. A.: Drought Effects on Water Quality in the South Platte River Basin, Colorado, J. Am. Water Resour. Assoc., 41(1), 11–24, doi:10.1111/j.1752-1688.2005.tb03713.x, 2005.

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M.: Climate change 2013: The physical science basis. Working group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press., 2013.

Tang, Q. and Lettenmaier., D. P.: 21st century runoff sensitivities of major global river basins, Geophys. Res. Lett., 39(6), doi:10.1029/2011GL050834, 2012.

Toreti, A., Naveau, P., Zampieri, M., Schindler, A., Scoccimarro, E., Xoplaki, E., Dijkstra, H. A., Gualdi, S. and Luterbacher, J.: Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models, Geophys. Res. Lett., 40(18), 4887–4892, doi:10.1002/grl.50940, 2013.

Trenberth, K. E.: Changes in precipitation with climate change, Clim. Res., 47(1), 123–138, doi:10.3354/cr00953, 2011.

UNFCCC: Adoption of the Paris Agreement (FCCC/CP/2015/L.9/Rev.1). [online] Available from: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf, 2015.

Vörösmarty, C. J., Green, P., Salisbury, J. and Lammers, R. B.: Global water resources: vulnerability from climate change and population growth, Science ~~(80-.)~~., 289(5477), 284–288, doi:10.1126/science.289.5477.284, 2000.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O. and Schewe, J.: The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework, Proc. Natl. Acad. Sci., 111(9), 1–5, doi:10.1073/pnas.1312330110, 2013.

Wentz, F. J., Ricciardulli, L., Hilburn, K. and Mears, C.: How much more rain will global warming bring?, Science ~~(80-.)~~., 317(5835), 233–235, doi:10.1126/science.1140746, 2007.

Westra, S., Alexander, L. V. and Zwiers, F. W.: Global increasing trends in annual maximum daily precipitation, J. Clim., 26(11), 3904–3918, doi:10.1175/JCLI-D-12-00502.1, 2013.

Wu, H., Adler, R. F., Hong, Y., Tian, Y. and Policelli, F.: Evaluation of Global Flood Detection Using

Satellite-Based Rainfall and a Hydrologic Model, J. Hydrometeorol., 13(4), 1268–1284, doi:10.1175/JHM-D-11-087.1, 2012.

Wu, H., Adler, R. F., Tian, Y., Huffman, G. J., Li, H. and Wang, J.: Real-time global flood estimation using satellite-based precipitation and a coupled land surface and routing model, Water Resour. Res., 50(3), 2693–2717, doi:10.1002/2013WR014710, 2014.

Table 1. Multi-model average change in ~~flood~~ high and ~~drought indicators~~low streamflow extremes, as well as percent of population and land area affected by each category, for RCP2.6 and RCP8.5 scenarios. Presented percentages are for total global land area and total global population, and sum up to the 75.9% of global land area and 95.9% of the year 2015 total global population considered in this study. The value of change for indicators are normalized change and the numbers in parenthesis show the changes reverted to the relative percentages.

	Normalized (and Percent~~-~~) of Change~~,~~ in ~~flood or drought~~magnitude of extremes		Land Area Affected (% of total 148.9 million km^2, sum up to 75.9%)		Population Affected (% of total 7.13 billion people, sum up to 95.9%)	
	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6
~~Flood Increased Cells~~High extreme (P95) Increased cells *(Increased flood potential)*	0.1093 (24.55 %~~ rel.~~)	0.0606 (12.90 %~~ rel.~~)	36.7%	45.4%	53.7%	62.7%
High extreme (P95) Decreased cells *(Decreased flood potential)*~~Flood Decreased Cells~~	-0.1178 (-21.10 %~~ rel.~~)	-0.0539 (-10.25 %~~ rel.~~)	39.2%	30.5%	42.2%	32.2%
Low extreme (P5) Decreased cells *(Increased drought potential)*~~Drought Increased Cells~~	-0.2045 (-51.40 %~~ rel.~~)	-0.1029 (-22.95 %~~ rel.~~)	43.2%	36.3%	67.8%	56.1%
Low extreme (P5) Increased cells *(Decreased drought potential)*~~Drought Decreased Cells~~	-0.1784 (-30.30 %~~ rel.~~)	-0.1018 (-18.50 %~~ rel.~~)	32.7%	39.6%	28.1%	39.8%

Formatted Table

Formatted: Font: Italic, Complex Script Fo Italic

Formatted: Font: Italic, Complex Script Fo Italic

Formatted: Font: Italic, Complex Script Fo Italic

Formatted: Font: Italic, Complex Script Fo Italic

Table 2. Percent of population and land area affected by each ~~flood and drought~~high and low extreme change quadrants, for RCP2.6 and RCP8.5 scenarios. Presented percentages are for total global land area and total global population. Hence, the percentages presented for quads. 1-4 sum up to the 75.9% of global land area and 95.9% of the year 2015 total global population considered in this study.

		Quad. 1. increased high extreme and decreased low extreme~~flood and drought increased~~	Quad. 2. increased high and low extreme~~flood increased, drought decreased~~	Quad. 3. decreased high and low extreme~~drought increased, flood decreased~~	Quad. 4. decreased high extreme and increased low extreme~~flood and drought decreased~~
Land area affected (% of total 148.9 million km^2)	RCP8.5	9.6%	27.0%	33.6%	5.7%
	RCP2.6	10.8%	34.5%	25.5%	5.1%
Population affected (% of total 7.13 billion people)	RCP8.5	29.6%	24.1%	38.2%	4.0%
	RCP2.6	27.1%	35.6%	28.9%	4.3%

Formatted Table

Table 3. Multi-model average change in ~~flood and drought indicators~~high and low streamflow extremes, averaged for each quadrant, for RCP2.6 and RCP8.5 scenarios. The numbers show the normalized change and the numbers in parenthesis show the changes reverted to the relative percentages.

	Quad. 1. increased high extreme and decreased low extreme~~Quad. 1. flood and drought increased~~		Quad. 2. increased high and low extreme~~Quad. 2. flood increased, drought decreased~~		Quad. 3. decreased high and low extreme~~Quad. 3. drought increased, flood decreased~~		Quad. 4. decreased high extreme and increased low extreme~~Quad. 4. flood and drought decreased~~	
	Change in ~~flood~~high ext.	Change in low ext.~~Change in drought~~	Change in high ext.~~Change in flood~~	Change in low ext.~~Change in drought~~	Change in high ext.~~Change in flood~~	Change in low ext.~~Change in drought~~	Change in high ext.~~Change in flood~~	Change in low ext.~~Change in drought~~
RCP8.5	0.0481 (10.10 %)	-0.0901 (-19.80 %)	0.1311 (30.20 %)	-0.1909 (-32.05 %)	-0.1290 (-22.85 %)	-0.2372 (-62.20 %)	-0.0508 (-9.65 %)	-0.1183 (-21.15 %)
RCP2.6	0.0306 (6.30 %)	0.0556 (-11.80 %)	0.0700 (15.05 %)	-0.1074 (-19.40 %)	-0.0593 (-11.20 %)	-0.1230 (-28.05 %)	-0.0267 (-5.20 %)	-0.0635 (-11.95 %)

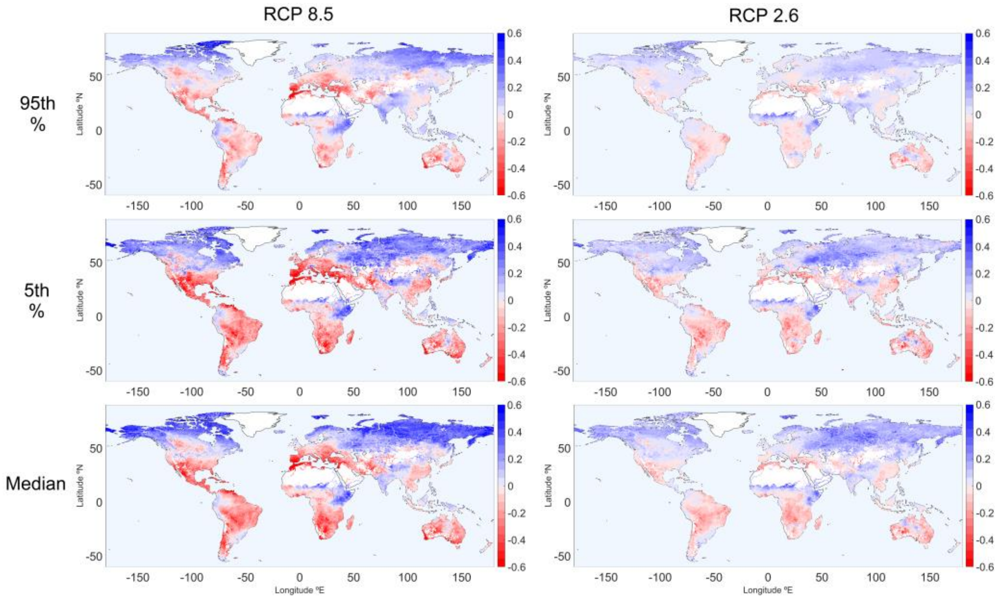

Figure 1. Global maps of normalized change in different streamflow percentiles (95th, 5th and median), under the RCP8.5 and RCP2.6 scenarios. Maps show the ensemble mean results of all 25 models. ~~It should be noted that the results presented are the values of the change in different percentiles and are not necessarily equal to the defined flood and drought indicators.~~

Formatted: Superscript

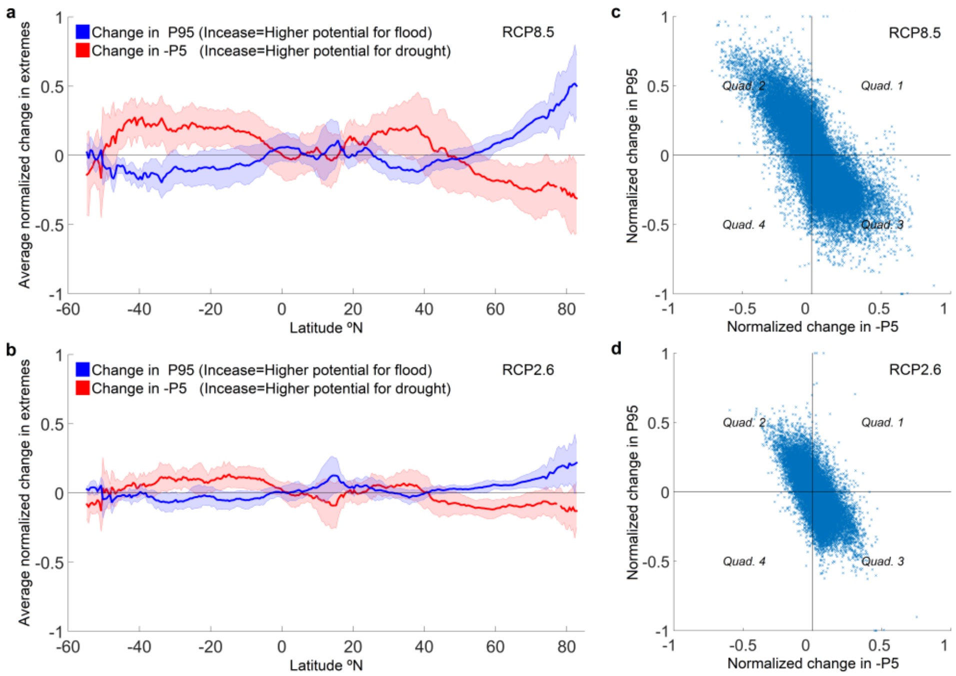

Figure 2. Multi-model change in ~~flood and drought indicators~~P95 and P5*-1 under (a) RCP8.5 and (b) RCP2.6 ~~–~~scenarios, averaged by latitude, and scatter plot of change ~~in flood and drought indicators~~ for each grid cell under (c) RCP8.5 and (d) RCP2.6 scenarios. The thick line in the panels a and b show the ensemble mean value of all 25 GCM-GHM combination datasets and the shading denotes ±1 st. dev.

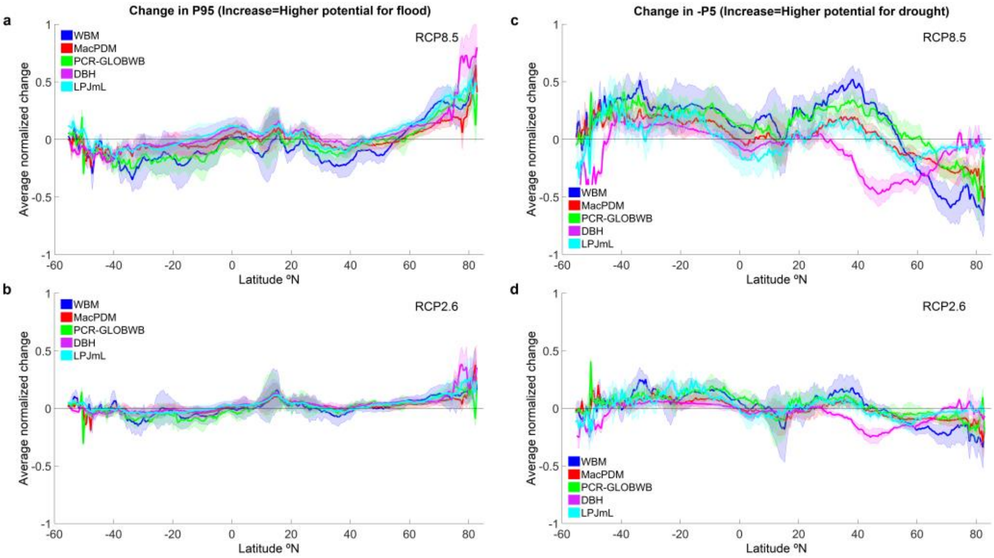

Figure 3. Multi-model change in ~~flood indicator~~P95 under RCP8.5 (a) and RCP2.6 (b) scenarios, and change in ~~drought indicator~~P5*-1 under RCP8.5 (c) and RCP2.6 (d) scenarios, averaged by latitude. The thick lines in the plots show the mean change in the indicator, based on the streamflow routings of each GHM based on inputs from multiple GCMs, and the shades denote ±1 st. dev.

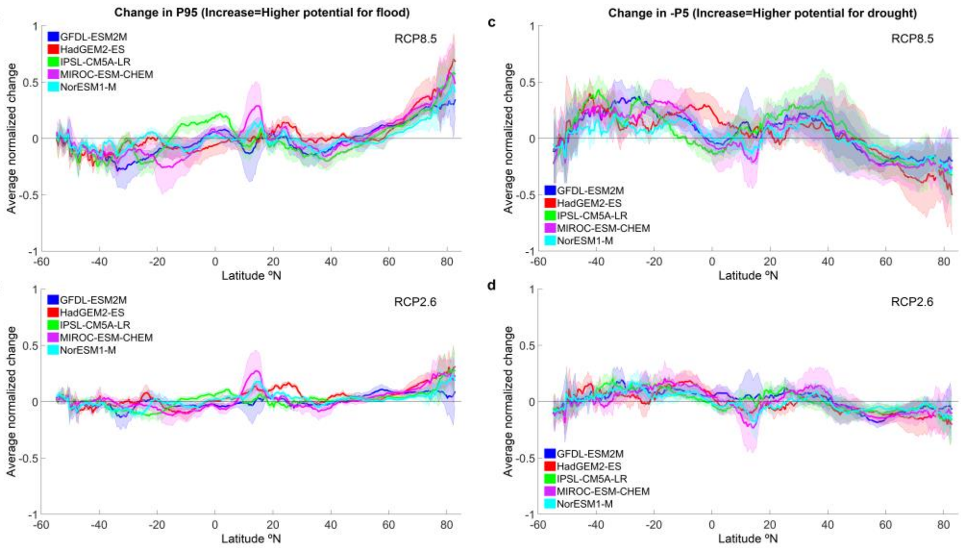

Figure 4. Multi-model change in ~~flood indicator~~P95 under RCP8.5 (a) and RCP2.6 scenarios (b), and change in P5*-1~~drought indicator~~ under RCP8.5 (c) and RCP2.6 scenarios (d), averaged by latitude. The thick lines in the plots show the mean change in the indicator, based on the streamflow from each GCM's simulated climate routed by multiple GHMs, and the shading denotes ±1 st. dev.

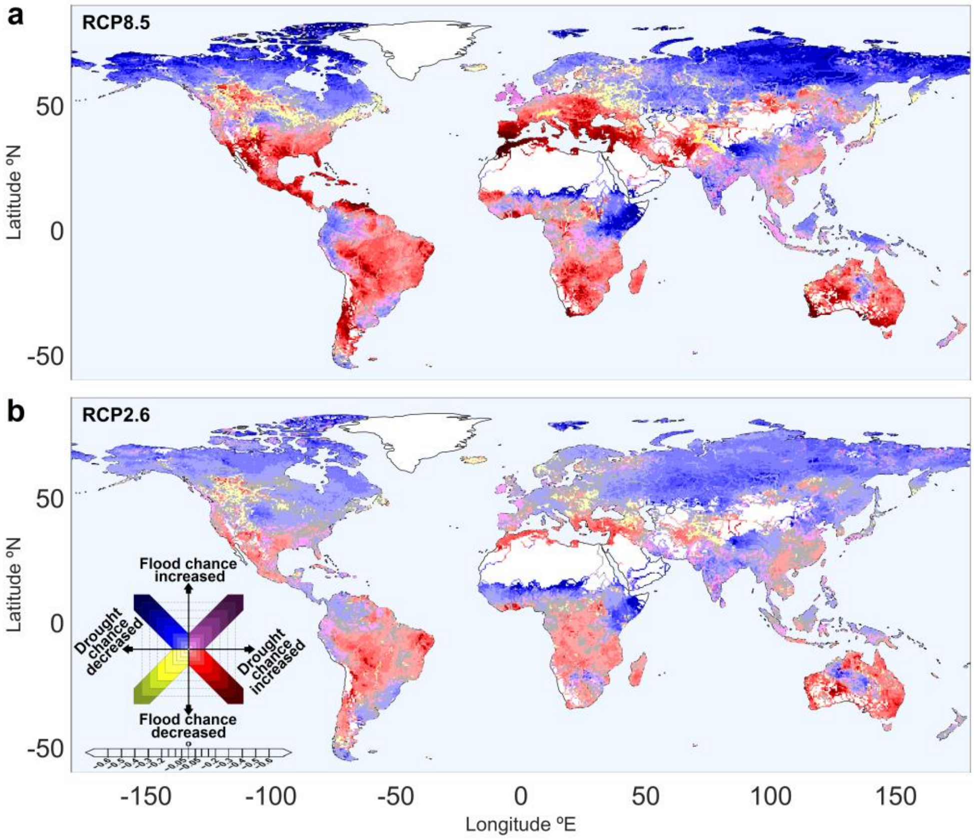

Figure 5. Global map of combined change in high and low extremes (related to change in flood and drought ~~indicators~~ chance) under (a) RCP8.5 and (b) RCP2.6 scenario. The maps show the ensemble mean results of all 25 GCM-GHM combination datasets. Grid cells with increase in both flood and drought chances (Quad. 1) are shown in purple shade, cells with increased flood chance (Quad. 2) and drought chance (Quad. 3) are shown in blue and red shades, respectively, and cells with decrease in both flood and drought chances (Quad. 4) are shown in yellow shade. The saturation of colors ~~shows~~ are chosen based on the ~~intensity~~ magnitude of change~~, based on the normalized change in indicators~~ in high and low extremes of streamflow, as shown in the legend. Distribution of cells in each of the quadrants are comparable to the Figures 2.c and d. Grid cells with normalized changes less than 1% (equal to 2% in relative terms) in each quadrant are considered as no change cells and are shown in gray. ~~Grid cells excluded from the calculations are shown in white.~~