Manuscript No.: hess-2015-140
Title: A Global Approach to Defining Flood Seasons
Authors: Donghoon Lee, Philip Ward and Paul Block

Dear Editor and Reviewers,

We would like to thank the Editor and three Reviewers for carefully reading our manuscript and providing critical and helpful comments. We have revised the manuscript accordingly and detailed these changes in the response, below. Reviewer comments are presented in indented text, our responses are in blue, and revised sentences are in italics. Page and line numbers are given with respect to the HESSD paper (hessd-12-4595-2015). The revised manuscript includes underlined (added text) and crossed out (deleted text) for easy reference.

In general we agree with most comments made by the three reviewers. Based on their suggestions, the following major changes are made:

(1) The title has been changed to "Defining Flood Seasons Globally using Temporal Streamflow Patterns."

(2) We have revised/restructured the focus of the abstract, introduction and conclusion to clarify the objectives and novelties of this study.

(3) We have extended analyses of minor flood seasons to enhance the contribution of this study.

We believe the suggestions and ensuing revisions have clearly resulted in a higher quality manuscript and eagerly look forward to any further comments.

Yours sincerely,

Donghoon Lee

<u>Replies to the Editor's comments</u>

Authors' replies are in blue color and revised sentences are in italics.

> In addition to the review comments I suggest that you consider one other point: What are the advantages to defining the new measure PM (and FS), in relation to existing published measures of flood seasonality? What shortcomings did the previous existing published measures have, and to what extent do your new measures overcome those shortcomings?

We thank you for the critical comments on our paper. The PM (Peak Month) and FS (Flood Season) presented in this study are conceptually similar to previous measures in terms of indicating the peak timing of streamflow (month or season), and this measure in and of itself is not novel. Rather, the novelty lies in the methodology and approach to define flood seasons. In the revised manuscript, we have reviewed key publications identifying global-scale flood peak months or seasons in which they base season definition on the streamflow amplitude rather than temporal pattern of streamflow. This can lead to large regions being lumped into one major season. This may occur at the margins of regions where streamflow patterns may not have a single defined major season (e.g. perpetually wet or dry, bi-modal, etc.). Instead of clustering or aggregation of streamflow amplitude, here we identify peak timing using a volume-based threshold technique and define PM and FS objectively at the cell and sub-basin scale. For clarification, we have added the following new text to our introduction.

Only a small number of studies have investigated global-scale seasonality and temporal patterns of streamflow, with minimal focus on objective streamflow timing. Haines et al. (1988) cluster 969 world rivers into 15 categories based on seasonality and average monthly streamflow data, and present one of the first maps providing a global classification. Burn and Arnell (1993) aggregate 200 streamflow stations into 44 similar climatic regions and subsequently combine these into 13 groups using hierarchical clustering based on similarity of the annual maximum flow index, providing spatial and temporal coincidences of flood response. Dettinger and Diaz (2000) aggregate 1345 sites into 10 clusters based on seasonality using climatological fractional monthly flows (CFMFs) to identify peak months and linkages with large-scale climate drivers.

In general, these studies define key seasons based on large-scale drivers/patterns and clustering, and describe annual peak timing based on streamflow amplitude. The clustering approach employed, however, tends to lump many smaller basins together into one major season, and may not be representative of local scale conditions, especially for those basins at the margins of the clusters where streamflow patterns may not have a single defined major season (e.g. perpetually wet or dry, bi-modal, etc.) In lieu of large-scale clustering and aggregation, we propose addressing basins (and even grid cells) individually, in a disaggregated fashion. Additionally, as an alternative to simply using the annual maximum streamflow amplitude to define the annual peak timing, we consider a volumetric approach based on surpassing a predefined threshold at the daily scale to define peak streamflow timing. Both of these advancements are conditioned on an objective approach to define major and *minor flood seasons globally. Parsing out these peak seasons – if they exist – can improve flood characterization, leading to better understanding of flood potential, causation, and management, particularly in ungauged or limited-gauged basins.*

Technically, the volume-based threshold technique could also be compared with other published methods in terms of identifying "timing of peak streamflow", such as AM (annual maximum), POT (peaks-over threshold) and etc. These methods are developed to focus on either streamflow volume or magnitude, however, here we propose the volume-based threshold technique with the purpose of considering both factors for numerous streamflow types in the world. The performance of volume-based threshold technique is validated by comparing with other classification techniques. Please see our revised text in section 3.1 of the revised manuscript.

<u>Relies to the comments of Anonymous Referee #1</u>

Authors' replies are in blue color and revised sentences are in italics.

> This paper proposes a method to identify the main flood season(s) in all large rivers in the world, based on a distributed hydrological simulation over a few decades, forced by an atmospheric reanalysis product. The article is well written and the storyline follows a sound structure. Although the flood regime of most world rivers is already well known, the findings of this research can be useful for some hydrological applications, such as for ungauged river basins and also to provide a continuous and consistent spatial dataset with global coverage with such type of information. I assume that the validity of the findings is limited to a specific range of basin size, given the spatial resolution used in the modeling, and its use in detecting extreme discharge values. I think that this research is worth of being published, provided that the few comments below are adequately addressed.

We thank the anonymous reviewer for the positive comments and further critical comments that we believe have enhanced the overall quality of the manuscript.

> P.4600-4602: the authors first highlight the benefits of POT approaches (e.g., p.4600, line 24-26) and then don't seem to implement this technique for peak selection. The method based on P_AMF is more like a percentile approach, while in the POT one should select only the peak within the same event, hence it is different. See the recent works by Mallakpour and Villarini (2015) and by Alfieri et al. (2015) for recent applications of POT on observed river discharge and simulated gridded streamflow, respectively.

We apologize for the misunderstanding that we have not applied the POT method in perhaps the traditional sense. In fact we do use aspects of POT not simply for peak selection, but to define Peak Month (PM.) We initially introduce two sampling methods (Annual Maximum and POT) and subsequently argue that the idea of a threshold in the POT approach is more appropriate for defining a flood season in terms of a volume-based threshold technique. Thus POT, in terms of volume, is critical for our classification approach. Additionally, PAMF metric is used to evaluate the defined flood seasons. Thanks also for the references on POT. We have added those as appropriate into the manuscript. For clarification, we have changed P.4600 line 20 - P.4601 line 7 text to read as:

In contrast to the AM method, this characteristic of threshold can capture multiple large independent floods within a year, including the annual maximum flow, but may also miss the annual maximum flow in years in which streamflow is less than the pre-defined threshold (Cunderlik and Ouarda, 2009; Cunderlik et al., 2004a; Ouarda et al., 1993.) Thus, deciding the proper threshold level is important.

Therefore, to define the FS, and specifically the PM, both volume and magnitude aspects need to be considered (Javelle et al. 2003). To do this, we adopt a volume-based threshold technique. This technique is similar to a streamflow volume-based method in terms of capturing the Julian *day by which a fixed percentage of the annual streamflow volume has occurred (Burn, 2008), however it also applies this fixed percentage across the entire streamflow record and records points where streamflow volume surpasses it, drawing from the prescribed threshold concept in the POT method. Here we select streamflow surpassing the top 5% of the flow duration curve (FDC) across all years (1958-2000) as the threshold for considering a high streamflow level, as commonly adopted in threshold approaches (Burn, 2008; Mishra et al., 2011.)*

> Indeed, methods based on fixed time windows are likely to be appropriate for river basins where floods occur with timing similar to that duration. In reality the flood duration vary a lot, and mostly depend on the size of the river basins. In small river basin the flood wave can be entirely contained in a single day, while for large rivers such as the Amazon or the Zambezi, there is a distinct single peak in each year, and the river discharge can be above flooding conditions for a month or more. The authors should consider this in defining the approach for peak selection and perhaps state the limitations/caveats of using the approach described. Other option would be to clarify that the focus of the article is more on detecting the season with on average higher river runoff, rather than looking at extremes causing floodplain inundation.

We agree with the reviewer's comments. Basically, the flood season defined in this study is designed as a fixed time window (3 months) to identify spatial and temporal patterns of dominant streamflow uniformly. To define PM and FS, we focus on the average timing of dominant streamflow, rather than flow duration – as suggested by the author. Thus, globally defined flood seasons are not necessarily representative of individual flood characteristic (e.g. flood duration), but rather the timing of dominant streamflow. For clarifying this, we have changed P.4600 line 1-5 to:

To identify spatial and temporal patterns of dominant streamflow uniformly, we design a fixed time window for representing flood seasons globally. Here we define major flood seasons as the 3-month period most likely to contain dominant streamflow and the annual maximum flow. The central month is referred to as the Peak Month (PM) and the full 3-month period is referred to as the Flood Season (FS.) Specifically, we define PM first, and then define FS as 1 month before and after the PM. This approach is performed for both observed (station) and simulated (model) streamflow to gauge performance.

> Sect. 3.3: As the authors write, there is a potential delay due to routing of the flood wave downstream and smoothing effect due to lakes and reservoirs. Anyway, I think that considering the start of the flood season is a more suitable parameter than the average PM, as the flood often originates upstream and then propagates downstream with a delay dependent on the travel time. Again, I bring up the example of the Amazon river (see, e.g., Rudorff et al., 2014) being the extreme case, where such approach of averaging would simply identify the peak month of a portion of the river basin located in its intermediate part (in terms of distance from the outlet location).

We agree with the reviewer's comments. In the case of large-scale river basins, long travel time and varying climate affects flood seasonality at different locations in the same basin. In section

3.3, we screened out stations having low PAMF values and defined the PM mode as a sub-basin's PM. The start of the PM with a high PAMF value would be a suitable approach to define the basin-scale PM (applicable for numerous management purposes), however, biased simulations or varying climate effects in parts of the basin may impact one or a few stations that could subsequently affect the entire basin's PM. The goal of section 3.3 is to define the sub-basin scale PM for comparing model outputs and observations; in this case considering the most frequent PM may be more robust overall as compared to the start of PM. In consideration of the review's comments, we have provided the following sentences after p.4604, line 4:

The sub-basin's PM is defined based on occurrence of PM rather than the PAMF value to diminish results being skewed by biased simulations or varying climate effects in small parts of the sub-basin. When there are an equal number of occurrences for different PMs, the average PAMF values are used to determine which PM is selected. In this case, the effect of stations downstream of reservoirs will be minimized given their typically low average PAMF values.

Figure 12: panels should refer to specific river sections rather than just river names

Thanks for the suggestion. We have now provided specific locations. The Figure caption has changed to:

Model-based streamflow climatology (left) and corresponding monthly PAMF (right.) Types and locations are: a) uni-modal streamflow – At Bom Lugar, Amazon river, Brazil, b) bimodal streamflow – At Saacow, Webi Shabeelie river, Somalia, c) constant streamflow – At Terapo Mission, Lakekamu river, Papua New Guinea and d) low-flow – At La Sortija, Quequen Salado river, Argentina.

References 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.

Mallakpour, I. and Villarini, G.: The changing nature of flooding across the central United States, Nature Clim. Change, 5(3), 250–254, doi:10.1038/nclimate2516, 2015.

Rudorff, C. M., Melack, J. M. and Bates, P. D.: Flooding dynamics on the lower Amazon floodplain: 2. Seasonal and interannual hydrological variability, Water Resources Research, 50(1), 635–649, doi:10.1002/2013WR014714, 2014.

Relies to the comments of Anonymous Referee #2

Authors' replies are in blue color and revised sentences are in italics.

General Comments:

The work presented in the manuscript with the title 'A Global Approach to Defining Flood Seasons', aims to develop a methodology that allows defining spatial and temporal characteristics of major flood seasons globally with the help of daily stream flow simulations.

As the work reuses of already existing and published modelled global streamflow data, the central scientific contribution of this manuscript is the development of an approach that allows defining flood seasons globally. With this in mind, it would be valuable for the authors of the manuscript to focus more on how they define floods seasons and to compare their results with other already existing flood season indicators.

We thank the anonymous reviewer for the positive comments and further critical comments that we believe have enhanced the overall quality of the manuscript.

Besides focusing on the major flood season globally, the study does also briefly consider minor floods seasons. As the authors point out, the study of minor flood seasons has not obtained much attention at a global scale and therefore merits further investigation.

Therefore, the manuscript would benefit from extending the scope to minor flood seasons not only at the local scale (i.e. with an example from East Africa as presented in the manuscript) but also to the global scale, which would also better match the overall global scope of the manuscript.

Thanks for the compliments on minor flood seasons. We have extended the scope of minor flood seasons to global scale. Please see below responses below on minor flood seasons.

In general, the paper need to be clearer about the different meaning and usage of the terms 'peak month (PM)', 'flood season (FS)' (is it always the 3 months (i.e. PM +-1 month)?), and 'PAMF' (Percentage of Annual Maximum Flow (AMF)). Sometimes these variables are used almost interchangeable. On this matter, also see the specific the comments below.

As the Reviewer surmised, the flood season (FS) is always the 3 month period with the peak month (PM) as the center month. We have addressed and clarified this in the specific comments below.

With the general comments above and the specific comments mentioned below, I recommend thoroughly revising the manuscript, as there are several instances that require further clarification, discussion, corrections, and amendments from the authors.

Overall, the paper is well written and has the potential to be of interest to the readership of HESS. Therefore, I suggest resubmitting the manuscript after a major revision.

Again, the authors thank the Reviewer for their constructive review.

Specific Comments:

Section Abstract:

P 4596 L4-6: The authors argue in their abstract that ‘forecasting systems in the order of months to seasons are a rarity’ and that ‘dominant flood seasons must be adequately defined’ for prediction and disaster preparedness.

I agree that there is a shortage of long-term forecasting systems; however, I would say that in general the flood regime and therefore the flood prone seasons of rivers are locally (the scale at which preparation for disasters take place) well know.

In addition, I presume that the hydrological model, from which the discharge data has been obtained, performs very different at different scale. This is of particular importance, as ungauged basins, for which this type of information would be useful, are often smaller than the grid scale of the model.

Therefore, it is suggested changing the reasoning/focus of the abstract (and also the introduction and conclusions), as the approach to define flood seasons (of 3 months in length) that has been developed here has only a marginal connection with disaster preparedness and flood forecasting.

We agree with the reviewer’s comment. The original motivation of this research was to understand temporal variability of global streamflow in order to improve global-scale flood prediction. However, as suggested, the major findings of this article are not directly connected to disaster preparedness and flood forecasting, thus we will revise/restructure the abstract, introduction and conclusion to focus more on flood seasons and their hydrological applications.

Section 1 Introduction:

The introduction focuses on long-range seasonal forecasts for guiding decision-making, seasonal predictability of streamflow impacts and the need for linking atmospheric indices with streamflow predictions at global scale. From this introduction, I would expect a paper that aims to PREDICT streamflow patterns, which is very different to the actual scope of the paper.

For that reason, I think the introduction should focus more on the actual topic (i.e. a data based approach concerned with the identification of flood seasons and the second objective of extending the approach to already existing globally modelled streamflow).

We agree with reviewer’s comments. We have revised the introduction to highlight the identification of flood seasons and tempered the discussion of prediction (which will be the subject of future work.)

To put the work presented in the manuscript into the context of already existing studies of flood seasonality and global streamflow characteristics, the authors may find the following articles useful: For previous work on different method of identifying/classifying flood seasonality see for example Ouarda et.al. 2006, Liu eta 2010 or Chen et.al. 2013. For more information on how the manuscript fits in the context of or differs to other global studies of streamflow characteristics see for example Dettinger and Diaz 2000 or Beck et.al. 2015.

Thanks for the valuable references on flood seasons and global streamflow characteristics. We have read and added these as appropriate to the manuscript.

Section 2 Data description:

2.1 Streamflow stations

P 4599 L 5-7: The current selection of the dataset cannot really be considered 'global' and has a particular bias towards to certain regions (particularly northern hemisphere).

Please provide further explanation on the how the stations were selected (see also comments below).

Thanks for the comments on this issue. To clarify, the hydrologic (gridded) model does have full spatial coverage, however the station data is, as the reviewer suggested, less well dispersed. Additionally, not all stations have equal record lengths or record quality, however for verification aspects, comparing model outputs with observations is obviously critical. We have provided specific procedures for selecting stations below,

Does 'having at least 20 years of continuous daily streamflow data' mean that all stations that had one measurement missing were excluded, or was a threshold on missing data applied?

Please further explain how the selection criterion 'continuous daily streamflow data' influenced the spatial coverage of the data.

We apologize for the misunderstanding. We have selected stations with more than 20 complete years not necessarily continuous 20 years. If missing values are found, corresponding years are excluded. The criteria of 20 complete years and locations on model's river network have, admittedly, reduced the number of stations, particularly for the southern hemisphere, and specifically the Africa and South America, because of relatively poor observed data.

To what period does the 'at least 20 years' refer to? Same the stream flow simulations (1958-2000)? Please specify.

Yes, the same period with model's simulation (1958-2000) was used. We have clarified this in the manuscript.

With a less stringent selection criterion ('having at least 20 years of continuous daily streamflow data'), could one have obtained a better compromise of spatial coverage and data quality?

The Reviewer makes a good point. Yes, if the station data criteria is relaxed, it is possible to add more stations and have better spatial coverage, however there are not many stations that were "close" to meeting the criteria, then dropped. Stations that did not meet the criteria were typically quite short in record length or had many missing data points. So in the end, the authors believe that revising this strict selection process is unlikely to make a significant difference in the number of stations added.

> Please add a paragraph further elaborates on these choices, as this step is crucial in determining the amount of data and spatial coverage available for method validation.

We have changed P.4599, line 5-7 to:

Daily streamflow observations utilized in this study are from the Global Runoff Data Centre (GRDC, 2007.) For comparing flood seasons between simulation and observation, stations located along with the model's drainage network are considered. Station records that are missing even short periods may effect how a flood season is defined, thus we have excluded years with any daily missing values from stations. In this study, a minimum of 20 hydrological years required for a station to be retained. Globally, 691 stations from all continents except Antarctica were selected with data more than 20 complete years, with upstream area ranging from 9,539 to 4,680,000 km^2 and period of record between 20 and 43 years from 1958 to 2000 (Figure 1.) Although this criteria is admittedly quite strict (no missing daily data), relaxing the criteria does not add a significant number of stations.

> 2.2. PCR-GLOBWB
>
> P 4599 L20: The authors mention that the model was forced with input data from ERA-40, which 'were subjected to a number of corrections'.
>
> Please specify how these corrections might or might not influence the model output.

The WATCH project performed these corrections to reproduce more realistic atmospheric data. Thus, it may affect the model's performance in simulating more accurate streamflow. For specifying these corrections, we have changed P.4599, line 18-21 to:

The WATCH forcing data were originally derived from the ERA-40 reanalysis product (Uppala et al., 2005), and were subjected to a number of corrections including elevation correction, time-scale adjustments of daily values to reflect monthly observations, and corrections for varying atmospheric aerosol-loading and separate precipitation gauge corrections. It is possible that this may have some minor effect on streamflow simulation, likely providing more realistic outcomes. Full details of corrections are described in Weedon et al. (2011).

> Please also discuss/analyse the influence of the hydrological model and the grid cell size on the ability of the model to generate the magnitude of hydrological extremes, which will be used as a key variable for the definition of the flood season using the volumetric-based threshold approach.

The authors agree that proper realization of hydrologic extremes in the model is important and validation of these characteristics is necessary. To support this, we have provided references illustrating the model's ability (as this is work performed prior to our analysis.). We have provided the following sentence after P.4599, line 12:

The PCR-GLOBWB model has not been calibrated, thus simulation results may be biased and uncertain at course spatial resolution, however it has the ability to provide long time-series of streamflow globally, which has is sufficient to estimate long-term flow characteristics with spatial consistence (Winsemius et al., 2013). Additionally, this model has been validated in previous studies in terms of streamflow (Van Beek et al., 2011), terrestrial water storage (Wada et al., 2011) and extreme discharges (Ward et al., 2013), indicating model performance.

3. Defining flood seasons

3.1 Methodology for defining grid-cell scale flood seasons

P 4061 L1-7: It is pointed out that it is important to consider not just the magnitude but also volume to define a flood season and that the authors therefore adopt a volume-based threshold technique. However, the authors then select the 'streamflow exceeding the top 5 % of the FDC', which is related to magnitude. If this is the case, it is not clear why the need for/use of a volume-based measurements is highlighted here and several times throughout the document.

We apologize for the misunderstanding that the volume-based threshold method is used to record streamflow occurrences (volume) based on the top 5% of the FDC (magnitude). For clarification, we have changed P.4601, line 1-7 to:

Therefore, to define the FS, and specifically the PM, both volume and magnitude aspects need to be considered (Javelle et al. 2003). To do this, we adopt a volume-based threshold technique. This technique is similar to a streamflow volume-based method in terms of capturing the Julian day by which a fixed percentage of the annual streamflow volume has occurred (Burn, 2008), however it also applies this fixed percentage across the entire streamflow record and records points where streamflow volume surpasses it, drawing from the prescribed threshold concept in the POT method. Here we select streamflow surpassing the top 5% of the flow duration curve (FDC) across all years (1958-2000) as the threshold for considering a high streamflow level, as commonly adopted in threshold approaches (Burn, 2008; Mishra et al., 2011.)

Additionally, please elaborate on the decision process of selecting the '5% threshold', as on the previous page the importance on selecting the 'proper threshold for POT' highlighted. Have other thresholds been tested and what was the outcome?

We selected the top 5% of the flow duration curve as a threshold as this is commonly used to consider high streamflow level in threshold approaches (p.4601, line 3-7). We did not test other threshold levels, but rather compared to other indices (section 3.2) to show that the volume-based threshold method is the best method to consider magnitude and volume simultaneously. That said, considering varying threshold levels could be an interesting aspect of future work.

P 4061 L10-12: From the description, it appears that after identifying the peak month, the flood season is defined as the month before and after the peak month. Is this the case or is the flood season related to the three month with the highest number of days above the 5% streamflow threshold?

We apologize for the misunderstanding. The FS is defined as the month before and after the PM. The PM is the key outcome here, however for the future (intended) prediction work, a seasonal approach will be undertaken, thus we have also defined the FS. For clarification, we have changed P.4600, line 2-5 to:

To identify spatial and temporal patterns of dominant streamflow uniformly, we design a fixed time window for representing flood seasons globally. Here we define major flood seasons as the 3-month period most likely to contain dominant streamflow and the annual maximum flow. The central month is referred to as the Peak Month (PM) and the full 3-month period is referred to as the Flood Season (FS.) Specifically, we define PM first, and then define FS as the period also containing the month before and after the PM. This approach is performed for both observed (station) and simulated (model) streamflow to gauge performance.

I could imagine a situation similar to the synthetic streamflow data used in Figure 2, with August (105 days) being the peak months but June with 60 days (instead of the 25 days used in the example)) and July with 75 days. Resulting in the peak month being off centre.

It needs to be clarified, if such a situation had been considered and if not how that will influence the results (including the calculation of the index 'Percentage of Annual Maximum Flow (PAMF)').

The intent of the Percentage of Annual Maximum Flood (PAMF) metric created for this analysis directly addresses the reviewer's concern. After defining the FS, it is evaluated in terms of how many of the annual maximums are contained within that 3-month period (see next response). So it certainly is possible that the PM could be "off center", however, generally the PAMF value will be highest in the PM. A good example is Figure 11(a) (please see updated Figure 11(a) below). Here, PM (April) could be regarded as being off center from largest streamflow volume (AMJ), however, PAMF value in April is higher than May. (Here, monthly PAMF is the PAMF value calculated at each month, please see below reformulated Eq. (1)).

P 4601 L 20-24: The index PAMF has been created to 'evaluate' the identified flood seasons. Therefore, it is suggested interpreting the 'high' or 'low' values of PAMF in that regard, (e.g. a high PAMF indicates a well represented Flood Season (FS), a low PAMF indicates poorly identified FS?). Additionally, as the index has been created to evaluate the defined FS, please also give an indication of what is considered by the authors of being a good or less acceptable value (i.e. what percentages are considered good ? And for the discussion of the results for what regions is the approach used to define flood seasons not working).

We appreciate the reviewer's comments on this. For clarifying this, P. 4601, line 13-14 has been changed to:

To evaluate the defined FS objectively in terms of how many of the annual maximum flows are contained, we develop a simple evaluating statistic called the Percentage of Annual Maximum Flow (PAMF).

To address what may be an acceptable value for PAMF, we have classified FS PAMF ranges. We have changed P. 4601, line 20-24 to:

For example, a high PAMF indicates that the FS is highly likely to contain the annual maximum flood each year. In contrast, a low PAMF indicates that the timing of the annual maximum flow is more likely to vary temporally, and may be a result of bimodal seasonality, consistently high or low streamflow throughout the year, streamflow regulated by infrastructure or natural variation. In this study, we subjectively classify FS PAMF values as: high = 80-100% PAMF, low = 60-80%, and poor = 40-60%.

> P 4601: Generally, after highlighting the advantages of the POT approach and the disadvantages of the annual maximum flows (AMF) (such as) it is not clear to me why the PAMF method uses AMF to evaluate the defined flood seasons. Has other values instead of the AMF been considered, and if so why has the AMF been chosen?

Yes, we used a threshold approach only for defining PM (volume-based threshold technique) for considering streamflow volume and magnitude. We had considered using threshold-based index for evaluating FS which may show higher scores than the AMF-based index, however we selected the AM-based statistic because it is more objective to evaluate how many of the annual maximum flows are contained in FS, compared to subjective threshold-based statistic. Additionally, this AM-based statistic is more applicable to further analysis of minor FS.

> 3.2 Classification techniques
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> P 4602 L 12-14: Please further elaborate why '1-7 days favour identifying flood magnitude, while 15- 30- days favour identifying flood volume'.

Thanks for the comments on this issue. As the reviewer's comments, it is be a subjective classification. Here we classified a QAM and Q7 index for flood magnitude and Q15 and Q30 for flood volume by comparison with full length of PM (30 days). For clarifying this, we have changed P. 4602, line 12-14 to:

Compared to the full length of PM (30 days), the flow-based classification techniques with a shorter time component (1-7 days) favor identifying flood magnitude while the techniques with longer time components (15-30 days) favor identifying flood volume.

> P 4602 L 16-21: I am having difficulties in understanding what this section means. Can you please rephrase and explain for what reason 'they may be considered slightly superior'.

The PAMF value is developed for evaluating FS in terms of how many of the annual maximum flows are contained. Therefore, if classification techniques define a FS differently at the same station, the technique showing the highest PAMF value should be superior to others in terms of containing annual maximum flows. For clarification, we have changed P. 4602, line 17-21 to:

The PAMF is also useful for comparing classification techniques' performances when they define PM differently at the same location. This occurs at 45% and 40% of stations for observation and simulation, respectively. The classification technique having the highest PAMF most often for those stations may be considered slightly superior in terms of containing more annual maximum flows in their defined FSs. The volume-based threshold technique has the highest PAMF values by at least 2% of stations more than other techniques for simulation, and at least 1% of stations more than other techniques without Q_AM for observation.

How can one calculate the PAMF for the other classification techniques?

The PAMF is calculated in the same way using Eq. (1). So, for example, if all classification methods define the same PM, all PAMF values are the same. However, if PMs are defined differently, the PAMF values would be unique to their corresponding PMs.

Can equation (1) be reformulated to be more generally applicable (see also comment on monthly PAMF below).

We have provided it in a general format. P.4601 line15-18 has been changed to:

$$PAMF(i) = \frac{\sum_{j=i-1}^{i+1} nAMF(j)}{\sum_{k=1}^{12} nAMF(k)},\ 1 \le i \le 12 \qquad (1)$$

where $nAMF(i)$ *denotes number of annual maximum flows that occurs in i month during entire records. In Eq. (1), when* i *is 1 (Jan),* $i-1$ *in the summation is 12 (Dec), and when* i *is 12 (Dec),* $i+1$ *is 1 (Jan). Here the PAMF provides the percent of time the annual maximum flows occurs in the defined FS across the evaluation period.*

General Comment on Section 3.1 and 3.2:

It is not clear to me, why these two sections are separate. I would expect to evaluate the PM that has been identified with the 5% threshold approach together with the other classification techniques and then pick the best indicator (i.e. here apparently the PM) for further analysis. In addition, if applicable compare the performance with other seasonal indicators that have been publish in other studies before and explain why the approach here is superior to the other methods (otherwise the new approach would not be needed).

Having first the 'Methodology for defining grid-cell scale flood seasons' and then having a separate section on '3.2 Classification techniques' is confusing.

Therefore, I suggest combining these two section together with an in depth analyses on the flood season classification approaches (e.g. how do global maps of differ?).

We agree with reviewer's comments. Section 3.2 has now been merged into section 3.1.

3.3 Methodology for defining sub-basin scale flood seasons

P 4603 L 21-22: I understand that under certain circumstances, the PAMF can be useful to indentify managed dams or reservoirs, but if the dams are managed in accordance with what is considered the 'natural flow regime', this will not help. Additionally, why not use the dataset mentioned a few lines above to find the location of the dams? Without the factual knowledge of the presence/absence of a dam, one will have difficulties in determining if the low values of the PAMF indicator obtained from the modelled data are due to management or due to difficulties of the model to represent the hydrological characteristics of that region.

We chose not to use the reservoir dataset explicitly, because if a station's seasonality is not affected by an upstream reservoir (as suggested by the author), it might contribute in defining the sub-basin PM, and we would want to retain that information. We have checked reservoir locations against downstream stations for many locations to verify our assumption. There may be cases of low PAMF due to presence of a dam that we have not discovered, but a cursory evaluation did not reveal this to be a point of concern. For clarifying this, we have changed P.4603, line 21-23 to:

The PAMF, as previously defined, can aid in identifying stations affected by upstream reservoir by showing low PAMF values. This is applied with the assumption that reservoir flood control disperses the annual maximum flows across months rather concentrated within a few months (e.g. akin to natural flow.)

4. Verification of selected flood seasons

P 4604: I suggest adding the characteristics of the data obtained from the DFO (such as available period...) here, instead of having it in section 4.2 (P 4606), where I would focus on discussing the results.

We agree with the reviewer's suggestions and have provided specific information about DFO records here. P.4604, line.24-25 has been changed to:

First, the model-based PMs are verified by comparing with observation-based PMs at station and sub-basin scales. Also, historic flood records from the Dartmouth Flood Observatory (DFO) are used to compare globally defined PMs to actual flooded areas spatially and temporally. Specifically, we used the following information from DFO: start time, end time, duration and geographically estimated area at 3,486 flood records during 1985-2008.

4.1 Observed vs. Modelled flood seasons

P 4605 L 6: How are the temporal differences calculate? Is it based on the (central?) peak months or on the entire 3 month long flood season? I.e. if I have an observed Flood season June to August, and a modelled season September to November, is the difference three or just one months?

Yes, the difference is between PMs, so in the example provided by the reviewer, it would be 3 months difference. For clarification, we have changed P. 4605, line 4-6 to:

For comparing modeled PMs to observations, the defined PMs and calculated PAMF are represented globally at the station scale (Figure 4-5) and sub-basin scale (Figure 6) with temporal differences of PMs (modeled PM – observed PM).

> I would suggest to calculate the differences not for the FS but for the PM (if the PM is centred in 3 month flood season (see also discussion on the definition of FS above)) and the PAMF respectively and then add a panel showing the differences in Figure 4-6 respectively directly, allowing a direct comparison (instead of having them separately in Figure 7).

We agree with the reviewer that this will be easier to interpret and have changed the name to temporal difference of PM, and provided direct comparison maps (temporal difference maps). Please see updated Figure 4 and 6 below.

> P 4605 L 6: In Figure 7 (P 4624), the temporal differences are shown.
>
> However, the colour scale of the Figure seems to omit basins with differences larger than +- 4 months (see catchments highlighted with red boarders in the Figure excerpt below)!
>
> Please check again, why these catchments are not shown. If these catchments actually have such extreme differences in the FS, please do not omit them from the discussion in section 4.1.
>
> This is an important part of the analysis, which is currently not apparent to the reader and should be highlighted and discussed!

Thank you for pointing out this. We have corrected this issue. Please see responses on corresponding figures below.

> P 4605 L 7: Is there is a mix-up with the % of stations used in the text to describe the bar plot. 62% and 44% seem to refer to the % of stations of the entire dataset but I rather think that the percent should read according to the height of the bars ~ 35% and ~50%. Please check.

Thanks for correcting this. We have checked all values mentioned in this section. P.4605, line 7-9 has been changed to:

For example, in the United States and Canada, 38% of stations and 51% of sub-basins produce identical PMs, growing to 82% of stations and 93% of sub-basins when considering a ±1 month temporal difference (Figure 7.)

> P 4606 L 6-7: I'm not sure how the authors come to the conclusion of 'Europe exemplifying a constant-flow region'. From my knowledge of the flood hydrology in

Europe, I would say that most of the regions in Europe have a well-defined seasonal flood regime. Could the authors please better explain how this had been concluded.

We made this conclusion based on the streamflow simulation around northeastern Europe, however there were some biased simulations (please see biased PM (large difference in PM) in updated figure 6(c) or 8 below). After considering the reviewer's comments, it is difficult to generalize about the entire Europe, thus we have removed this sentence.

General Comment on Section 4.1:

As the main aim of the paper is to define flood seasons globally, I recommend a more in depth analysis of the obtained differences in the PM or the FS.

For example, it would be valuable to analyse if the differences between the observed and modelled PM and FS are systematically linked to station/sub-basin characteristics such as catchment size, latitude/ longitude or altitude. The results will then give a better fell on the reliability of the modelled PM and FS not only in light of possible human influences (e.g. dams or reservoirs) as discussed in the manuscript

Thanks for the comments. We had planned to do more analyses discovering characteristics on difference of PM between simulation and observation, however, we thought any other conclusions about them would be beyond the scope of section 4.1 which is to show the performance of modeled PM compared to observation. Additionally, we have focused more on the minor flood seasons that might physically explain significance of flood season. We do agree that this is relevant and interesting, however, and will consider further detailed analysis in this direction in the future.

4.2. Modelled flood seasons vs. actual flood records

As mentioned before, I would move the characterisation of the DFO data into section 4 and focus here on a more quantitative assessment of the differences.

P 4606 L 23: To me the there is no 'striking similarity' between the DFO and the modelled data. Maybe if the authors summarise the gridded model data to the same sub-basin scale as the DFO, similarity may becomes more apparent. I therefore suggest to also providing some sort quantification (not only qualitatively discussing the maps), before calling it 'striking'.

It is possible to perform a quantitative assessments for comparing DFO records and cell-based PM using GIS applications, however, the DFO data used in this study was generated by different sources, and polygons in the DFO map are not spatially observed areas, but spatially *estimated* areas. Also, each polygon has qualitative information, such as main cause, mortality, damage and so on, therefore we thought any spatially drawn conclusions based on a quantitative comparison between globally defined PM and DFO records could be unreasonable or unjustifiable. We indeed explored this initially.

The previous color code was not continuous from Dec to Jan, thus we have changed it to be continuous (we appreciate reviewer's comments.) The updated PM and DFO maps (please see updated Figure 8 and 10 below) are similar, and mostly dissimilar areas have low PAMF values, indicating "unstable" Annual Maximum Floods. In section 5, we have defined the minor FS that helps to explain low PAMF values at the corresponding regions, and compared global major and minor FS maps and monthly DFO maps (please see updated figure 13 below).

> 5. Defining minor flood seasons
>
> Defining minor flood seasons is a very relevant research topic that has obtained little attention in global studies, as the authors point out (P 4607 L 14-21).
>
> This is where I would see a great contribution of this manuscript in advancing the scientific understanding of flood seasons.
>
> Unfortunately, this aspect is only covered briefly and appears to be appended to the main analysis, currently with limited added value.

The authors appreciate the reviewer's comment and thus we have extended the defined Minor FS to global-scale, and provided more analyses.

> P 4607 L 23: Please explain how monthly PAMF values were calculated. (I suggest using a more general formula for equation 1).

We have provided general formula for Eq. (1). Here the monthly PAMF values are calculated by Eq. (1) at each month. For clarifying this, we have changed P. 4607, line 22-24 to:

To detect noteworthy minor flood seasons globally, we classify streamflow regimes by climatology and monthly PAMF value, which is calculated using Eq. (1) at each month (Figure 11.)

> P 4608 L 14-16: after describing in length the methods used to define the minor PM, the authors only show an example of East Africa. Here, I would have expected a global map showing regions where such minor flood seasons are existing and if possible indicating the PM as well on global maps.

We have provided more analyses on minor flood seasons and extended the scope to global-scale as suggested. P.4607, line 23 – P.4608, line 16 have been changed to (please also see new figure 12 below):

To detect noteworthy minor flood seasons globally, we classify streamflow regimes by climatology and monthly PAMF value, which is calculated using Eq. (1) at each month (Figure 11.) Classifications include unimodal, bimodal, constant, and low-flow. The unimodal streamflow climatology has high values of PAMF around the PM; the bi-modal classification is represented by two peaks of PAMF; both constant and low-flow classifications represent low values of PAMF between months. Distinguishing between bi-modal and other classifications is nontrivial. For example, upon initial inspection of the constant streamflow classification (both climatology and *monthly PAMF, Figure 11 (c)), it could be mistaken for a non-dominant bi-modal distribution. In other words, bi-modal streamflow could be detected correctly or incorrectly, depending on how to define bi-modal streamflow. We adopt the following criteria to differentiate bi-modal streamflow from uni-modal, constant and low-flow conditions.*

- *The low-flow classification is defined for annual average streamflow less than 1 cms.*
- *The major and minor PMs must be separated by at least two months in order to prevent an overlap of each FS (3-month.)*
- *If there is a peak in monthly PAMF values around major FS, it is regarded as potential minor PM.*
- *If the sum of both major and minor PM's PAMF is greater than 60% (minimum of 29 out of 43 annual maximums fall in one of the FS), it is defined as bi-modal streamflow.*

For considering potential flooding, the minor PM is identified by the secondary peak of monthly PAMF rather than the magnitude or shape of streamflow. Also, the minor FS is not defined when a major PM's PAMF is greater than 80% (minimum of 35 out of 43 annual maximums), indicating a robust uni-modal streamflow character (Figure 11 (a)). The sum of both major and minor PM's PAMF is used to determine the significance of both FSs in terms of containing annual maximum flows; a high value of the joint PAMFs (80-100%) indicates that both FSs are significant (Figure 11 (b)), moderate values (60-80%) imply less significance with some probability of being classified as constant streamflow (Figure 11 (c)); low values (50-60%) are likely constant or low streamflow (Figure 11 (d)). After defining the major PM, the minor PM is identified globally with the corresponding joint PAMF values (Figure 12), and the minor FS is also defined as the month before and after the minor PM. In Figure 12, minor FSs are evident in the tropics and sub-tropics and spatially consistent with bi-modal rainfall regimes discovered by Wang (1994). Well-known bi-modal flood seasons are also defined in East Africa (second rainy season in winter) and Canada (rainfall-dominated runoff in autumn) with high joint PAMF values (80-100%) indicating strong significance of both FSs. Minor FSs are also associated with bi-modal rainy seasons, for example the major FS (NDJ) and minor FS (MAM) in Central Africa consistent with the latitudinal movement of the ITCZ, intra-Americas' major FS (ASON) due to the major rainy season and minor FS (AMJJ) due to minor rainy season (Chen and Taylor, 2002), and coastal regions of British Columbia in Canada and southern Alaska's minor FS (SOND) due to wintertime migration of the Aleutian low from the central north Pacific (Figure 12). Also, distinct runoff process from different climate systems can induce a bi-modal peak within a large-scale basin, such as the upstream sections of the Yenisey and Lena river systems in Russia where their major FS (AMJ) is dominated by snowmelt and thawing and minor FS (JAS) is spurred on by the Asian monsoon period. The same mechanism produces minor FSs around the extents of the Asian summer monsoon with high significances (90-100% of sum of PAMFs) (Figure 9 and 12). Moderate minor FSs include, for example, the southern United States (Texas and Oklahoma) bi-modal rainfall pattern (AMJ and SON) and southwestern United States (Arizona) where summer major FS (JJA) is produced by the North American monsoon and winter minor FS (DJF) is affected by the regional large-scale low pressure system (Woodhouse, 1997). Southeastern Brazil's summer major FS (NDJF) and post-summer minor FS (AMJ) are dominated by formation and migration of the South Atlantic Convergence Zone (Herdies, 2002;

Lima and Satyamurty, 2010). In central and eastern Europe, the major FS (FMAM) and minor FS (JJA) are defined as moderate (60-80% of joint PAMF values for central Europe and 70%-90% for eastern Europe); for northeastern Europe the major FS (MAM) and minor FS (NDJ) are have high joint PAMF values (80%-100%.).

For the major FS and minor FS with joint PAMF values exceeding 60% (Figure 13), flood records (DFO) occurring over more than one month are counted in each month based on the reported duration of all records. Although one distinct flood event dominate a monthly DFO record, strong similarity is evident between the FSs and monthly flood records (Figure 13.) The minor FSs with high PAMF values corresponding well with the observed DFO flood records are in East Africa (notable bi-modal streamflow), intra-Americas and Northern Asia; only a few reported flood records occur in the minor FSs in high latitudes. The minor FSs with moderate PAMF values are evident in the southern US, southeastern Brazil and central Europe.

6. Conclusions and discussions

P 4608 L 20-23: The authors highlight that the streamflow model was evaluated 'to define dominant and minor flood seasons globally'. This has only been partly archived for the case of the dominate season, not for the minor seasons (see comments for section 5 above).

We have now provided global-scale major and minor flood season maps.

P 4609: As already mentioned in the comments to the introduction, the conclusion of the manuscript focuses on many other aspects surrounding the topic of prediction and links to global and regional climate links, which has little to do with the main focus of the manuscript in the current form.

Therefore, I would suggest, revising this section.

We agree with reviewer's comments. We have revised it in the manuscript.

Comments to Tables and Figures

P 4616: Table 1 Please add the '5% ' to the threshold column heading.

Thanks, we have added it.

P 4618: Figure 1. When printing the manuscript on my printer (printer-friendly version form the HESSD website), the background polygons are not visible. Please check.

Thanks, we have changed the background color to be darker for all figures.

P 4621: Figure 4: When printing the manuscript, the colour code for the points does not allow me to identify the different months properly. For example, I cannot distinguish points indicating April from March or May. Please use a different colour scheme.

Thanks, we changed the color scheme for Peak Month (Figure 4, 6 and 8) and DFO months (Figure 10). Please see updated figures below.

P 4624 Figure 7: Adjustment of the plotting procedure is necessary to accommodate basins that have differences larger than 4 months and therefore currently are hidden and not visible at all.

P 4624 and P 4624: Please add to the Figure captions, what the meaning or + and - are. (i.e. Do positive red values mean that the observed PM/FS is x months earlier and negative blue values indicate that the observed PM occur x months later?)

Thanks for catching this mistake. The difference of PM is calculated by PM (simulation) – PM (observation). We have provided the inadvertently omitted stations and sub-basins, and also captions. Please see updated Figure 4 (c) and 6 (c) below.

References.

Ouarda, T., Cunderlik, J., St-Hilaire, A., Barbet, M., Bruneau, P. and Bobée, B.: Data-based comparison of seasonality-based regional flood frequency methods, Journal of Hydrology, 330(1), 329–339, 2006.

Liu, P., Guo, S., Xiong, L. and Chen, L.: Flood season segmentation based on the probability change- point analysis technique, Hydrological Sciences Journal, 55(4), 540–554, 2010.

Chen, L., Singh, V. P., Guo, S., Fang, B. and Liu, P.: A new method for identification of flood seasons using directional statistics, Hydrological Sciences Journal, 58(1), 28–40, 2013.

Dettinger, M. D. and Diaz, H. F.: Global characteristics of stream flow seasonality and variability, Journal of Hydrometeorology, 1(4), 289–310, 2000.

Beck, H. E., de Roo, A. and von Dijk, A.: Global maps of streamflow characteristics based on observations from several thousand catchments, Journal of Hydrometeorology, published online, doi: 10.1175/JHM-D-14-0155.1; 2015.

Updated figures

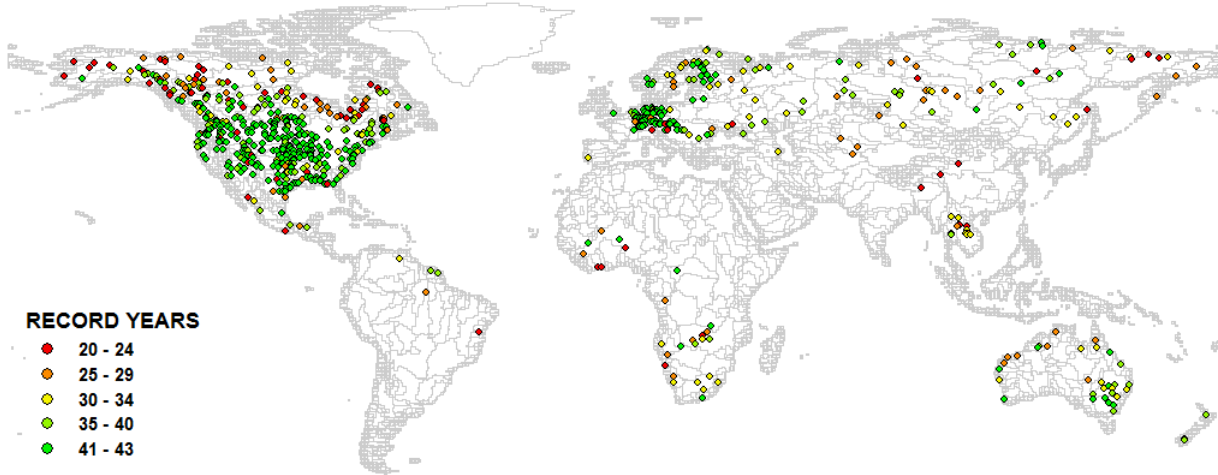
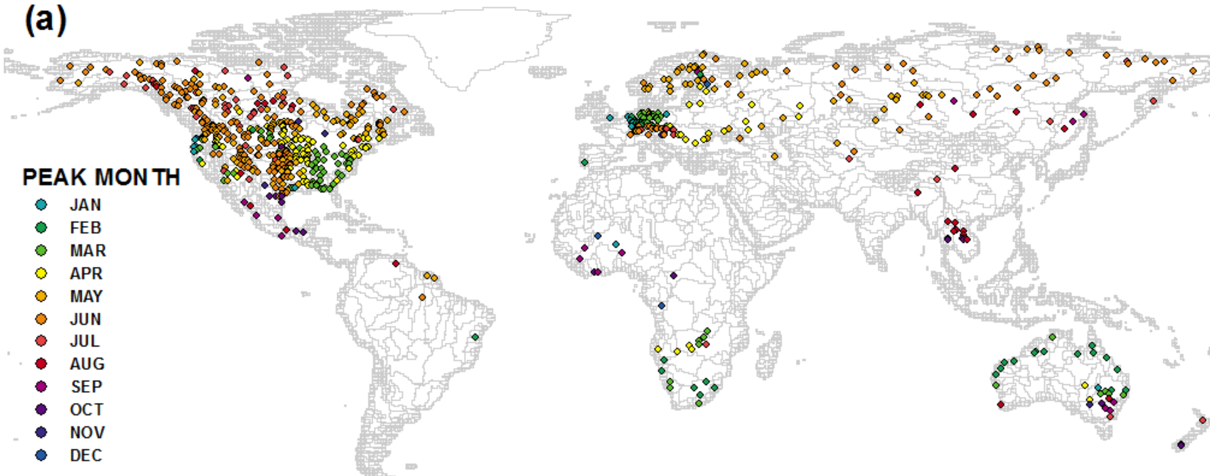


Figure 1. Location of 691 selected GRDC stations with corresponding number of years per station. Background polygons are world sub-basins based on 30′ drainage direction maps (Döll and Lehner, 2002) with separation of large basins (Ward et al., 2014).

(a)



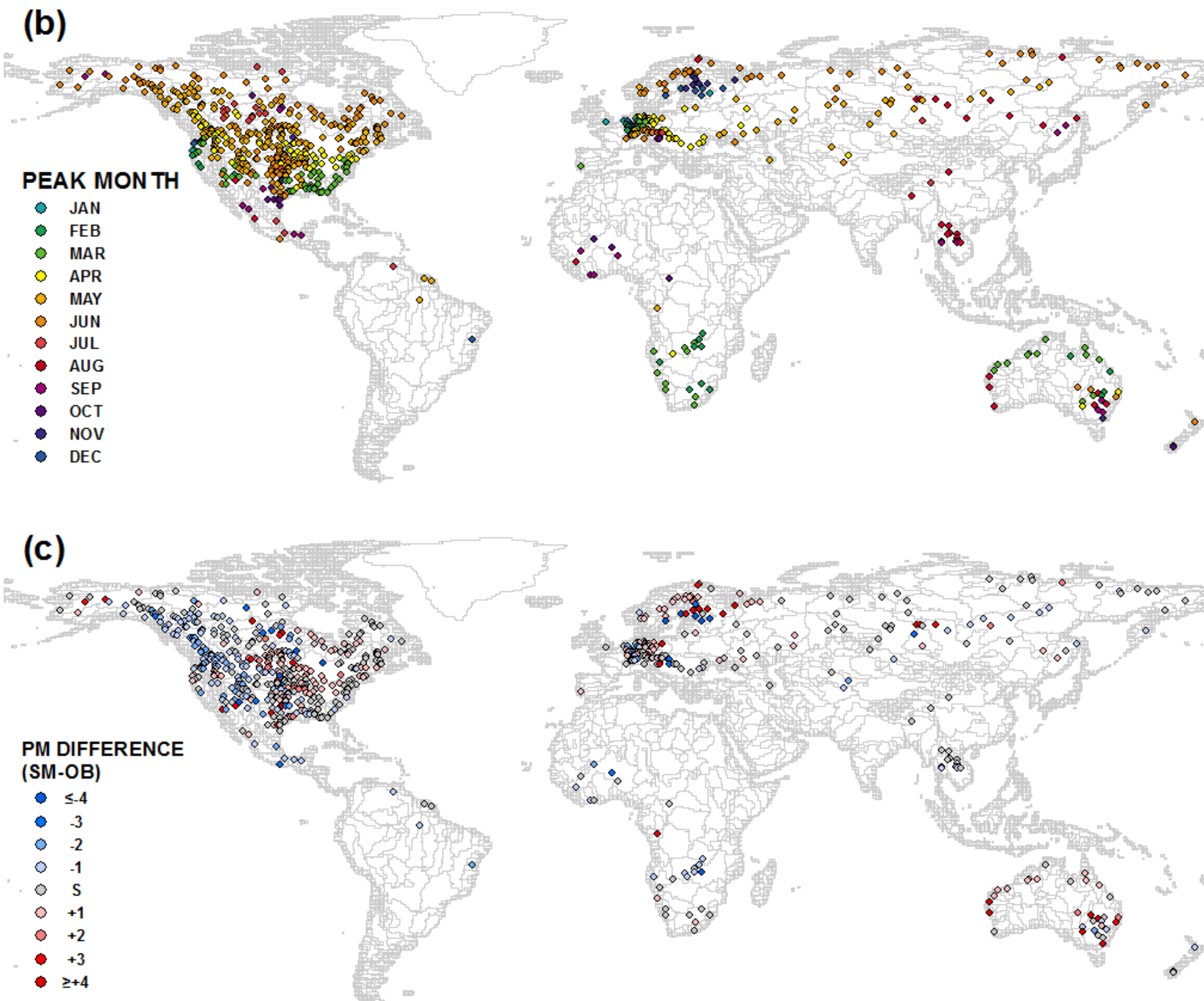
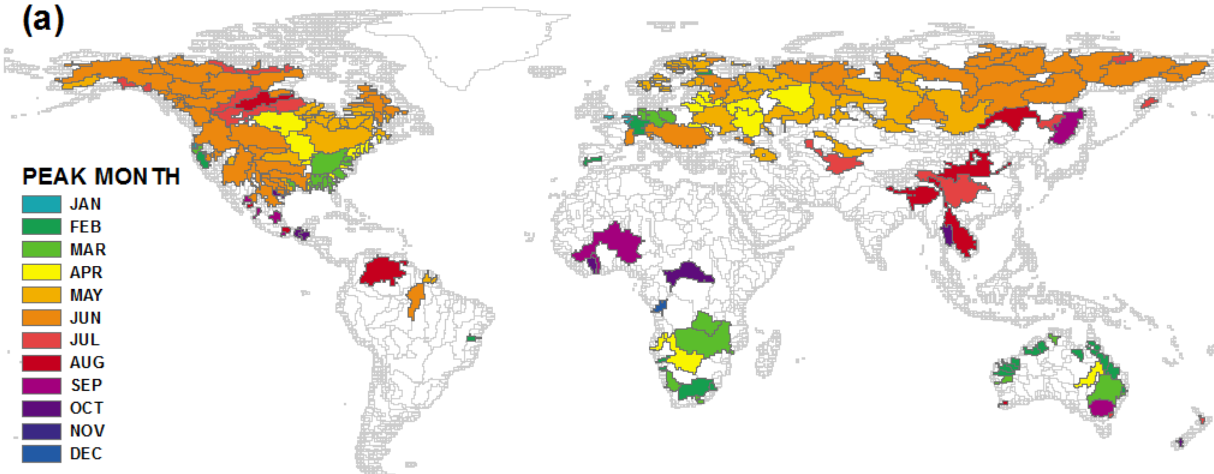


Figure 4. Peak Month (PM) for flooding as defined by (a) 691 GRDC observation stations, (b) simulated streamflow at associated locations and (c) Temporal difference (SM-OB, number of months) in PM between observations and model outputs.

(a)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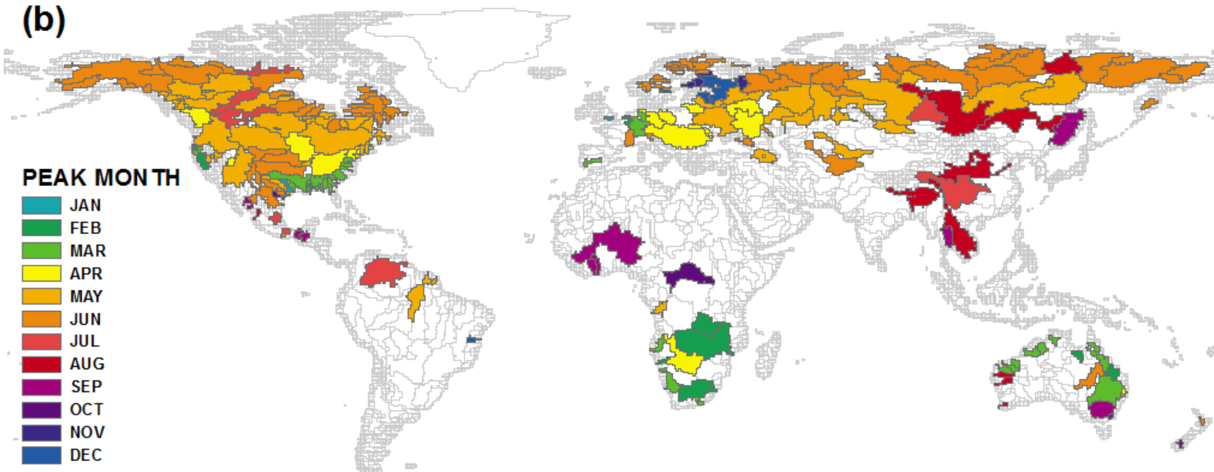
(b)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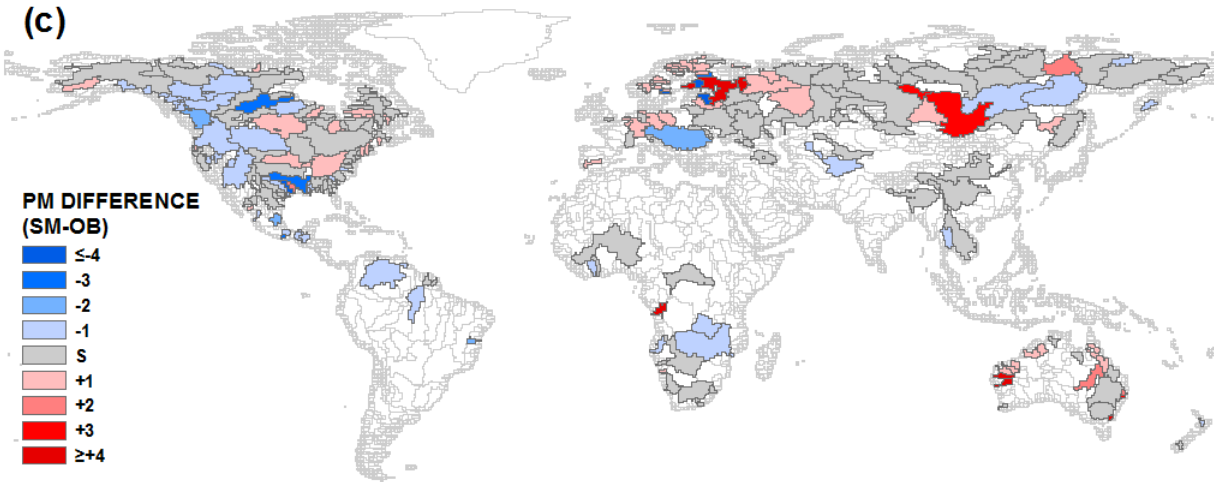

Figure 6. Peak Month (PM) for flooding by sub-basin as defined by (a) 691 GRDC observation stations, (b) simulated streamflow at associated sub-basins and (c) Temporal difference (SM-OB, number of months) in PM between observations and model outputs.

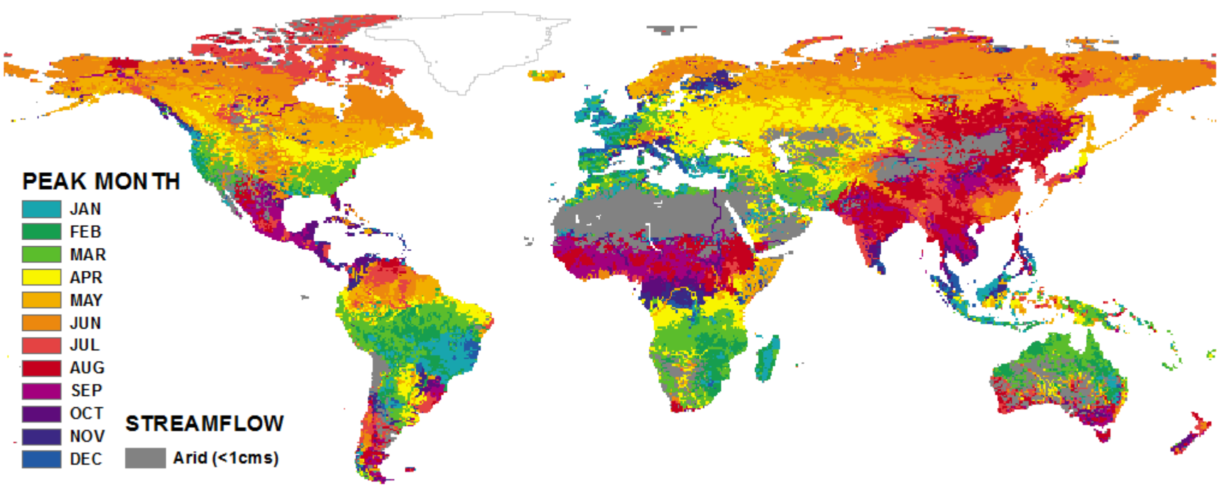

Figure 8. Peak Month (PM) for flooding as defined at all modeled grid cells.

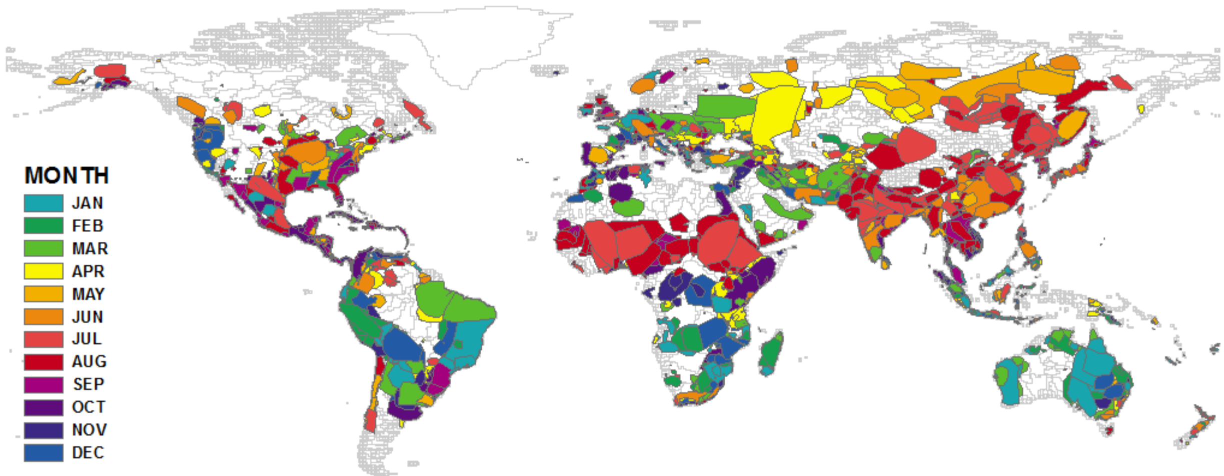

Figure 10. Archive of major flood events globally from the Dartmouth Flood Observatory (DFO) over 1985-2008.

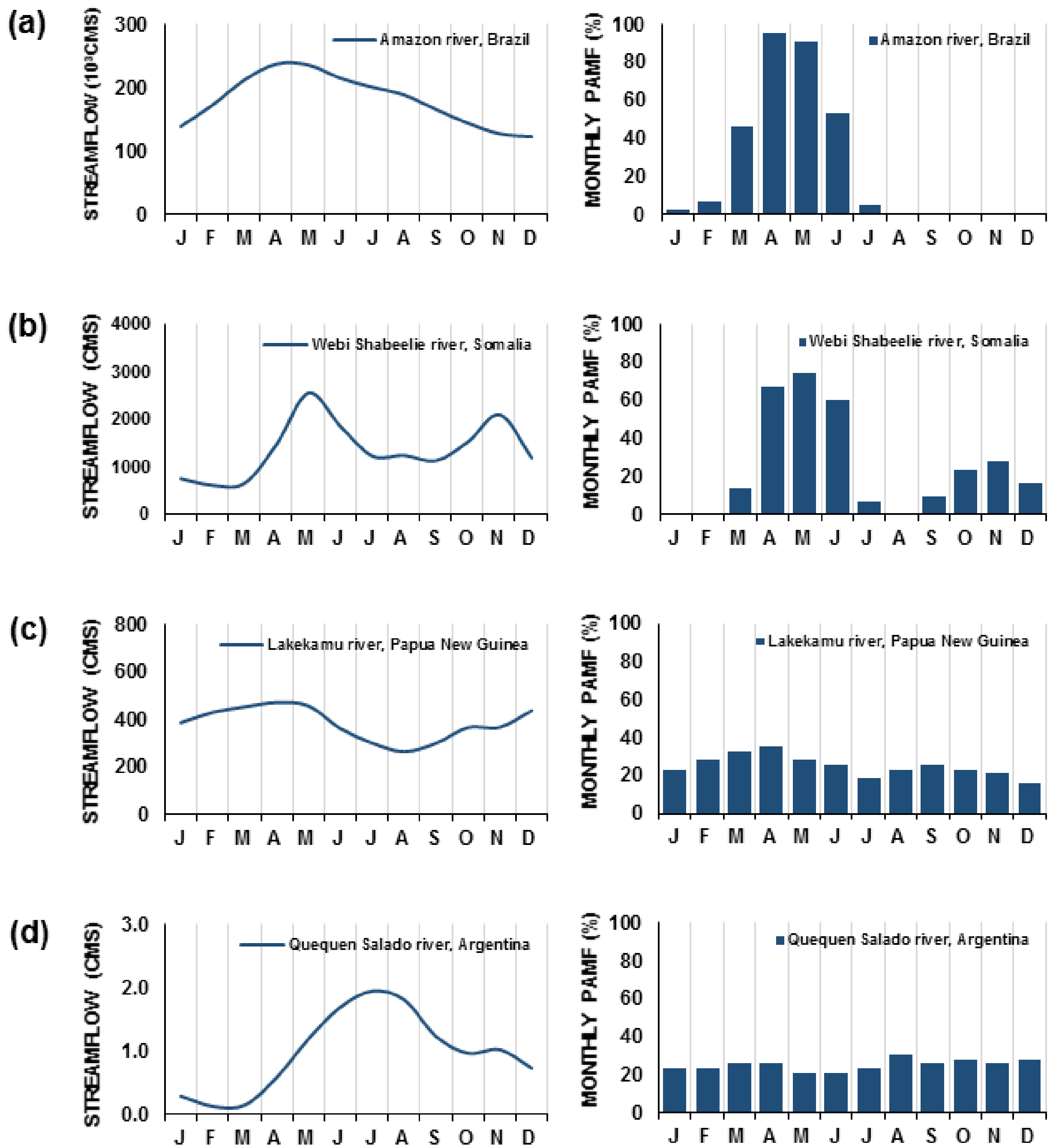

Figure 11. Model-based streamflow climatology (left) and corresponding monthly PAMF (right.) Types and locations are: a) uni-modal streamflow – At Bom Lugar, Amazon river, Brazil, b) bimodal streamflow – At Saacow, Webi Shabeelie river, Somalia, c) constant streamflow – At

Terapo Mission, Lakekamu river, Papua New Guinea and d) low-flow – At La Sortija, Quequen Salado river, Argentina.

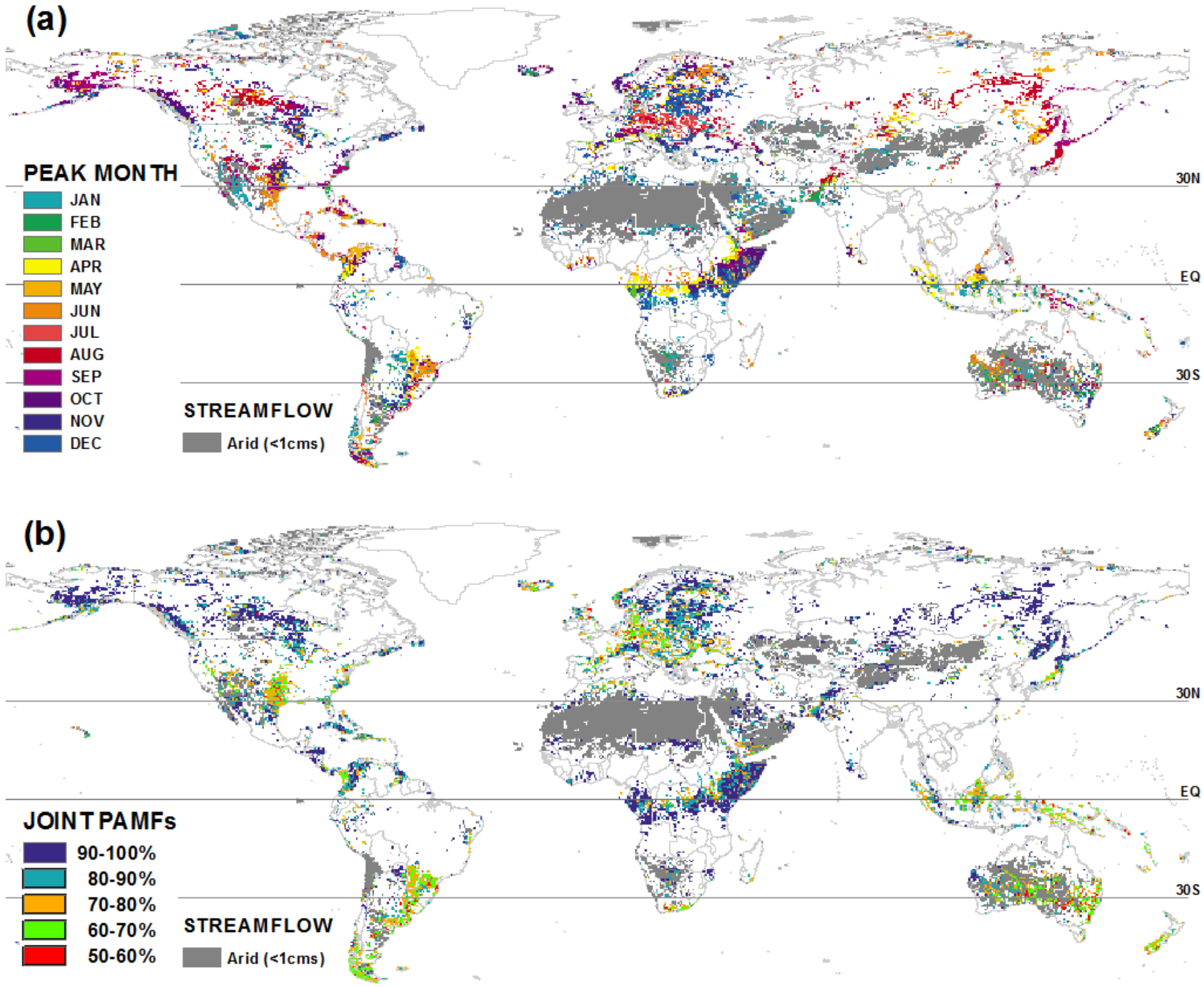

Figure 12. (a) Minor Peak Month (PM) for flooding as defined at detected grid cells and (b) joint PAMFs of major and minor PMs at corresponding cells.

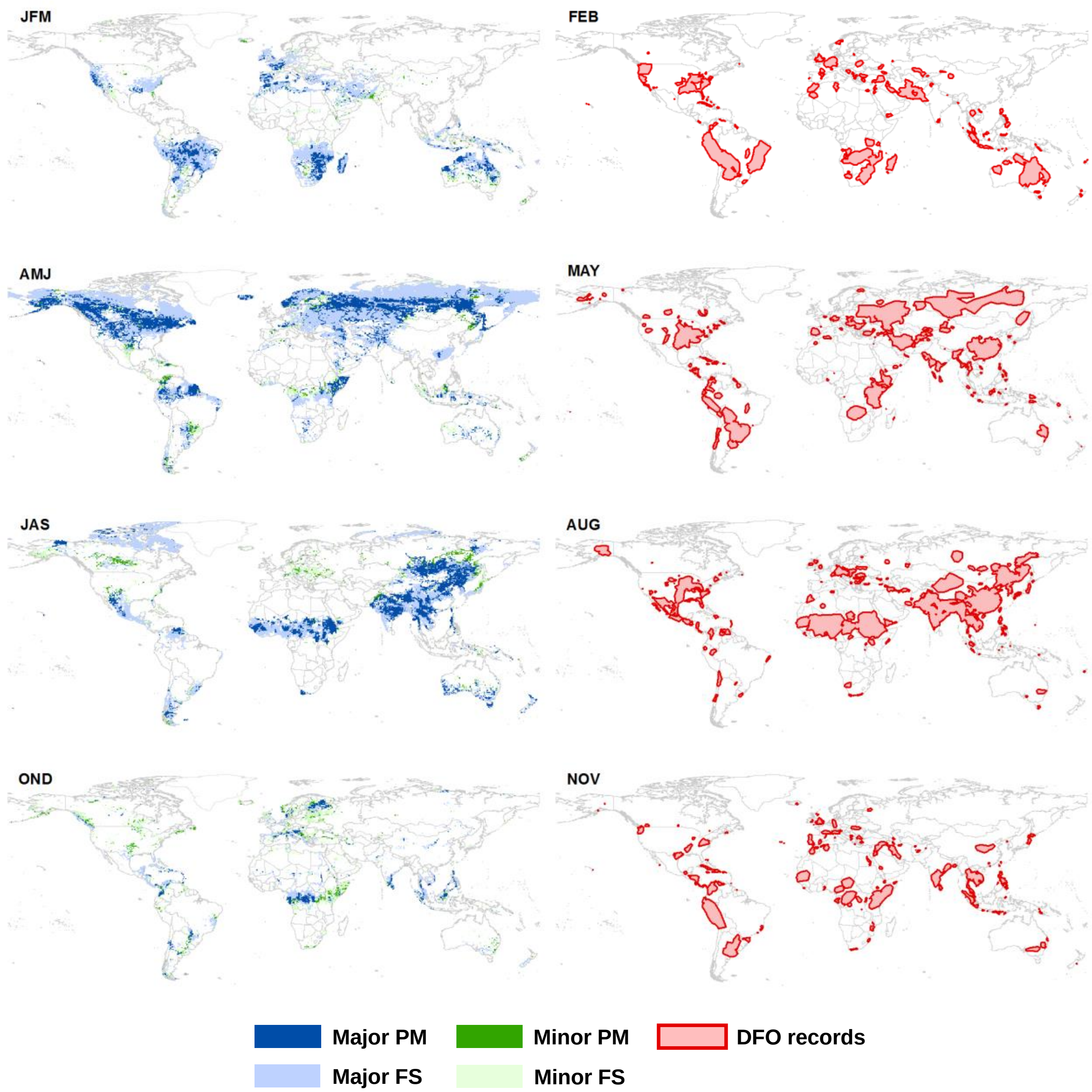

Figure 13. Total flood seasons (left); peak month of major and minor FSs (dense color) and post-month of prior FS and pre-month of next FS (light color.) Monthly accumulated actual flood records (DFO) during 1958-2008 (right.)

Relies to the comments of Anonymous Referee #3

Authors' replies are in blue color and revised sentences are in italics.

> I general I think this manuscript lacks a coherent structure. Firstly, the introduction is mainly focussing on seasonal and long range forecasting, whereas the work actually reported is mostly concerned with classification of runoff time series. Critically, there is little or no discussion of other existing classification schemes, especially why they might not be adequate, and as a consequence it is not clear what scientific knowledge gaps is being addressed here.

We agree with the reviewer's general sentiment here. The original motivation of this research was to understand temporal variability of global streamflow in order to improve global-scale flood forecasting framework. However, the major findings of this article are not directly connected to flood forecasting, thus we have revised/restructured the focus of the abstract, introduction and conclusion to highlight the identification of flood seasons and more focus on existing methodologies.

> Secondly, I don't think there is much scientific merit in the comparison between the observed and simulated runoff series. Especially in section 4.1 where it is reported that the observed and simulated FS only share the same three months at (only?) 40% of the considered time series. Importantly, there is no discussion of what the authors would suggest is a lower limit of acceptable performance. It would have been more interesting if the mismatch between the observed and simulated series had somehow been used in a more quantitative assessment of the reliability of the model predictions.

The reviewer makes a good point, especially considering the relatively low value for identical FSs, however the original motivation of this work was not to explicitly determine the FS for hydrologic purposes alone, but rather for prediction purposes that can lead to better management. From that perspective, even if the "wrong" flood season is identified, streamflow in that season could still be predicted and used for decision-making (e.g reservoir, etc.) That said, it is of course ideal to identify the peak flood season if possible. It should be noted that the modeled PM is within one month of the observed PM > 80% of the time (i.e. within the FS), which is quite respectable in our opinion. And as the FS is defined as 3 months, the FS should contain the PM at least that % of the time. The Percent Annual Maximum Flow (PAMF) metric has been introduced to better gauge this. We have added categories (high [80%-100%], low [60%-80%], and poor [<50%]) of the PAMF to better provide the reader with a sense of PAMF performance, with some caveats. We have not provided a lower limit of acceptable performance as there are factors such as regulated streamflow and low and constant flow that may also influence PAMF value. These are all now explicitly detailed in the manuscript. One sentence explicitly addressing this review comment we have changed is P.4605, line 25-27:

Overall, however, more than 80% of both stations and sub-basins having similar PMs (± 1 month) supports that the global water balance model performs appropriately well in defining flood seasons globally at locations where observations are available.

As it is, it seems like the performance has been accepted as it is in order to enable the production of some global map, but the usefulness (or reliability) of these maps is not really discussed. In my opinion, this makes the outcome of the study seem too open-ended with no firm conclusion, which is also partly down to the lack of a clear hypothesis in the beginning (i.e. identification of a knowledge gap).

Thanks for the comment. Because the PAMF is a good metric for the reliability of flood seasons in terms of containing annual maximum flows, we have not provide other usefulness/reliability. As authors' previous response, we have added categories of PAMF values to better provide a sense of performance for major FS. Additionally, we have further analyzed minor flood seasons and subsequently provided significance values (joint PAMF) for minor FS (please see updated figures below). The performance of minor FS has also been explained in the revision according to the categories of joint PAMF with well-known climate characteristics on there.

Finally, I think the presentation of the methodology could be made more refined. In the current version it reads, I think, too much like a working paper where the individual sections are reported in the order that the authors encountered and fixed problems. Maybe group together 3.1, 3.3 and 5 to first present a coherent methodology and then apply it to the two datasets?

We agree with the reviewer's comments. We merged sections 3.1 and 3.2 and have reduced the "working paper" feel in the text.

Specific comments:

Section 2.2: Was the PCR-GLOBWB model calibrated against observed streamflow data?

The modeled streamflow used in this study was simulated by PCR-GLOBWB model without calibration against observations, however the model's performance has been validated by previous studies. We have provided the following sentence after P.4599, line 12:

The PCR-GLOBWB model has not been calibrated, thus simulation results may be biased and uncertain at course spatial resolution, however it has the ability to provide long time-series of streamflow globally, which has is sufficient to estimate long-term flow characteristics with spatial consistence (Winsemius et al., 2013). Additionally, this model has been validated in previous studies in terms of streamflow (Van Beek et al., 2011), terrestrial water storage (Wada et al., 2011) and extreme discharges (Ward et al., 2013), indicating model performance.

Page 4600, line 17-18: I think the POT model was proposed somewhat earlier than this - see e.g. Shane and Lynn (1964) or Todorovic and Zelenhasic (1970)

Thanks for the references on POT. We have added these as appropriate into the manuscript.

Page 4600, line 25: What is meant by 'bi or multi-model flood conditions'?

The bi- or multi-modal flood conditions imply that there are two or multiple peak flows occurring annually. Because of incoherence in the context, P.4600, line 24:25 has been removed.

Page 4601, line3-4: Is this really a volume-based threshold? Seems to me it only considers a particular threshold based on daily runoff data. What part does volume play in this?

We apologize for the confusion here. For clarification, we have changed P.4600, line 20 – P.4601, line 7 to:

In contrast to the AM method, this characteristic of threshold can capture multiple large independent floods within a year, including the annual maximum flow, but may also miss the annual maximum flow in years in which streamflow is less than the pre-defined threshold (Cunderlik and Ouarda, 2009; Cunderlik et al., 2004a; Ouarda et al., 1993.) Thus, deciding the proper threshold level is important.

Therefore, to define the FS, and specifically the PM, both volume and magnitude aspects need to be considered (Javelle et al. 2003). To do this, we adopt a volume-based threshold technique. This technique is similar to a streamflow volume-based method in terms of capturing the Julian day by which a fixed percentage of the annual streamflow volume has occurred (Burn, 2008), however it also applies this fixed percentage across the entire streamflow record and records points where streamflow volume surpasses it, drawing from the prescribed threshold concept in the POT method. Here we select streamflow surpassing the top 5% of the flow duration curve (FDC) across all years (1958-2000) as the threshold for considering a high streamflow level, as commonly adopted in threshold approaches (Burn, 2008; Mishra et al., 2011.)

Page 4602, line 15-: The high degree of correlation is to be expected as these different criteria are extracted from the same dataset using only minor variations in threshold levels. However, I don't understand the statement that this should somehow indicate successful success in capturing volume and magnitude. Please clarify (see also comment above).

We apologize for the misunderstanding. The objective of the volume-based threshold technique is to consider both volume and magnitude of streamflow to define the PM. Thus, if the modeled and observed PMs have "similar" correlation with indices favoring streamflow magnitude (Q_AM and Q_7days) and with indices favoring streamflow volume (Q_15 and Q_30) simultaneously, it supports that the volume-based threshold method is likely best for defining the FS. For clarification, we have changed P.4602, line 11-17 to:

Compared to the full length of PM (30 days), the flow-based classification techniques with a shorter time component (1-7 days) favor identifying flood magnitude while the techniques with longer time components (15-30 days) favor identifying flood volume. The volume-based threshold method is an attempt to bridge these two criteria.

Cross-correlations of PM between the volume-based threshold technique and other classification techniques are quite similar (0.87-0.90; Table 1), preliminarily indicating some success in capturing both magnitude and volume.

Page 4603, line8: The statement that seasonality if often used to delineate catchments is backed-up by three (out of four) references to the same (excellent) research group. However, I don't that is enough to suggest that it is often used. Also, how did these publications define seasonality?

These references (e.g. Burn, 1997; Cunderlik et al., 2004a) define seasonality using various techniques including directional methods, POT and fixed percentage of streamflow volume, however, the key point of regionalizing/grouping catchments is to differentiate seasonality within a basin. For clarification, we have changed P.4603, line 5-11 to:

Previous studies have investigated flood seasonality as it relates to basin characteristics; for example, basins are often delineated/regionalized and grouped according to similarity/dissimilarity of flood streamflow seasonality (Burn, 1997; Cunderlik et al., 2004a), or conversely, flood seasonality is occasionally used to assess hydrological homogeneity of a group of regions (Cunderlik and Burn, 2002a; Cunderlik et al., 2004b), thus evaluating at the sub-basin scale is warranted.

Page 4607, line7-9: Why are seven references needed to state a well-known fact?

The reviewer makes a good point. We have selected one reference (Seleshi and Zanke, 2004) instead.

Page 4608, line 7: what unit does 'cms' refer to?

It refers to cubic meters per second (m^3/s). For clarification, we have changed the P.4608, line 7 to:

The low-flow classification is defined for annual average streamflow less than 1 m^3/sec.

Page 4608, line 25: why does (50%) refer to?

It refers to results for sub-basins. For clarifying, we have changed P.4608, line 24 – P.4609, line 2 to:

As a result, 40% of stations and 50% of sub-basins have identical peak months and 81% of stations and 89% of sub-basins are within 1 month, indicating strong agreement between model and observed flood seasons.

Page 4609, line 7-15: This reads more like the motivation for the study than a conclusion of the work undertaken. I think this belongs in an introduction.

We agree with reviewer's comments. We have moved it to the introduction.

References

Shane, R. M., & Lynn, W. R. (1964). Mathematical model for flood risk evaluation. Journal of the Hydraulics Division, 90(6), 1-20.

Todorovic, P., and E. Zelenhasic (1970), A Stochastic Model for Flood Analysis, Water Resour. Res., 6(6), 1641–1648

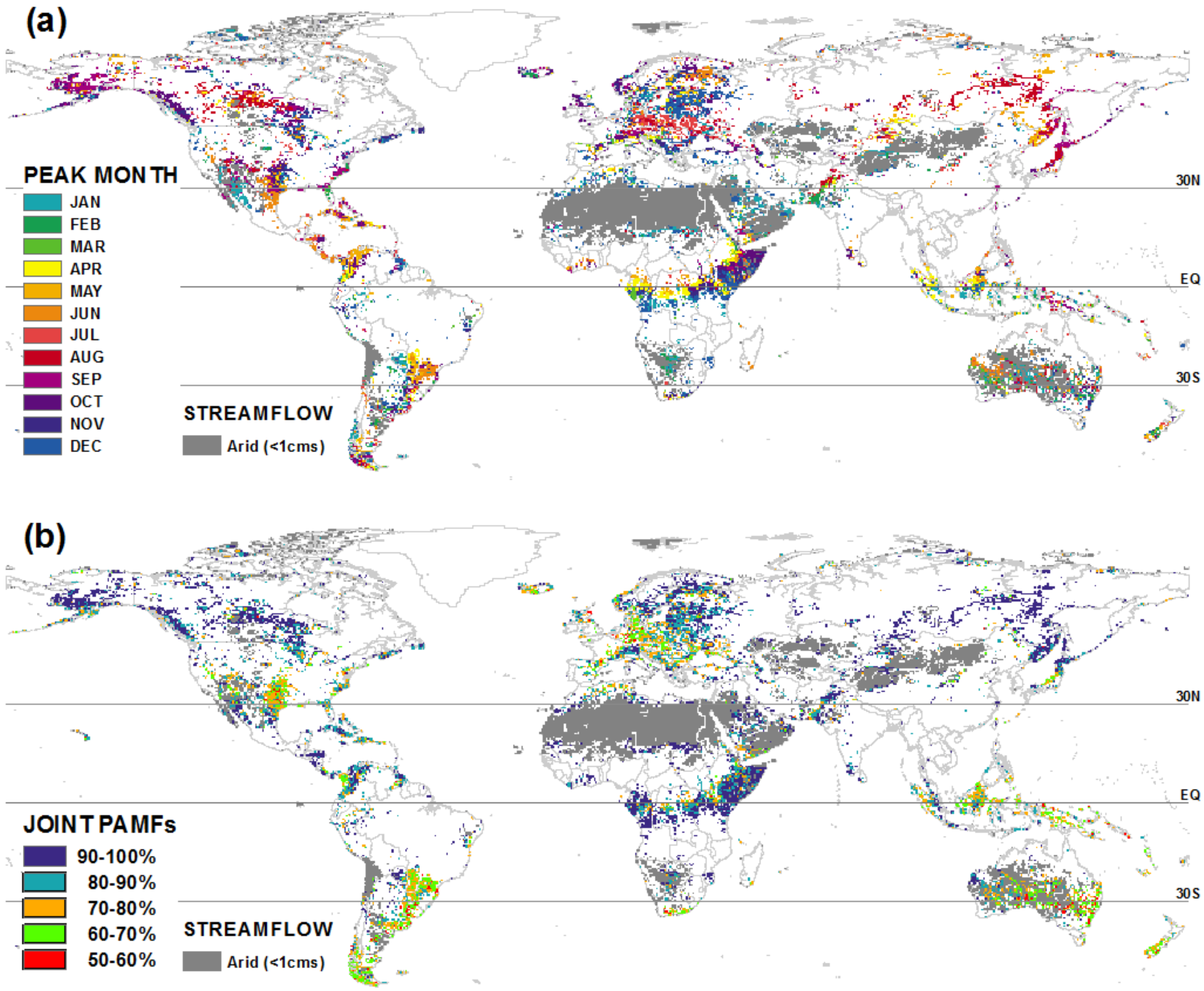

Figure 12. (a) Minor Peak Month (PM) for flooding as defined at detected grid cells and (b) joint PAMFs of major and minor PMs at corresponding cells.

~~A Global Approach to~~ Defining Flood Seasons Globally using Temporal Streamflow Patterns

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Abstract

Globally, flood catastrophes lead all natural hazards in terms of impacts on society, causing billions of dollars of damages annually. ~~While short-term flood warning systems are improving in number and sophistication, forecasting systems on the order of months to seasons are~~Here, a ~~rarity, yet may lead to further disaster preparedness. To lay the groundwork for prediction, dominant flood seasons must be adequately defined. A global~~novel approach ~~is adopted here, using the PCR-GLOBWB model to define spatial and temporal characteristics of major~~to defining flood seasons globally~~.~~ is presented by identifying temporal patterns of streamflow objectively. The main flood season is identified using a volume-based threshold technique and the PCR-GLOBWB model. In comparison with observations, 40% (50%) of locations at a station (sub-basin) scale have identical peak months and 81% (89%) are within 1 month, indicating strong agreement between ~~model~~modeled and observed flood seasons. Model defined flood seasons are additionally found to well represent actual flood records from the Dartmouth Flood Observatory, further substantiating the models ability to reproduce the appropriate flood season. Minor flood seasons are also defined for ~~regions with bi-modal streamflow climatology. Properly defining flood seasons can lead to prediction through association of streamflow with local and large-scale hydroclimatic indicators, and eventual integration into early warning systems for informed advanced planning and management.~~bi-modal flood regimes. This is especially attractive for regions with limited observations and/or little capacity to develop early warning flood systems. The temporal patterns of global streamflow identified can lead to improved understanding of flood frequency, trends, and inter-annual variability and further benefit flood risk planning and preparation efforts.

1 Introduction

Flood catastrophes lead all natural hazards in terms of impacts on society (Doocy et al., 2013.) For example, the EM-DAT database (Centre for Research on the Epidemiology of Disasters) reports that hydrologic disasters in 2013 accounted for 48% of all natural disasters and 45% of global disaster mortality (Guha-Sapir et al., 2014). This is partially attributable to large populations living in flood-prone areas, growing by as much as 114% between 1970 and 2010 (UNISDR, 2011.) Flood disasters also rank as one of the most destructive natural hazards in terms of economic damage, causing billions of dollars of damage each year (Munich Re, 2012.) These flood damages have risen starkly over the past half-century given the rapid increase in global exposure (Bouwer, 2011; UNISDR, 2011; Visser et al., 2014.)

In some regions, flood early warning systems have helped reduce loss of lives and assets by integrating with emergency planning and preparedness, from local to national scales (Golnaraghi et al., 2009; Kundzewicz et al., 2014; Revilla-Romero et al., 2014.) Such systems have played an important role in various international initiatives, including the “Hyogo Framework for Action 2005-2015” and the “European Commission’s Flood Action Programme” (Revilla-Romero et al., 2014.) The need remains, however, for additional early warning systems to foster improved flood risk management. Typically, flood forecast systems emphasize the short-term scale (hours to days) to inform immediate warnings and actions. Some examples of organizations and institutes having developed global early warning systems that target both early detection and early forecasting include CEOS (2014), GDACS (2014), GloFAS (2014), International Charter (2014), UNOSAT (2014) and the Dartmouth Flood Observatory (http://floodobservatory.colorado.edu/) (Alfieri et al., 2013; Revilla-Romero et al., 2014; Wu et al., 2012.) Longer-range forecasts, on the order of months to seasons, however, can compliment short-range forecasts by focusing on disaster preparedness. For example, the International Federation of the Red Cross (IFRC) has been one of very few organizations to act on a long-range flood forecasts. In 2008, the IFRC implemented an early warning / early action strategy by mobilizing resources into the Niger River basin in West Africa in response to flood predictions. A flood did occur, and as a result of preparedness, relief supplies reached flood victims within days instead of weeks, preventing further loss of life and damages to livelihoods (Braman et al., 2013.) Longer-range seasonal forecasts of streamflow also provide prospects for guiding water managers and basin organizations in decision-making beyond floods, including operation of water resources infrastructure, allocations, water trades, policy, regulation, and

~~emergency response (Chiew et al., 2003; van Dijk et al., 2013; Pappenberger et al., 2011; Ritchie et al., 2004; Sankarasubramanian and Lall, 2003.)~~

~~Only a small number of studies have investigated the seasonal predictability of streamflow impacts at continental or global scales, with minimal focus on flood forecasts. For example, Bierkens and van Beek (2009) evaluate seasonal predictability of winter and summer streamflow across the European continent with predictions of the North Atlantic Oscillation (NAO) Index as a main hydro-climatic driver, van Dijk et al. (2013) compare theoretical and actual skill in bi-monthly streamflow forecasts using a global ensemble streamflow prediction (ESP) system for 6192 small catchments across the world. Ward et al. (2014a) have shown that there is a strong link between El Niño–Southern Oscillation (ENSO) and annual river floods; and that these relationships also lead to anomalies in flood risk (in terms of economic damage and affected population) between normal years and the El Niño or La Niña years (Ward et al., 2014b.) However, whilst they demonstrate this strong relationship, they did not explicitly link this to seasonal predictability. Therefore, there is a need to expand analyses targeting long-range streamflow predictions at the global scale.~~

~~To specifically address large-scale (annual) flood prediction from a global perspective, understanding and identifying seasonal spatial and temporal patterns of global streamflow becomes increasingly important, linking to global and regional climate behavior. In regions with dominant flood seasons, this may be trivial, however many regions express no dominant flood~~Flood disasters rank as one of the most destructive natural hazards in terms of economic damage, causing billions of dollars of damage each year (Munich Re, 2012.) These flood damages have risen starkly over the past half-century given the rapid increase in global exposure (Bouwer, 2011; UNISDR, 2011; Visser et al., 2014.) To specifically address flood disasters from a global perspective, understanding of global-scale flood processes and streamflow variability is important (Dettinger and Diaz, 2000; Ward et al., 2014). In recent decades, studies have investigated global-scale streamflow characteristics using observed streamflow from around the world (Beck et al., 2013; McMahon, 1992; McMahon et al., 2007; Peel et al., 2001, 2004; Poff et al., 2006; Probst and Tardy, 1987) and modeled streamflow from global hydrological models (Beck et al., 2015; van Dijk et al., 2013; McCabe and Wolock, 2008; Milly et al., 2005; Ward et al., 2013, 2014) to investigate ungauged and poorly gauged basins (Fekete and Vörösmarty, 2007). Despite this broad attention on annual streamflow and its connections to global climate processes and precursors, there has been relatively little attention paid to the intra-annual timing of streamflow, emphasizing the need for analysis of seasonal streamflow patterns to further improve understanding of large-scale hydrology and atmospheric behaviors on the main (flood) streamflow season globally (Dettinger and Diaz, 2000). Moreover, better assessment of streamflow timing and seasonality is important for addressing frequency and trend analyses, flood protection and preparedness, climate-related changes, and other hydrological applications that possess important sub-annual characteristics (Burn and Arnell, 1993; Burn and Hag Elnur, 2002; Cunderlik and Ouarda, 2009; Hodgkins et al., 2003). This motivates further investigation of intra-annual temporal streamflow patterns globally.

Only a small number of studies have investigated global-scale seasonality and temporal patterns of streamflow, with minimal focus on objective streamflow timing. Haines et al. (1988) cluster 969 world rivers into 15 categories based on seasonality and average monthly streamflow data, and present one of the first maps providing a global classification. Burn and Arnell (1993) aggregate 200 streamflow stations into 44 similar climatic regions and subsequently combine these into 13 groups using hierarchical clustering based on similarity of the annual maximum flow index, providing spatial and temporal coincidences of flood response. Dettinger and Diaz (2000) aggregate 1345 sites into 10 clusters based on seasonality using climatological fractional monthly flows (CFMFs) to identify peak months and linkages with large-scale climate drivers.

In general, these studies define key seasons based on large-scale drivers/patterns and clustering, and describe annual peak timing based on streamflow amplitude. The clustering approach employed, however, tends to lump many smaller basins together into one major season, and may not be representative of local scale conditions, especially for those basins at the margins of the clusters where streamflow patterns may not have a single defined major season (e.g. perpetually wet or dry, bi-modal flood seasons, etc.) , etc.) In lieu of large-scale clustering and aggregation, we propose addressing basins (and even grid cells) individually, in a disaggregated fashion. Additionally, as an alternative to simply using the annual maximum streamflow amplitude to define the annual peak timing, we consider a volumetric approach based on surpassing a predefined threshold at the daily scale to define peak streamflow timing. Both of these advancements are conditioned on an objective approach to define major and minor flood seasons globally. Parsing out the annual flood season – if one exists – lays the groundwork for season-ahead flood prediction through the association of dominant streamflow with local and large-scale hydroclimatic indicators, and eventual integration into early warning systems for informed advanced planning and management. This is especially attractive for regions with

~~limited observations and or little capacity to develop early warning flood systems. In this paper, we present an approach to properly define flood seasons using a global water balance model at the sub-basin and grid scale. These modeled flood seasons are subsequently validated with streamflow observations and historic flood records.~~ these peak seasons – if they exist – can improve flood characterization, leading to better understanding of flood potential, causation, and management, particularly in ungauged or limited-gauged basins.

2 Data description

2.1 Streamflow stations

Daily streamflow observations utilized in this study are from the Global Runoff Data Centre (GRDC, 2007~~.)~~)~~ Only stations having at least 20 years of continuous daily streamflow data were used (691 stations; Figure 1.)~~, specifically those, stations located along the global hydrology model's drainage network. Since station records that are missing even short periods may effect how a flood season is defined, we have excluded years with any daily missing values. In this study, a minimum of 20 hydrological years is required for a station to be retained, leaving, 691 stations from all continents except Antarctica, with upstream basin areas ranging from 9,539 to 4,680,000 km² and periods of record between 20 - 43 years across 1958 - 2000 (Figure 1.) Although this criteria is admittedly quite strict (no missing daily data), relaxing the criteria does not add a significant number of stations.

2.2 PCR-GLOBWB

In this study, we evaluate simulations of daily streamflow over the period 1958-2000 taken from ~~Ward et al. (2013),~~Ward et al. (2013), carried out using PCR-GLOBWB (PCRaster GLOBal Water Balance), a global hydrological model with a 0.5° x 0.5° resolution ~~(Van Beek and Bierkens, 2009; Van Beek et al., 2011.)~~(Van Beek and Bierkens, 2009; Van Beek et al., 2011.) Although the PCR-GLOBWB model is not calibrated, and simulations may contain biases and uncertainty at course spatial resolution, the long time-series of streamflow provided globally has been deemed sufficient to estimate long-term flow characteristics with spatial consistency (Winsemius et al., 2013). Additionally, this model has been validated in previous studies in terms of streamflow (Van Beek et al., 2011), terrestrial water storage (Wada et al., 2011) and extreme discharges (Ward et al., 2013), with strong model performance. Note that for the simulations used in this study, the maximum storage within the river channel is based on geomorphological laws that do not account for existing flood protection measures such as dikes and levees.

For the simulations used in this study, the PCR-GLOBWB model was forced with daily meteorological data from the WATCH (Water and Global Change) project (Weedon et al., 2011), namely precipitation, temperature, and global radiation data. These data are available at the same resolution as the hydrological model (0.5° x 0.5°.) The WATCH forcing data were originally derived from the ERA-40 reanalysis product (Uppala et al., 2005), and were subjected to a number of corrections~~, described in (Weedon et al., 2011.)~~ including elevation, precipitation gauges, time-scale adjustments of daily values to reflect monthly observations, and varying atmospheric aerosol-loading. It is possible that this may have some minor effect on streamflow simulation, likely providing more realistic outcomes. Full details of corrections are described in Weedon et al. (2011).

3 Defining flood seasons

To identify spatial and temporal patterns of dominant streamflow uniformly, we design a fixed time window for representing flood seasons globally. Here we define major flood seasons as the 3-month period most likely to contain dominant streamflow and the annual maximum ~~flood~~flow. The central month is referred to as the Peak Month (PM) and the full 3-month period is referred to as the Flood Season (FS.) Specifically, we define PM first, and then define FS as the period also containing the month before and after the PM. This approach is performed for both observed (station) and simulated (model) streamflow to gauge performance.

3.1 Methodology for defining grid-cell scale flood seasons

In the last few decades, a number of studies have investigated the timing of floods in the context of analyzing seasonality, frequency and trends. Generally, two main factors are emphasized regarding flood timing: streamflow volume and streamflow magnitude. For streamflow volume an occurrence date is commonly recorded, often in the context of trend analysis. For examples, Hodgkins and Dudley (2006) use winter-spring center of volume (WSCV) dates to analyze trends in snowmelt-induced floods, and Burn (2008) uses percentile of annual streamflow volume dates as indicators of flood timing, also for trend analysis. The second factor (streamflow magnitude) is traditionally more focused on peak-flood timing. Two sampling methods are frequently applied in hydrology. The first and most common is the annual-maximum (AM) method, which samples the largest streamflow in each year. The second method is the peaks-over-threshold (POT) method~~, first introduced by Smith (1984, 1987)~~(Smith, 1984, 1987; Todorovic and Zelenhasic, 1970), in which all distinct, independent dominant peak flows greater than a fixed threshold are counted, prior to a specified date. In contrast to the AM method, ~~the POT method~~this threshold characteristic can ~~record~~capture multiple large independent floods within a single year, including the annual maximum flow, but ~~it can~~may also miss the annual maximum flow in years in which streamflow is less than the pre-defined threshold ~~(Cunderlik and Ouarda, 2009; Cunderlik et al., 2004a; Ouarda et al., 1993.) Thus, deciding the proper threshold for the POT method is important. Additionally, the POT method performs well under significant bi- or multi-modal flood conditions, and is typically more reliable than AM (e.g. see Cunderlik et al. (2004a)).~~

~~Therefore, to define the FS, and specifically the PM, globally~~(Cunderlik et al., 2004a). Thus, deciding the proper threshold level is important. Therefore, to define the FS, and specifically the PM, both volume and magnitude aspects need to be considered (Javelle et al. 2003). To do this, we adopt a volume-based threshold technique. ~~This technique applies a prescribed streamflow volume threshold to identify flood occurrences.~~This technique is similar to a streamflow volume-based method in terms of capturing the Julian day by which a fixed percentage of the annual streamflow volume has occurred (Burn, 2008), however it also applies this fixed percentage across the entire streamflow record and records points where streamflow volume surpasses it, drawing from the prescribed threshold concept in the POT method. Here we select streamflow surpassing the top 5% of the flow duration curve (FDC) across all years (1958-2000) as the threshold for considering a high streamflow level, as commonly adopted in threshold approaches (Burn, 2008; Mishra et al., 2011.) The month containing the greatest number of ~~days~~occurrences in the top 5% is ~~subsequently~~ defined as the PM, and subsequently the FS is defined as the period containing the PM plus the month before and after the PM. Figure 2 provides an example based on seven years of synthetic streamflow; the number of days surpassing the 5% threshold is listed for each month. In this example, August has the largest number of days over the threshold (105 days), thus August is defined as PM and July-September is defined as FS.

To evaluate the defined FS objectively, by evaluating the number of annual maximum flows captured, we develop a simple evaluating statistic called the Percentage of Annual Maximum Flow (~~P_{AMF}). P_{AMF}~~PAMF). PAMF is computed as shown in ~~Equation~~Eq. 1:

~~$$P_{AMF} = \frac{nAMF_{FS}}{nAMF_{total}} \qquad (1)$$~~

$$PAMF(i) = \frac{\sum_{j=i-1}^{i+1} nAMF(j)}{\sum_{k=1}^{12} nAMF(k)}, \; 1 \le i \le 12 \qquad (1)$$

where ~~$nAMF_{FS}$ is~~ $nAMF(i)$ denotes the number of annual maximum flows that ~~occurs~~occur in ~~the FS (3-~~month~~) and $nAMF_{total}$ is~~ i across the ~~total number of years. Thus,~~full record. In Eq. (1), when i is 1 (Jan), $i-1$ in the ~~P_{AMF}~~summation is 12 (Dec), and when i is 12 (Dec), $i+1$ is 1 (Jan). Here the PAMF provides the percent of time the annual maximum flows occurs in the defined FS across the evaluation period. The ~~P_{AMF}~~PAMF is relatively simple, yet inherently contains magnitude and volume properties of streamflow. For example, a high ~~P_{AMF}~~PAMF indicates that the FS is highly likely to contain the annual maximum flood each year. In contrast, a low ~~P_{AMF}~~PAMF indicates that the timing of the annual maximum ~~flood~~flow is more likely to vary temporally, and may be a result of bimodal seasonality, consistently high or low streamflow throughout the year, ~~or~~ streamflow regulated by infrastructure~~.~~ or natural variation. In this study, we subjectively classify FS PAMF values as: high = 80-100%, low = 60-80%, and poor = 40-60%. The ~~P_{AMF}~~PAMF is calculated for both the observed streamflow at the selected 691 GRDC stations and the simulated streamflow at the associated 691 grid locations.

~~3.2 Classification techniques~~

Clearly the volume-based threshold method is not the only available classification technique for defining the PM. To gauge its performance, the AM method and other volume methods with different given durations are selected for comparison, namely Q_{AM}, Q_{7day}, Q_{15day} and Q_{30day}. For the Q_{AM} approach, which is based on the AM method, the FS is simply centered on the PM containing the largest number of annual maximum flow occurrences across the total years available. The $Q_{7\mathrm{day}}$ approach defines the PM as the month with maximum streamflow volume during any seven consecutive day period; the month with the most periods across all years becomes the PM for the defined FS. The $Q_{15\mathrm{day}}$ and $Q_{30\mathrm{day}}$ approaches are similar to the $Q_{7\mathrm{day}}$ approach, respectively using 15 and 30 days consecutively. ~~The~~Comparitavely, the flow-based classification techniques with a shorter time component (1-7 days) favor identifying flood magnitude while the techniques with longer time components (15-30 days) favor identifying flood volume. The volume-based threshold method is an attempt to bridge these two criteria.

Cross-correlations of PM between the volume-based threshold technique and other classification techniques are quite ~~high~~similar (0.87-0.90; Table 1), preliminarily indicating some success in capturing both magnitude and volume. The ~~P_{AMF}~~ PAMF is also useful for comparing classification ~~techniques~~techniques' performance when they define PM differently at ~~stations and associated grid cells for which~~ the ~~selected PMs differ for at least one of the techniques.~~same location. This occurs at 45% ~~of observed~~or stations and 40% of associated ~~grid cells.~~grids for observed and modeled streamflow, respectively. The classification technique having the highest ~~P_{AMF}~~ PAMF most often for ~~these~~those stations ~~and cells~~or girds may be considered slightly superior~~. For model-based outputs, the~~ in terms of containing more annual maximum flows in their defined FSs. The volume-based threshold technique has the highest ~~P_{AMF}~~PAMF values by at least 2~~%.~~% of grids (1% of stations) more than any other technique for modeled (observed) streamflow. Finally, classification technique performance may be evaluated by comparing the temporal difference (number of months) between model-based and observed PMs; closer is clearly superior. Overall the volume-based threshold technique produces a greater degree of similarity between model-based and observed PMs (2-5% higher in ±1 month difference and 1-5% higher in ±2 month difference.) Based on these findings, the remainder of the analysis is carried out utilizing the volume-based threshold technique only.

~~3.3~~3.2 Methodology for defining sub-basin scale flood seasons

~~In addition to evaluating the FS at the 691 grid cells based on model outputs, the FS is also defined at the sub-basin scale globally where observations are present. Previous studies have investigated flood seasonality as it relates to basin characteristics; for example, basins are often delineated and grouped according to similar flood seasonality (Burn, 1997; Cunderlik and Burn, 2002b; Cunderlik et al., 2004a; Ouarda et al., 1993), or conversely, flood seasonality is occasionally used to assess hydrological homogeneity of a group of regions (Cunderlik and Burn, 2002a; Cunderlik et al., 2004b), thus evaluating at the sub-basin scale is warranted.~~

In addition to evaluating the FS at the 691 grid cells based on model outputs, the PM and FS can also be defined at the sub-basin scale globally where observations are present. Previous studies have investigated flood seasonality as it relates to basin characteristics; for example, basins are delineated/regionalized and grouped according to similarity/dissimilarity of streamflow seasonality (Burn, 1997; Cunderlik et al., 2004a), or conversely, flood seasonality is occasionally used to assess hydrological homogeneity of a group of regions (Cunderlik and Burn, 2002; Cunderlik et al., 2004b), thus evaluating at the sub-basin scale is warranted.

While defining a single ~~FS~~PM for a large-scale basin may be convenient, it may be difficult to justify given the potentially long travel times and varying climate, topography, vegetation, etc. Additionally, infrastructure may be present to regulate flow for flood control, water supply, irrigation, recreation, navigation, and hydropower (WCD, 2000), causing managed and natural flow regimes to differ drastically. This becomes important, as globally more than 33,000 records of large dams and reservoirs are listed (ICOLD, 1998-2009), with geo-referencing available for 6,862 of them (Lehner et al., 2011). Nearly 50% of large rivers with average streamflow in excess of 1,000 m^3/s are significantly modulated by dams (Lehner et al., 2011), often significantly attenuating flow hydrographs and flood volumes. ~~The P_{AMF}, as previously defined, can aid in identifying stations downstream of a managed dam and reservoir.~~The PAMF, as previously defined, can aid in identifying stations affected by upstream reservoirs through low PAMF values. This is applied with the assumption that reservoir flood control disperses the annual maximum flows across months rather concentrated within a few months (e.g. akin to natural flow.) In this study, we used the global sub-basins from the 30’ global drainage direction map (DDM30) dataset (Döll and Lehner, 2002) with separation of large basins (Ward et al., 2014).

To define a sub-basin’s ~~FS~~PM, the maximum ~~P_{AMF}~~PAMF and associated PM for each station within the sub-basin are considered according to the following:

- If multiple stations exist within the sub-basin, the PM is defined as the PM occurring for the largest number of stations
- If there is a tie between months, their average ~~P_{AMF}~~PAMF values are compared, and the month having the higher average ~~P_{AMF}~~PAMF is defined as the PM.
- If there is a tie between months and equivalent average ~~P_{AMF}~~PAMF values, the month having the higher average annual streamflow is defined as the PM.

The sub-basin’s PM is defined based on the occurrence of station or grid-level PMs rather than the PAMF values to diminish results being skewed by biased simulations or varying climate effects in small parts of the sub-basin. When there are an equal number of occurrences for different PMs, the average PAMF values are used to determine which PM is selected. In this case, the effect of stations downstream of reservoirs will be minimized given their typically low average PAMF values. This procedure is applied for both stations (observations) and corresponding grid cells (model) in each sub-basin. To illustrate, consider the 6 GRDC stations in the Zambezi River Basin (Figure 3.) For most of the stations, the observed PM is defined as a month later than the model-based PM (Table 2), an apparent bias in the model. The ~~P_{AMF}~~PAMF of STA06 observations is noticeably lower than for other stations (36%; Table 2) given its location downstream of the Itezhi-Tezhi dam (STA05) (Figure 3.) Otherwise, ~~P_{AMF}~~PAMF values are consistently high across all stations. March is the PM identified most often, thus the final sub-basin PM selected is March.

In contrast, the model-based simulated streamflow produces a high ~~P_{AMF}~~PAMF at STA06 (97%), as the Itezhi-Tezhi dam is not represented in the simulations used for this study, and subsequently does not account for modulated streamflow. Across other stations, the ~~P_{AMF}~~PAMF is also high, however an equal number of stations select February and March. In this case, February is selected as the final basin PM given its higher average ~~P_{AMF}~~PAMF value (96% vs. 91%.)

By this approach, all 691 GRDC stations are grouped into 223 sub-basins to define the PM (Figure 6.); 58% of sub-basins are defined by a single station, only 7.6% (observations) and 8.1% (model) of sub-basins have ties when defining PMs, and only one sub-basin has a tie between PMs and average ~~P_{AMF}~~PAMF values.

4 Verification of selected flood seasons

Model-based ~~FSs~~PMs are verified by comparing with observation-based PMs at station ~~observations~~ and ~~also~~sub-basin scales. Additionally, historic flood records from the Dartmouth Flood Observatory (DFO) are used to compare basin-level PMs to actual flooded areas spatially and temporally. Specifically, we apply the following information from DFO: start time, end time, duration and geographically estimated area at 3,486 flood records across 1985-2008.

4.1 Observed versus modeled flood seasons

Ideally the model-based and observed GRDC stations have fully or partially overlapping FS periods. If so, this builds confidence in interpreting FSs at locations where no observed data are available. For comparing modeled ~~FSs~~PMs to observations, the defined PMs and calculated ~~P_{AMF}~~PAMF are represented globally at the station scale (Figure 4-5) and sub-basin scale (Figure

6.) Temporal) with temporal differences of PMs (modeled PM – observed PM). These temporal differences are also compared at the continental scale (Figure 7-8.) For example, in the United States and Canada, 6238% of stations and 4451% of sub-basins produce identical PMs, growing to 82% of stations and 9693% of sub-basins when considering a ±1 month temporal difference (e.g. FS; Figure 87.) GRDC stations in the southeastern United States express relatively lower P_{AMF}PAMF values for observations (40-60%) than model outputs (60-80%), due to the high level of managed infrastructure. In the central United States and Europe, low P_{AMF}PAMF values are computed for both observation and model outputs (Figure 5) with notable temporal differences in (Figure 7.)4 (c).) This is attributable, at least in part, to reservoirs and dams along the Mississippi, Missouri and Danube rivers.

Globally, comparing model and GRDC data, 40% of the locations share the same 3-month FSPM. Considering a difference of ± 1 month, this jumps to 81%, and 91% for ± 2 months (Figure 87.) From a sub-basin perspective, the similarities are even stronger (50% identical FSPM, 88% ± 1 month and 92% ± 2 month), indicating a relatively high level of agreement. For locations having dissimilar FSsPMs (≥ ± 3 months, 9% of locations and 8% of sub-basins), a substantial portion are located downstream of reservoirs directly, such as STA06 in the Zambezi example (Table 1), or are low-flow (dry) locations, both producing exceedingly low P_{AMF}PAMF values. Differences in FSsPMs are not unexpected for low-flow locations, given the propensity for the annual streamflow maximum to potentially occur in a wide number of months. Overall, however, as more than 80% of both stations and sub-basins have similar PMs (± 1 month), it appears that the global water balance model performs appropriately well in defining flood seasons globally at locations where observations are available.

This may be subsequently extended to defining FSsPMs and P_{AMF}PAMF at all grid cells (Figures 8-9-10.) Generally, a low P_{AMF}PAMF indicates an unstable FSannual maximum flow, which occurs in cases of constant-flow, low-flow, bi-modal flow and regulated flow. All cases, except regulated flow, are simulated within the PCR-GLOBWB simulations used, thus the cell-based P_{AMF}PAMF values (Figure 109) can provide a sense of confidence for the defined FSPM (Figure 98.) Examples of low-flow regions include the central United States and Australia; Europe exemplifies a constant-flow region, having low P_{AMF}PAMF regional values (Figure 109.) Bi-modal regions, such as much of East Africa with its two rainy seasons, may also be associated with low P_{AMF}PAMF values.

4.2 Modeled flood seasons versus actual flood records

Model-based ~~FSs~~PMs may also be verified (subjectively) by surveying historic flood records. One such source is the Dartmouth Flood Observatory (DFO), a large, publically accessible repository of major flood events globally over 1985-2008, based on media and governmental reports and instrumental and remote sensing sources. Delineations of affected areas are best estimates (Brakenridge, 2011.) The DFO records provide duration of each flooding event, as defined by the report or source, and represented as occurrence month (Figure ~~11~~10.) DFO flood events and grid cell based PMs (Figure ~~9~~8) may be compared outright, however their characteristics differ slightly. The DFO covers 1985-2008 while the model represents 1958-2000. Also, the model-based PM represents the month most likely for a flood to occur; the DFO is simply a reporting of when the event did occur, regardless of whether it fell in the expected flood season or not. Nevertheless, model-based PMs and historic flooding records illustrate a striking similarity (compare Figures ~~9~~8 and ~~11~~10), further supporting the model's ability to appropriately identify the PM spatially. Consistently, regions with high model-based ~~P_{AMF}~~PAMF (80-100%), such as Eastern South America, Central Africa and Central Asia, tend to agree well with DFO records, while ~~low P_{AMF}~~poor or less than poor PAMF (0-~~40~~60%) regions, such as Central North America, Europe, and East Africa, tend not to be in agreement with DFO records. In these low ~~P_{AMF}~~PAMF regions, however, DFO records also illustrate floods occurring sporadically throughout the year, further supporting accordance between cell-based ~~P_{AMF}~~PAMF and DFO records (Figures ~~10~~9 and ~~11~~10.)

5 Defining minor flood seasons

In some climatic regions, there is no one single, well-defined flood season. For example, East Africa has two rainy seasons, the major season from June to September and the minor season from January to April/May. These two seasons are induced by northward and southward shifts of the inter-tropical convergence zone ~~(Awange et al., 2014; Block and Strzepek, 2012; Chukalla et al., 2012; Romilly and Gebremichael, 2011; Segele et al., 2009a, 2009b; Seleshi and Zanke, 2004.)~~(ITCZ) (Seleshi and Zanke, 2004.) This bi-modal East African pattern allows for potential flooding in either season. In Canada, as another example, the dominant spring snowmelt season (Mar-May) and fall rainy season (Aug-Oct) allow for flood occurrences in either period (Cunderlik and Ouarda, 2009.)

Previous studies have investigated techniques to differentiate seasonality from uni-, bi- and multi-modal streamflow climatologies and evaluate trends in timing and magnitude of streamflow, including the POT method, directional statistics method, and relative flood frequency method (Cunderlik and Ouarda, 2009; Cunderlik et al., 2004a). These methods may perform well at the local (case-specific) scale to define minor flood seasons, however applying them uniformly at the global scale can be problematic, given spatial heterogeneity. Additionally, even though bimodal streamflow climatology may be detected, the magnitude of streamflow in the minor season may or may not be negligible in regards to flooding potential as compared with the major season.

To detect noteworthy minor flood seasons globally, we classify streamflow regimes by climatology and monthly ~~P_{AMF}~~ PAMF value, ~~which is the seasonal frequency of annual maximum flows~~calculated using Eq. (1) at each month (Figure ~~12~~11.) Classifications include unimodal, bimodal, constant, and low-flow. The unimodal streamflow climatology has high values of ~~P_{AMF}~~PAMF around the PM; the bi-modal classification is represented by two peaks of ~~P_{AMF} ;~~PAMF (and may therefore contain a minor season); both constant and low-flow classifications represent low values of ~~P_{AMF}~~PAMF between months. Distinguishing between bi-modal and other classifications is nontrivial. For example, ~~upon~~ initial inspection of the constant streamflow classification (both climatology and monthly ~~P_{AMF} ;~~PAMF, Figure ~~12~~11 (c~~)), it~~)) could be mistaken for a non-dominant bi-modal distribution. ~~In other words, bi-modal streamflow could be detected correctly or incorrectly, depending on how to define bi-modal streamflow.~~ We adopt the following criteria to differentiate bi-modal streamflow from uni-modal, constant, and low-flow conditions.

- The low-flow classification is defined for annual average streamflow less than 1 ~~*cms*~~m^3/sec.
- The major and minor PMs must be separated by at least two months in order to prevent an overlap of each FS (3-month.)
- If there is a peak in the monthly PAMF values outside the major FS, it is regarded as a *potential* minor PM. If the sum of ~~both major and minor FS's P_{AMF}~~ the major and *potential* minor PM's PAMF is greater than 60% (minimum of 29 out of 43 annual maximums fall in one of the FS), the *potential* minor PM is confirmed as a minor PM; the major PM's PAMF cannot exceed 80%.

A *potential* minor PM is identified by a secondary peak in the monthly PAMF rather than the magnitude or shape of streamflow. A minor FS is not defined when a major PM's PAMF is greater than 80% (minimum of 35 out of 43 annual maximums fall in one of the FS), it is defined as bi-modal streamflow), indicating a robust uni-modal streamflow character (Figure 11 (a)). The sum of both major and minor PM's PAMF (joint PAMF) is used to determine the likelihood that one of the FSs contains the annual maximum flow; a high value of the joint PAMFs (80-100%) indicates strong likelihood (Figure 11 (b)), moderate values (60-80%) imply moderate likelihood, with some probability of being classified as constant streamflow (Figure 11 (c)); low values (40-60%) are likely constant or low streamflow (Figure 11 (d)). Minor FSs are similar to major FSs, containing the minor PM and the month before and after. Minor FSs are evident in the tropics and sub-tropics and are spatially consistent with bi-modal rainfall regimes discovered by Wang (1994) (Figure 12.) Examples include East Africa (second rainy season in winter) and Canada (rainfall-dominated runoff in autumn) both having high joint PAMF values (80-100%.) Additional examples include the major FS (NDJ) and minor FS (MAM) in Central Africa consistent with the latitudinal movement of the ITCZ, intra-Americas' major FS (ASON) and minor FS (AMJJ) (Chen and Taylor, 2002), and coastal regions of British Columbia in Canada and southern Alaska's minor FS (SOND) due to wintertime migration of the Aleutian low from the central north Pacific (Figure 12.) Distinct runoff process controlled by different climate and hydrology systems can induce a bi-modal peak within a large-scale basin, such as the upstream sections of the Yenisey and Lena river systems in Russia where the major FS (AMJ) is dominated by snowmelt and the minor FS (JAS) is spurred on by the Asian monsoon. The same mechanism produces minor FSs around the extents of the Asian summer monsoon (90-100% of sum of PAMFs) (Figure 9 and 12.) Moderate minor FSs include, for example, the southern United States' (Texas and Oklahoma) bi-modal rainfall pattern (AMJ and SON) and in the southwestern United States (Arizona) where the summertime major FS (JJA) is produced by the North American monsoon and the wintertime minor FS (DJF) is affected by the regional large-scale low pressure system (Woodhouse, 1997). Southeastern Brazil's summertime major FS (NDJF) and post-summer minor FS (AMJ) are dominated by formation and migration of the South Atlantic Convergence Zone (Herdies, 2002; Lima and Satyamurty, 2010). In central and eastern Europe, the major FS (FMAM) and minor FS (JJA) are defined as moderate (60-80% of joint PAMF values for central Europe and 70%-90% for eastern Europe), indicating that a minor FS is not overly pronounced; for northeastern Europe the major FS (MAM) and minor FS (NDJ) contain high joint PAMF values (80%-100%.)

~~After defining the major FS globally, the minor FS is identified if it matches the specified conditions. As previously mentioned, East Africa is a notable example of bi-modal streamflow, with evidence of floods in both the major and minor seasons (Figure 13.)~~

For the major FS and minor FS with joint PAMF values exceeding 60% (Figure 13), flood records (DFO) occurring over more than one month are counted in each month based on the reported duration. Although one distinct flood event may dominate a monthly DFO record, strong similarity is evident between the FSs and monthly flood records (Figure 13.) Minor FSs with high PAMF values corresponding well with observed DFO flood records include East Africa (bi-modal streamflow), the intra-Americas, and Northern Asia; only a few reported flood records occur in the minor FSs in high latitudes.

6 Conclusions and Discussion

In this study, a ~~global~~novel approach to ~~define~~defining flood seasons globally is ~~proposed to identify seasonal spatial and~~presented by identifying temporal patterns of ~~global~~ streamflow objectively. Simulations of daily streamflow from the PCR-GLOBWB model are evaluated to define the dominant and minor flood seasons globally. In order to consider both streamflow magnitude and volume characteristics of floods, a volume-based threshold technique is applied to define the flood season and subsequently evaluated by the ~~P_{AMF} .~~PAMF. To verify model defined flood seasons, we compare with observations at both station and sub-basin scales. As a result, 40% ~~(50%)~~ of ~~locations at the station (~~stations and 50% of sub-~~basin) scale~~basins have identical peak months and 81% ~~(~~of stations and 89~~%)~~% of sub-basins are within 1 month, indicating strong agreement between model and observed flood seasons. Model defined flood seasons are additionally found to well represent actual flood records from the Dartmouth Flood Observatory, further substantiating the models ability to reproduce the appropriate flood season. Regions expressing bi-modal streamflow climatology are also defined to illustrate potential for noteworthy secondary (minor) flood seasons.

~~Identifying major flood seasons globally has numerous advantages, including improved understanding of flood potential, causation, and management, particularly in ungauged or limited gauged basins, potentially leading to development of season-ahead flood warning systems. Another advantage, and main motivation behind this work, is to lay the groundwork for season-ahead flood prediction through the association of dominant streamflow with local and large-scale hydroclimatic indicators. Information at this scale can be complimentary to~~

short-term flood predictions, motivating governments and relief agencies to plan and mobilize resources accordingly to minimize flood impacts on lives and livelihoods.

Outcomes of this work also link global and regional climate behavior with seasonal spatial and temporal patterns of streamflow. For example, global monsoon systems are clearly evident, as driven by the ITCZ, in central and southern Africa, Asia and northern South America (Figure 9.) Latitudinal patterns in the extra-tropics are also quite distinct, with flood seasons often occurring across similar months in the year. The fingerprints of regional climate systems influencing flood seasons are also prevalent, including the North American monsoon and South Atlantic Convergence Zone. In some cases non-adjacent regions express similar flood seasons and characteristics, indicating similar influence by large-scale climate dynamics, ENSO being the best understood; regions of similarity and their associated climate dynamics warrant further attention.

Defining major flood seasons and the climate precursors leading to those seasons offer strong prospects for developing season-ahead flood prediction models. To examine seasonal predictability of annual floods globally, the co-variability between streamflow and global and regional climatic indicators will be identified and related through empirical models to gauge predictive skill. Concurrently, basin-level tailored flood forecast models will be constructed at selected locations for comparing predictive capabilities with the global approach. While both scales play an important part, for basins in which the global approach is sufficiently skillful, it may serve as a useful tool for international disaster management, particularly in vulnerable un-gauged regions, without necessitating a data-heavy, physically-based, local model.

-Large-scale temporal phenomena associated with the defined major and minor flood seasons are also identified. For example, global monsoon systems are clearly evident, as driven by the ITCZ, in central and eastern Africa, Asia and northern South America (Figure 8.) Latitudinal patterns in the extra-tropics are also quite distinct, with flood seasons often occurring across similar months in the year. These broad temporal patterns are consistent with previous findings (e.g. Burn and Arnell, 1993; Dettinger and Diaz, 2000; Haines et al., 1988), however this analysis goes further by not being constrained to large-scale patterns for seasonal definition (via clustering) and also providing a sense of the reliability of the defined flood seasons. Specifically, the defined PM (Figure 8) has extended Dettinger and Diaz (2000)'s Peak Months by focusing on basin and grid scale streamflow volumes and providing likelihood type maps using the PMAF metric developed here (e.g. Figure 9) to represent the reliability of the defined PM. This can provide a clear sense of whether the identified flood season is pronounced or vague. The

identification of minor flood seasons and deciphering bi-modal from constant streamflow regimes is another notable contribution of this study; minor seasons have not been well identified in previous studies. These identified flood seasons are also consistent with DFO flood records both spatially and temporally, further substantiating their appropriateness.
Although biased simulations may theoretically contribute to a misidentified flood season, the global hydrological model's ability to well define flood seasons is highlighted in this study. The full global coverage of streamflow data in the model enables complete flood season identification globally. This is advantageous for many reasons, including hydrologic assessment in ungauged and poorly gauged basins and also for investigating flood season timing within large basins having diverse physical processes, for example, how the PM may shift along long rivers (e.g. Congo River) or basins with both snowmelt and rain-dominated processes. These spatially heterogeneous flood seasons at high resolution have the potential to better characterize streamflow regimes than previous studies (e.g. Dettinger and Diaz, 2000; Haines et al., 1988). Additional analysis to include upstream management and regulations is required to further classify global streamflow regimes and major flood seasons (or the elimination of them) for specific subbasin-level hydrologic applications.

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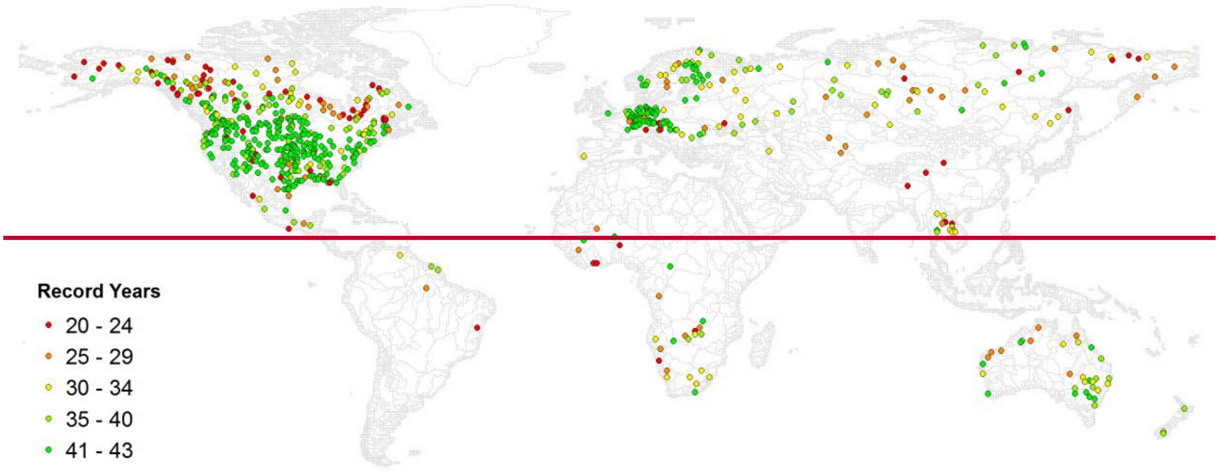
Table 1. Cross-correlations of Peak Month (PM) at GRDC stations for each classification technique for (a) observed and (b) simulated streamflow.

Classification Technique		5% Threshold	Q_{AMF}	Q_{7day}	Q_{15day}	Q_{30day}
Observed	5% Threshold	1				
	Q_{AMF}	0.866	1			
	Q_{7day}	0.894	0.912	1		
	Q_{15day}	0.895	0.880	0.945	1	
	Q_{30day}	0.900	0.832	0.881	0.890	1
Simulated	5% Threshold	1				
	Q_{AMF}	0.849	1			
	Q_{7day}	0.873	0.926	1		
	Q_{15day}	0.884	0.912	0.940	1	
	Q_{30day}	0.888	0.880	0.902	0.911	1

Table 2. Comparison of Peak Month (PM) for flooding and calculated P_{AMF} at 6 GRDC stations in the Zambezi River Basin.

Station (GRDC sta. numb.)	STA01 (1591001)		STA02 (1291100)		STA03 (1591406)		STA04 (1591404)		STA05 (1591403)		STA06 (1591401)		Final PM
Station name	Senanga		Katima Mulilo		Machiya Ferry		Kafue Hook Bridge		Itezhi-Tezhi		Kasaka		
River name	Zambezi		Zambezi		Kafue		Kafue		Kafue		Kafue		
Cumulative catchment area (km^2)	284,538		339,521		23,065		96,239		105,672		153,351		
Mean annual streamflow (m^3/s)	975		1168		139		287		353		988		
Streamflow type	Natural		Natural		Natural		Natural		Natural (Reservoir inflow)		Regulated		
Classification Technique	PM (month)	~~P_{AMF}~~ PAMF (%)	PM (month)	~~P_{AMF}~~ PAMF (%)	PM (month)	~~P_{AMF}~~ PAMF (%)	PM (month)	~~P_{AMF}~~ PAMF (%)	PM (month)	~~P_{AMF}~~ PAMF (%)	PM (month)	~~P_{AMF}~~ PAMF (%)	
Observed	4	96	4	100	3	93	3	100	3	94	7	36	3
Simulated	3	100	3	97	2	97	3	75	2	94	2	97	2



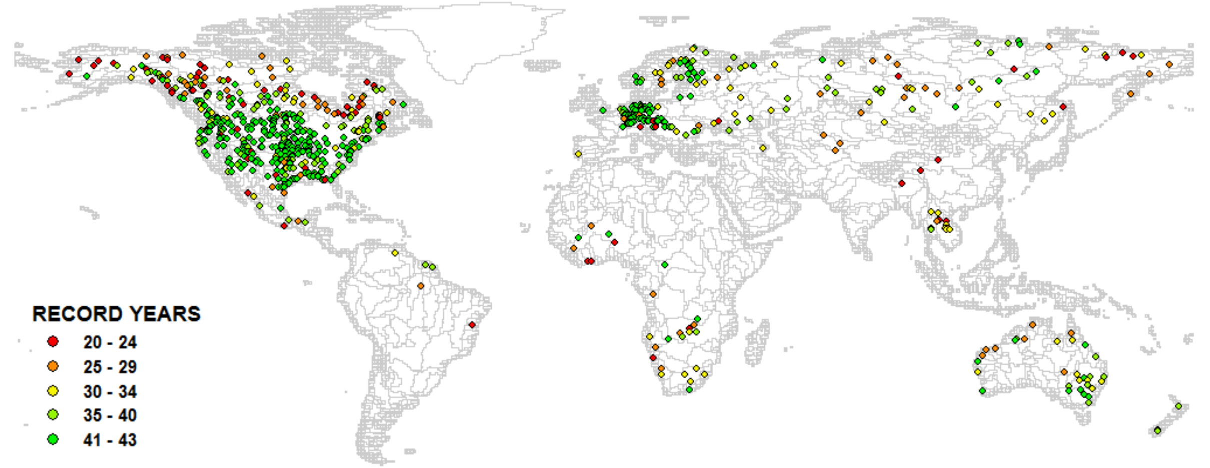


Figure 1. Location of 691 selected GRDC stations with corresponding number of years per station. Background polygons are world sub-basins based on 30′ drainage direction maps (Döll and Lehner, 2002). with separation of large basins (Ward et al., 2014).

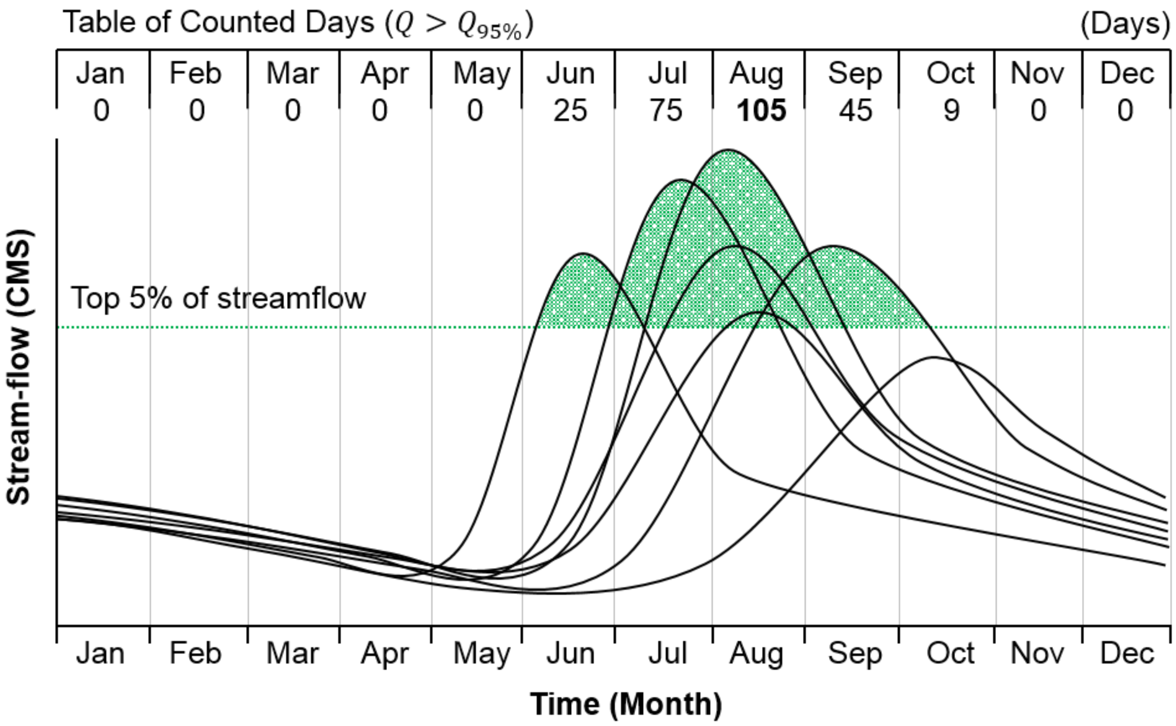


Figure 2. Seven years of synthetic streamflow data. Dotted line represents the 5% streamflow threshold. Numbers indicates the total days above the threshold for each month.

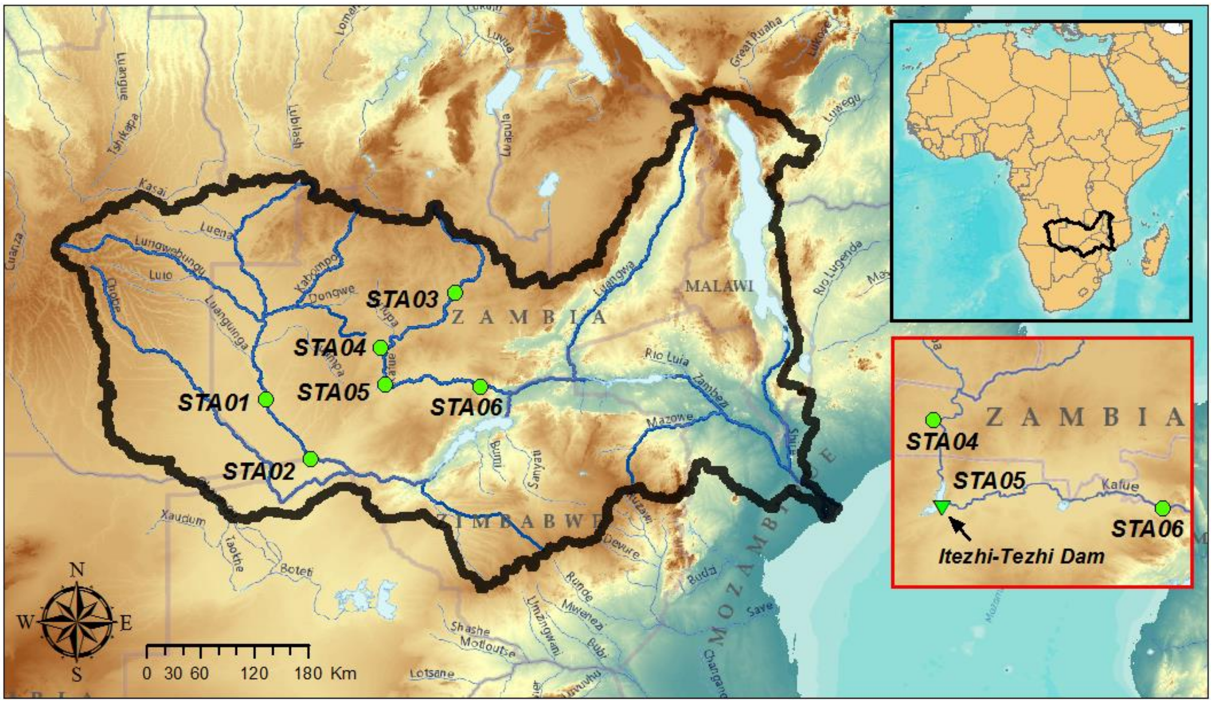
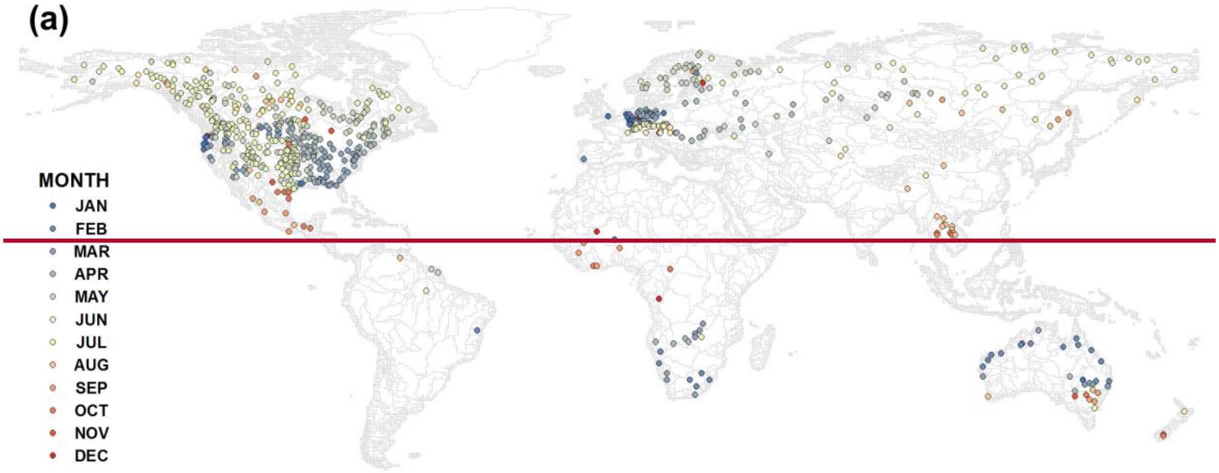
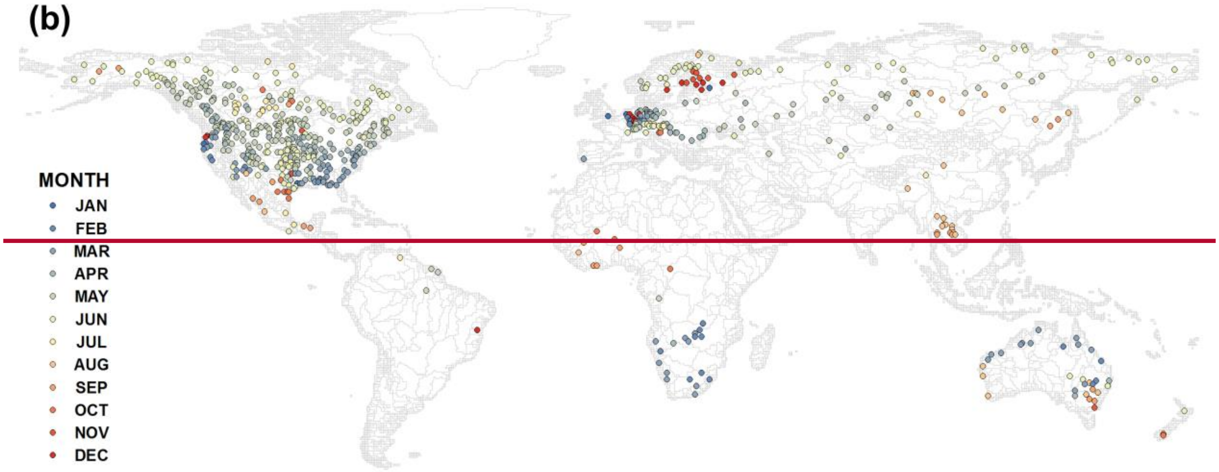


Figure 3. Map of Zambezi River Basin; the solid black line delineates the basin and the green points are the 6 GRDC stations (STA01-06), with STA06 downstream of the Itezhi-Tezhi dam (STA05.)


(a)
MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


(b)
MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

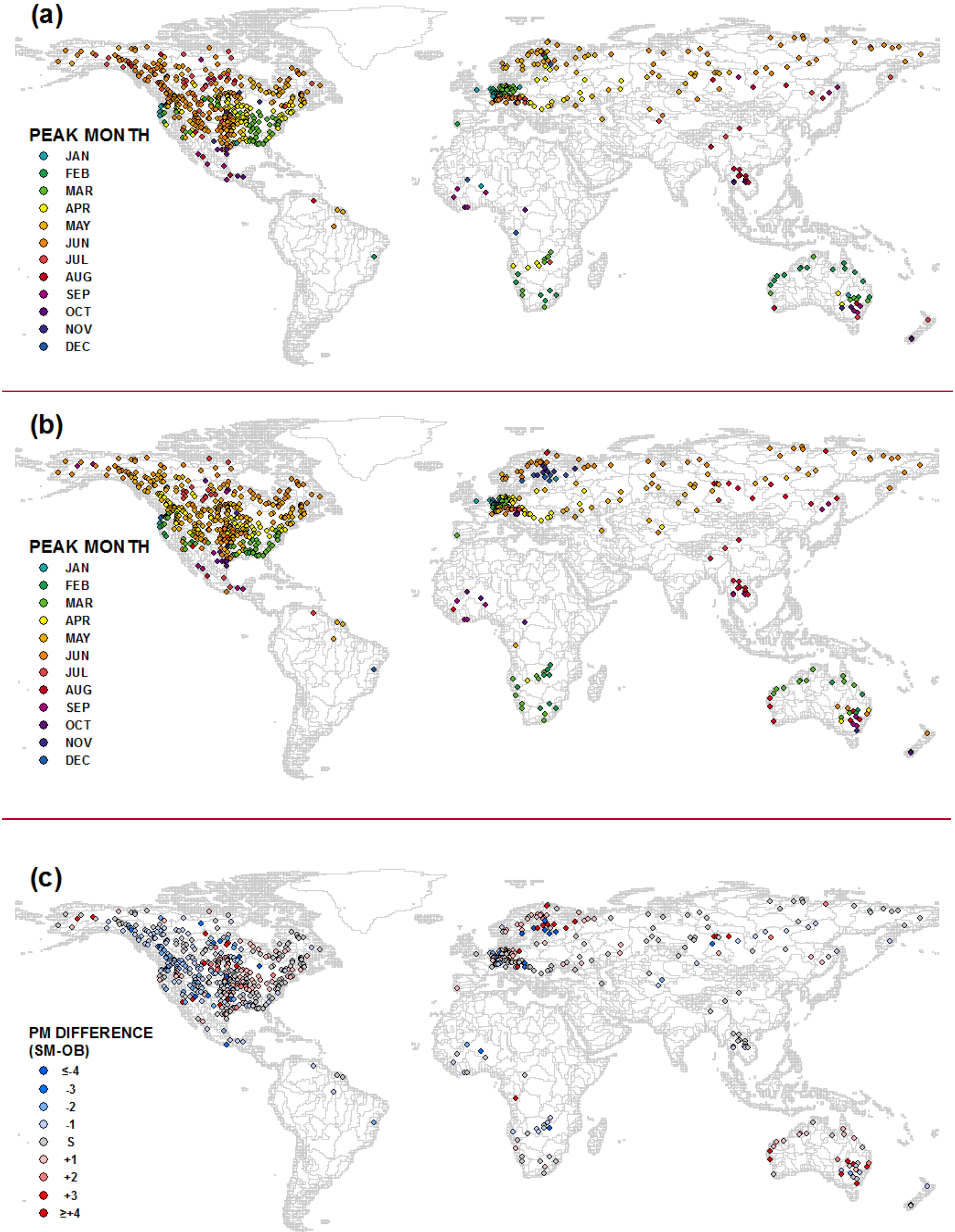
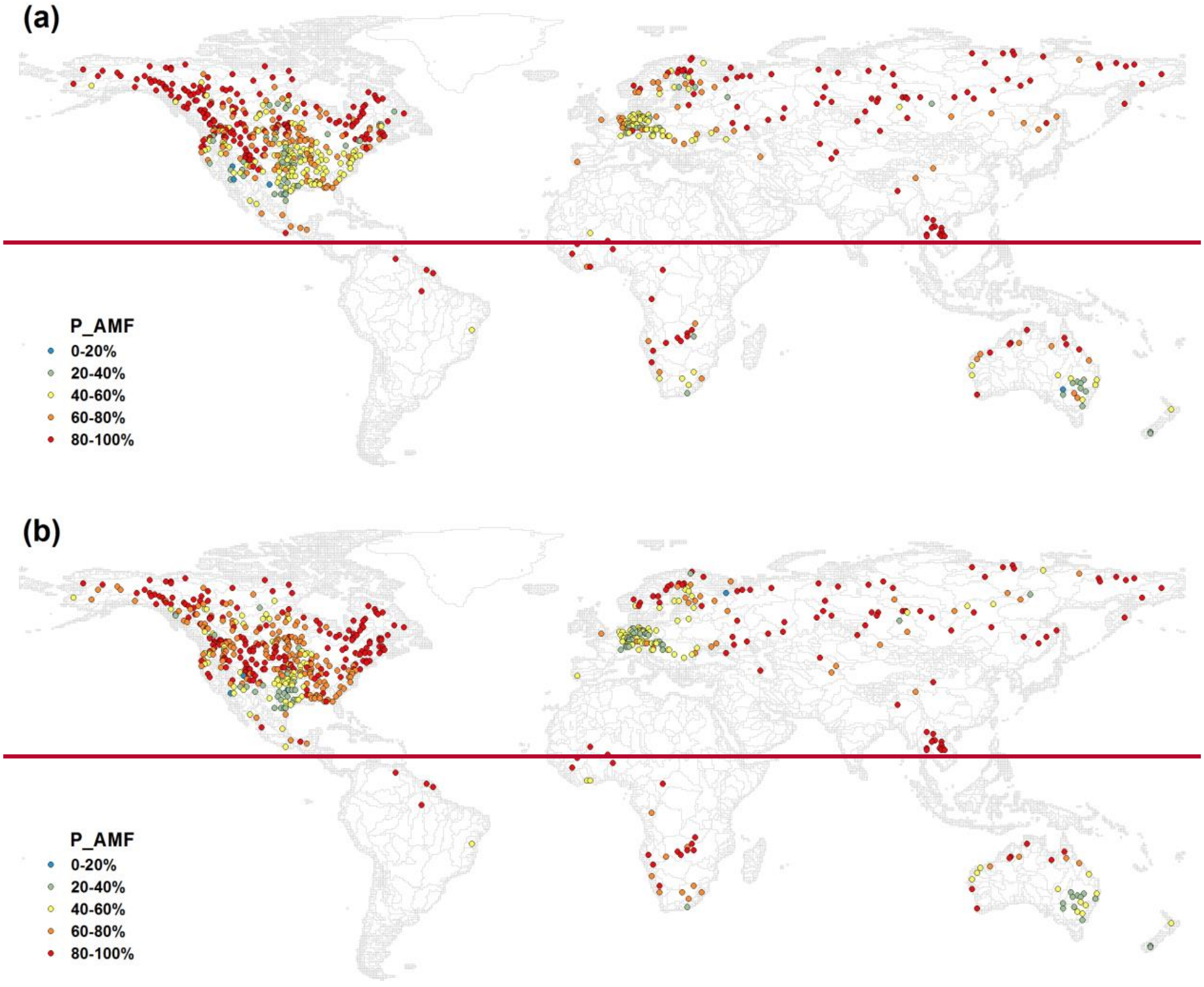


Figure 4. Peak Month (PM) for flooding as defined by (a) 691 GRDC observation stations, and (b) simulated streamflow at associated locations. and (c) Temporal difference in PM between observations and simulation (SM-OB, number of months).


(a)
P_AMF
0-20%
20-40%
40-60%
60-80%
80-100%
(b)
P_AMF
0-20%
20-40%
40-60%
60-80%
80-100%

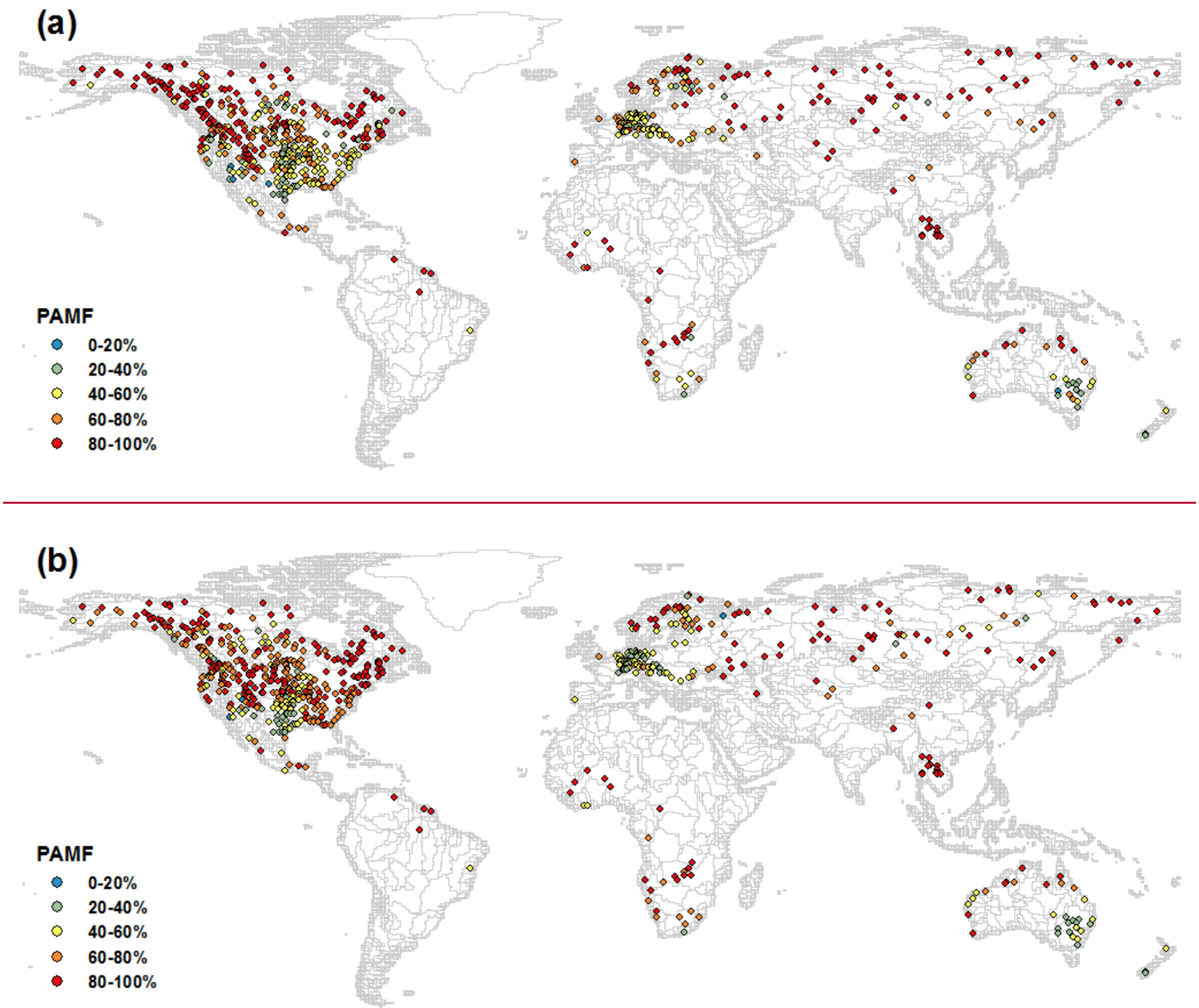
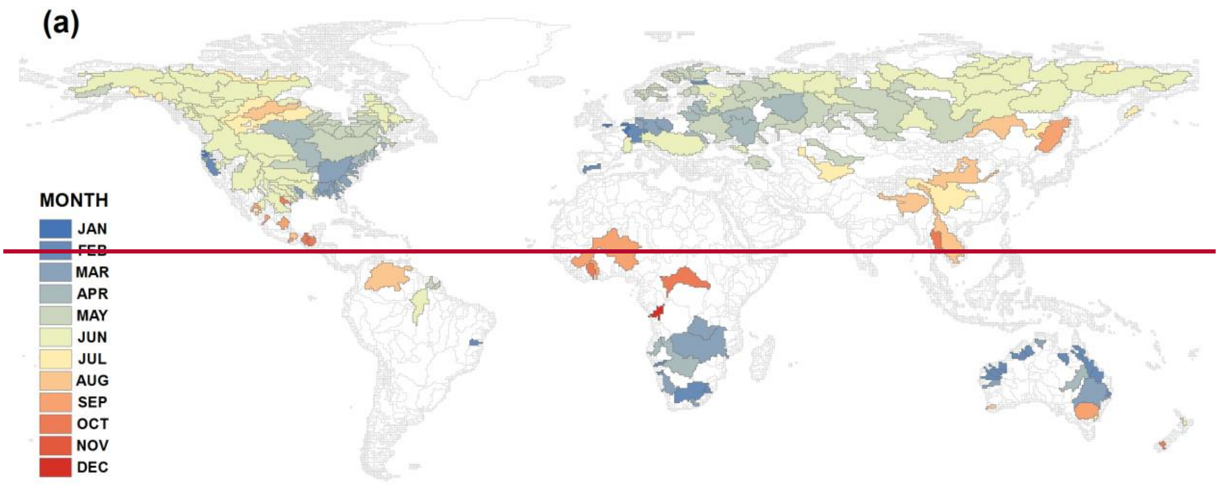
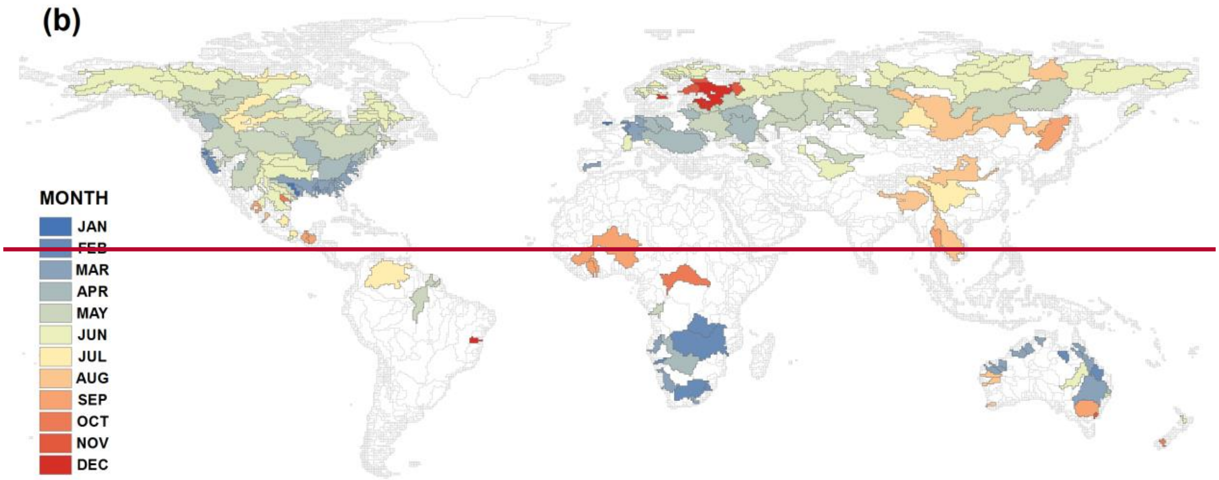
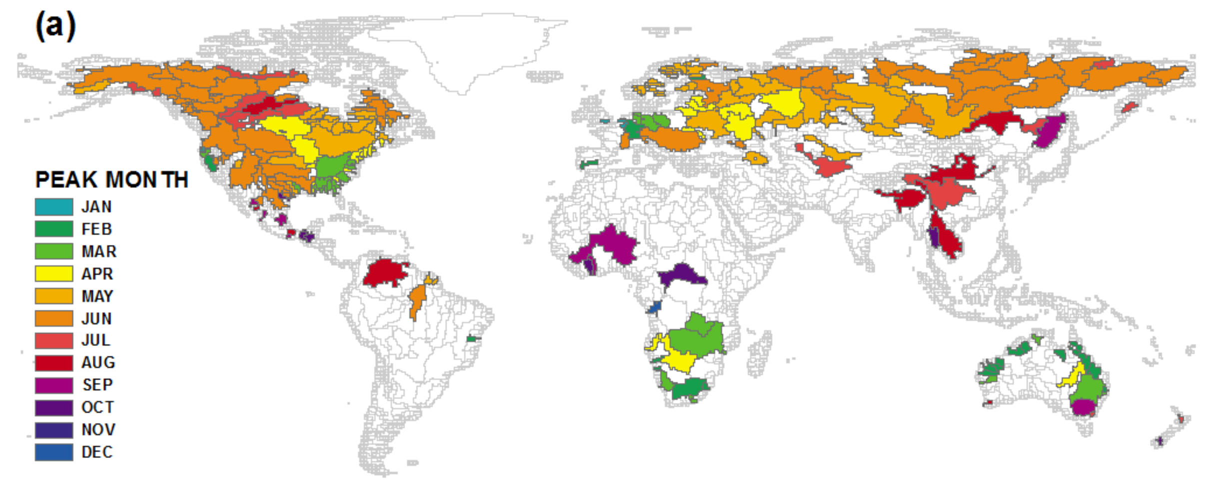


Figure 5. Calculated ~~P_{AMF}~~ Percentage of Annual Maximum Flow (PAMF) values for (a) 691 GRDC observation stations, and (b) simulated streamflow at associated locations.


(a)
MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


(b)
MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


(a)
PEAK MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

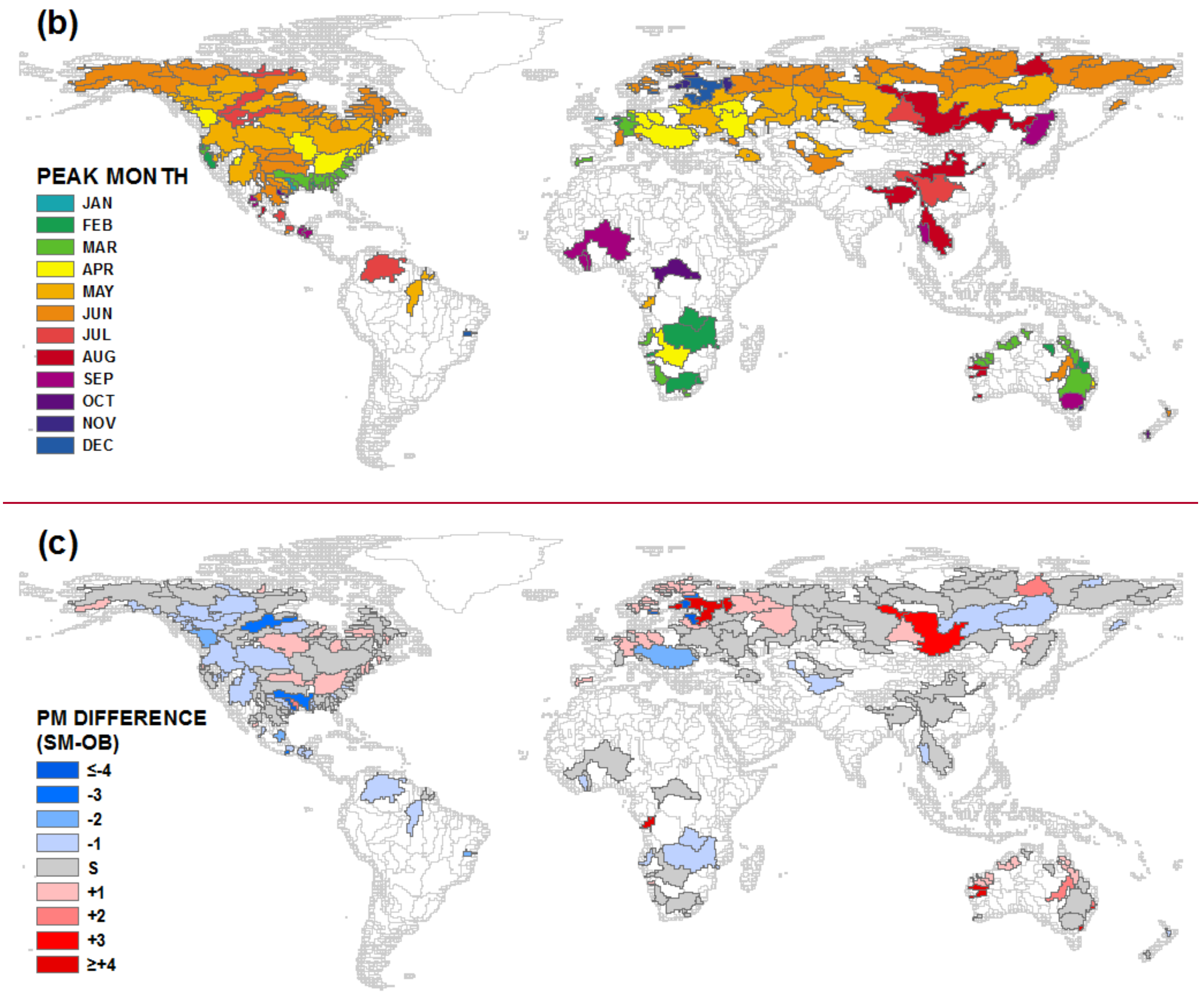
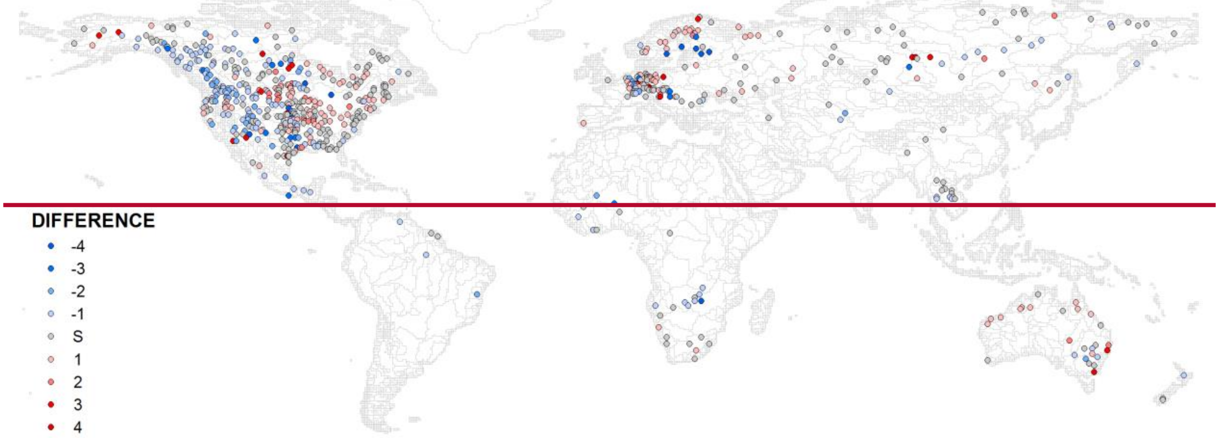


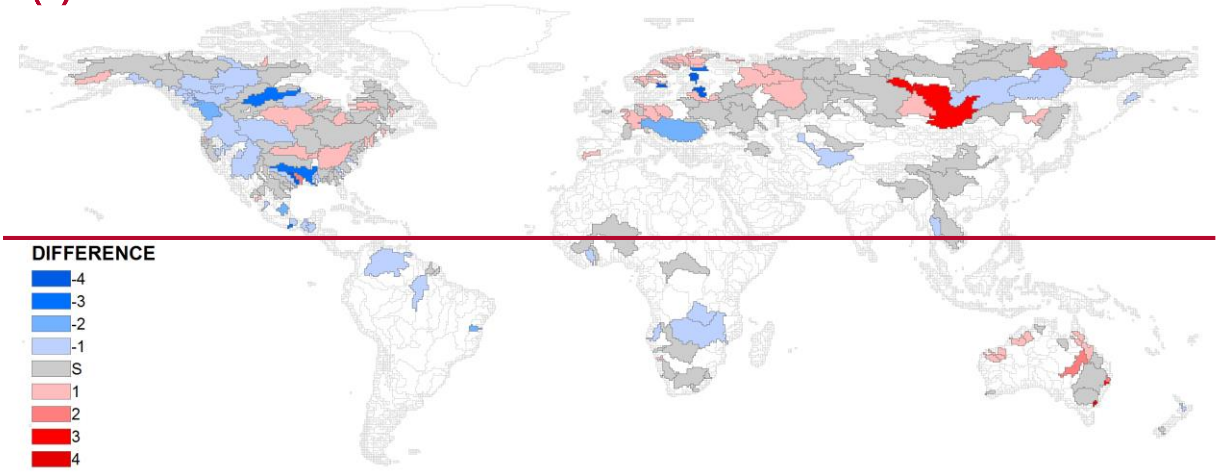
Figure 6. Peak Month (PM) for flooding by sub-basin as defined by (a) 691 GRDC observation stations, ~~and (~~(b) simulated streamflow at associated sub-basins~~.~~

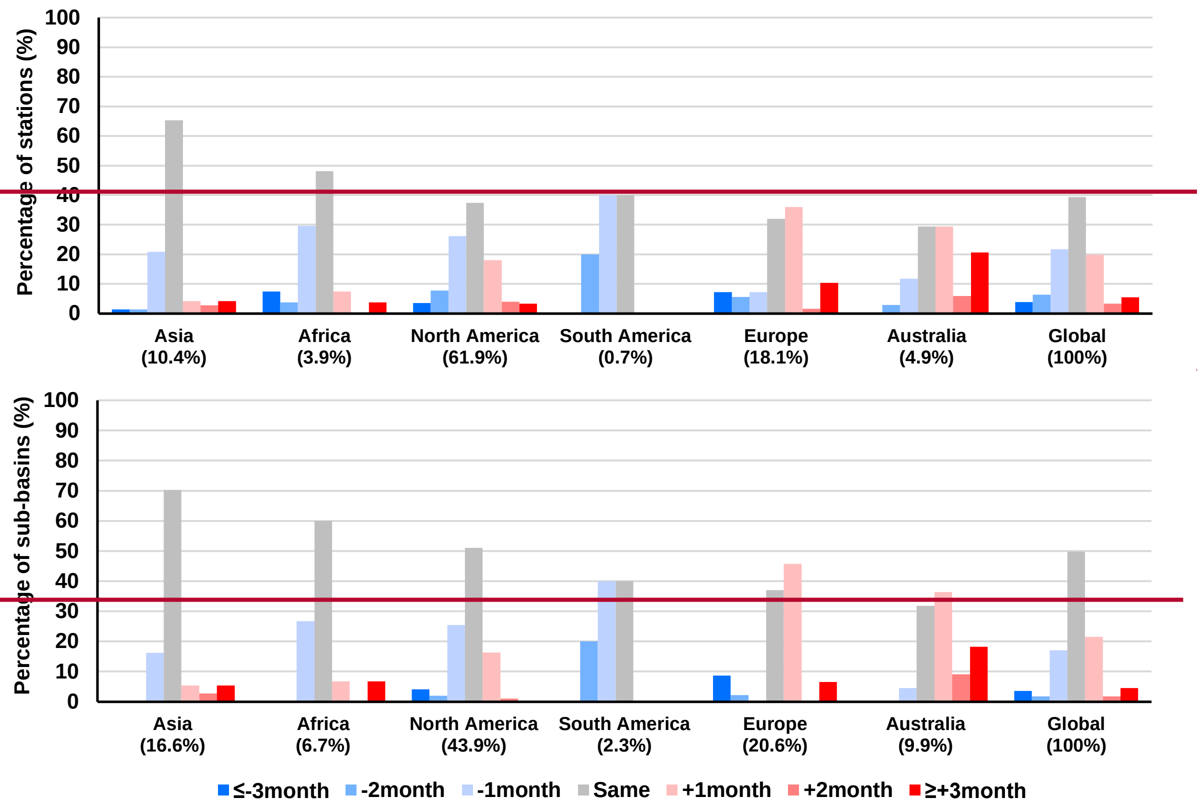
and (c) Temporal difference in PM between observations and simulation (SM-OB, number of months).

~~(a)~~



~~(b)~~





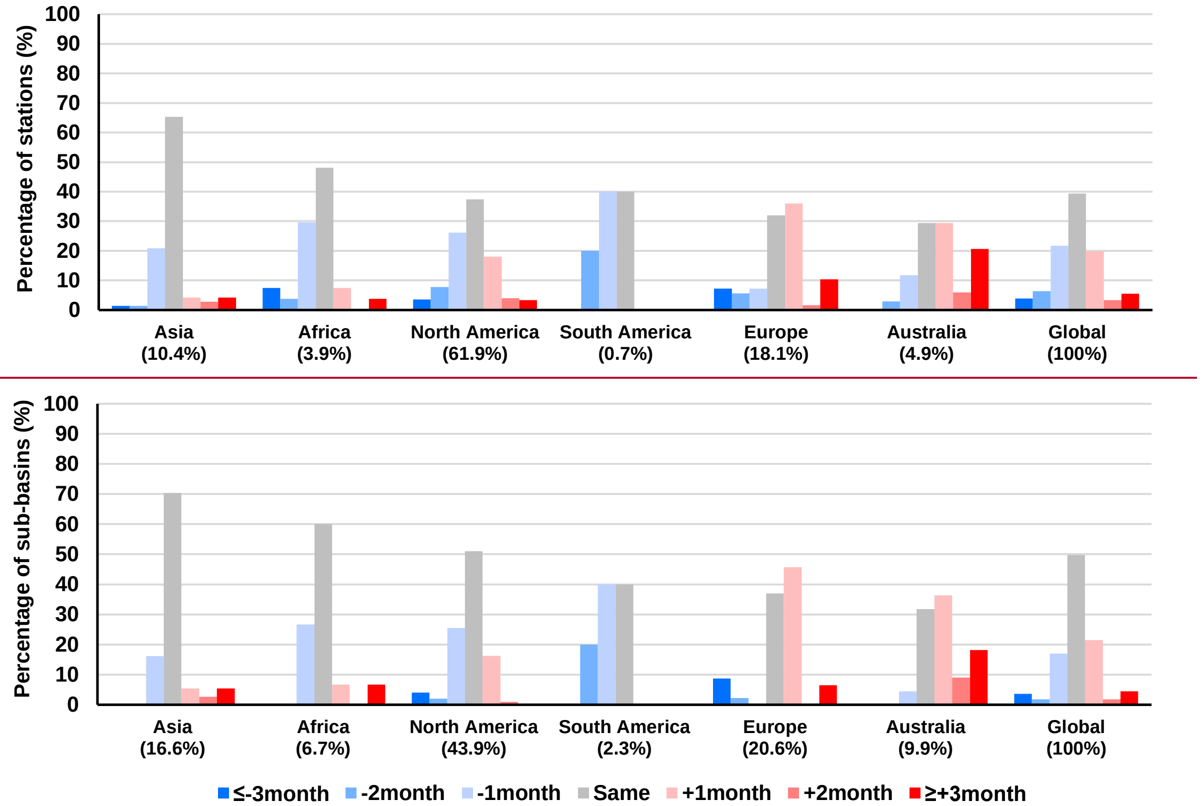
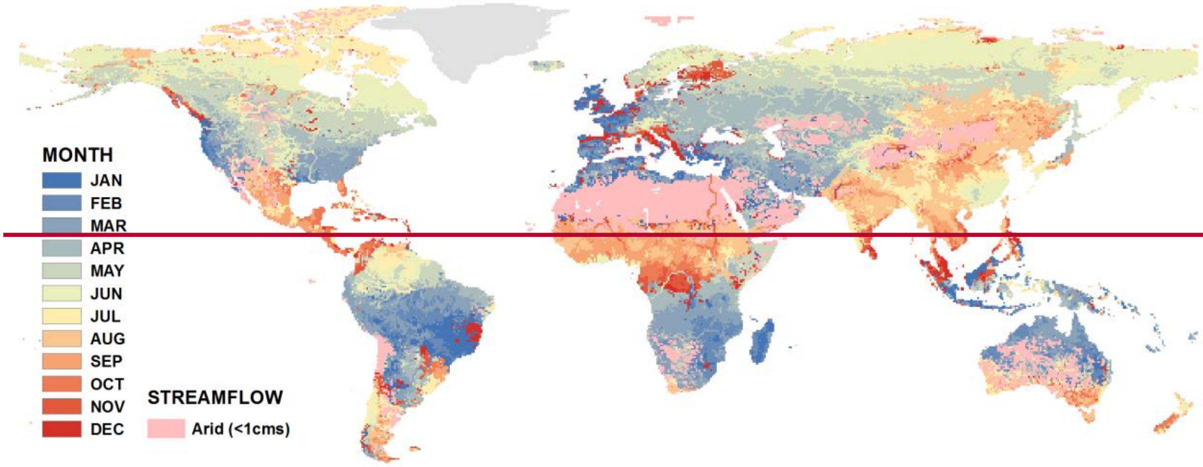


Figure 7. ~~Temporal difference (number of months) in Flood Season (FS) between observations and model outputs by a) station locations, and b) sub-basins.~~ ~~Figure 8.~~ Percentage of stations (above) and sub-basins (below) according to temporal difference of

~~FS~~PM between observations and model outputs (SM-OB, number of months) in each continent.



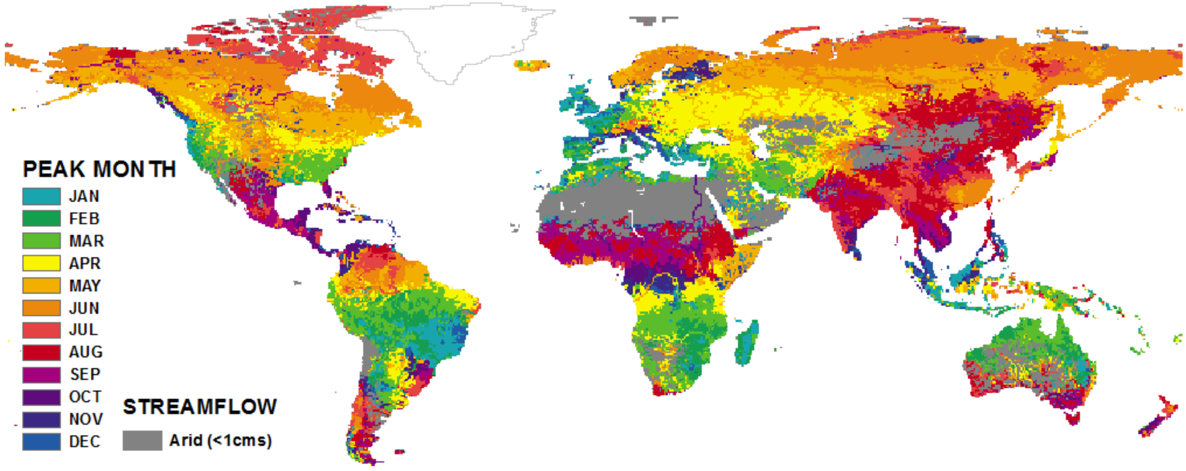


Figure 8. ~~*Figure 9.*~~ Peak Month (PM) for flooding as defined at all modeled grid cells.

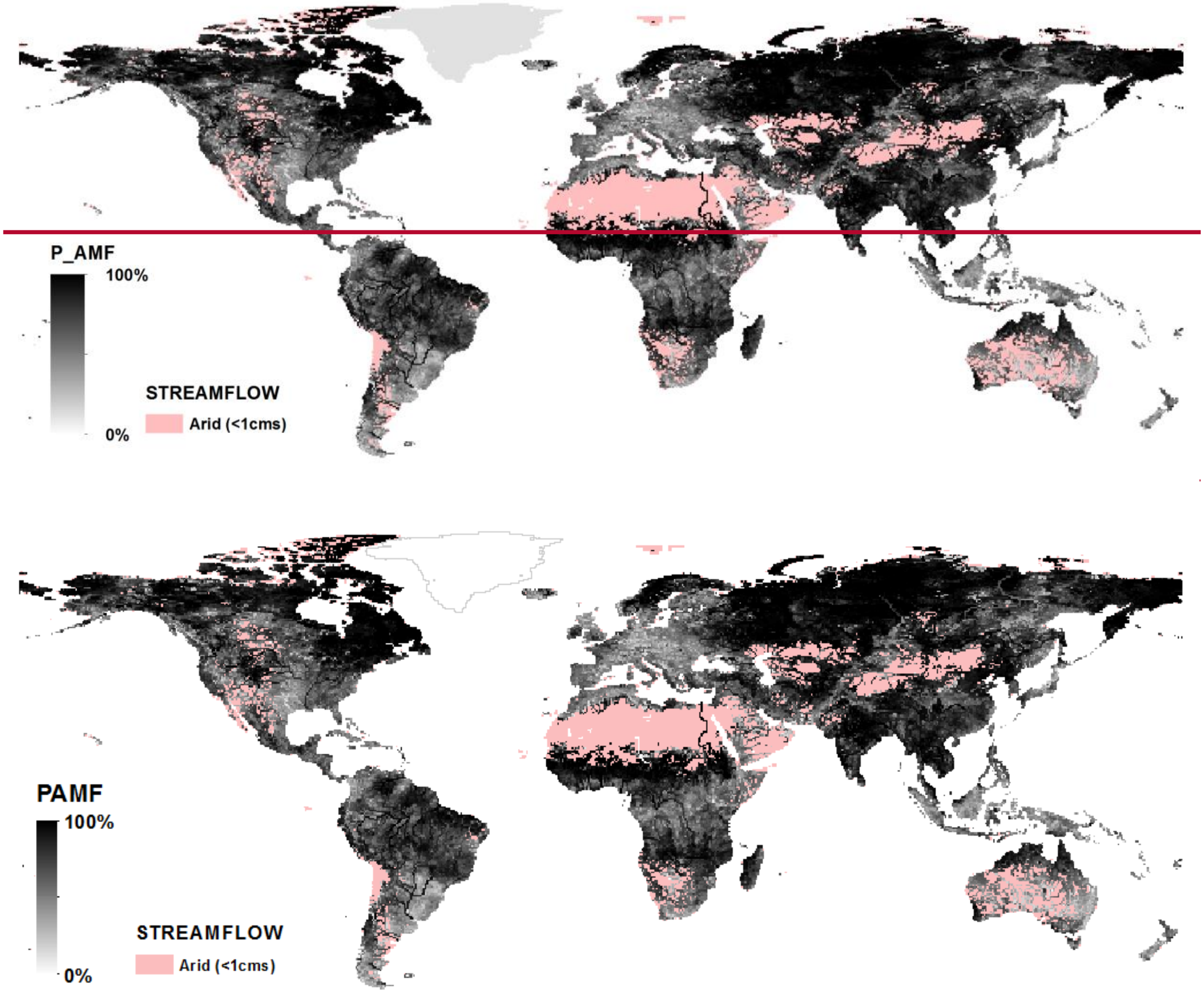


Figure 9. ~~Figure 10.~~ Calculated ~~P_{AMF}~~ Percentage of Annual Maximum Flow (PAMF) values for at all modeled grid cells.

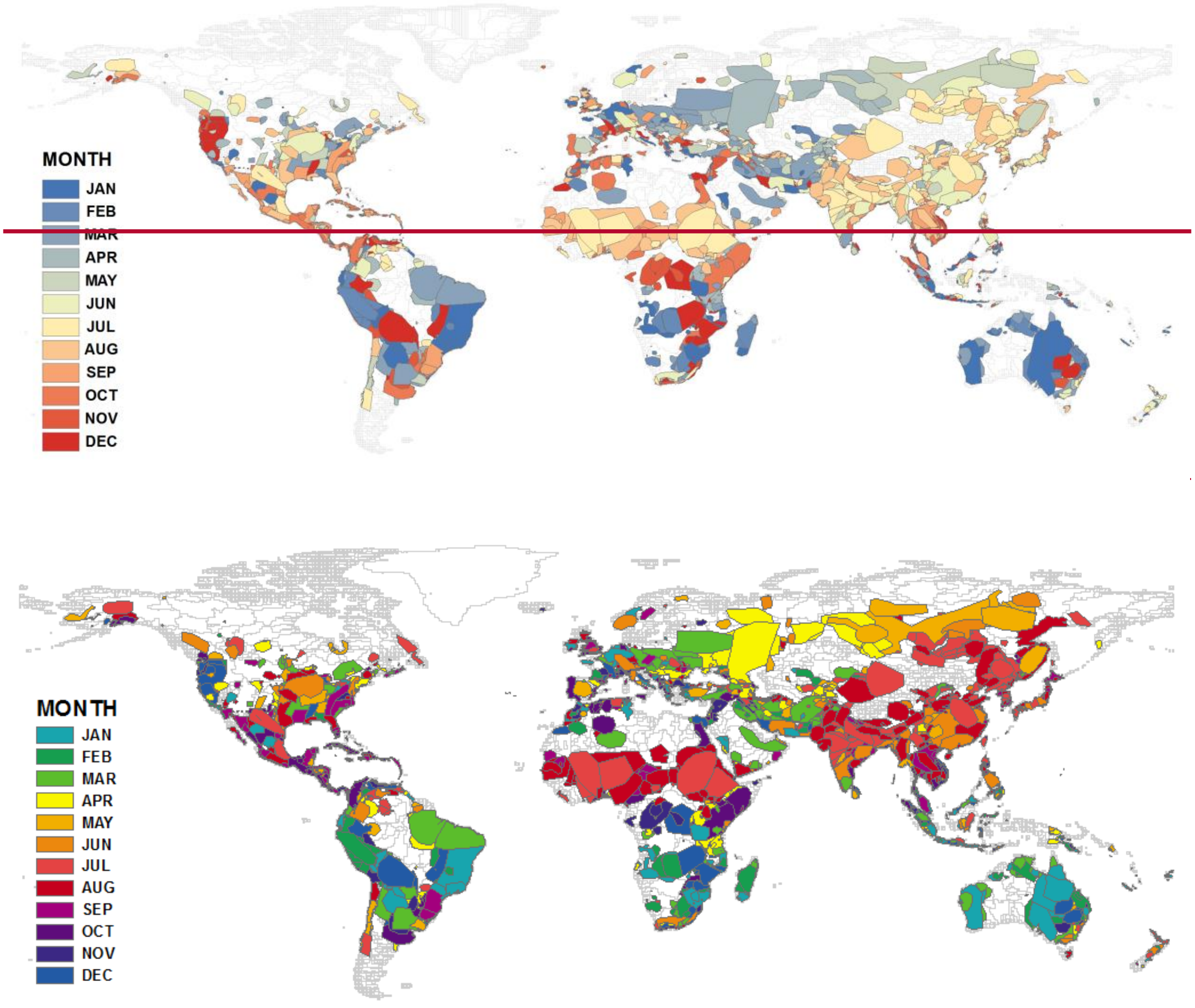
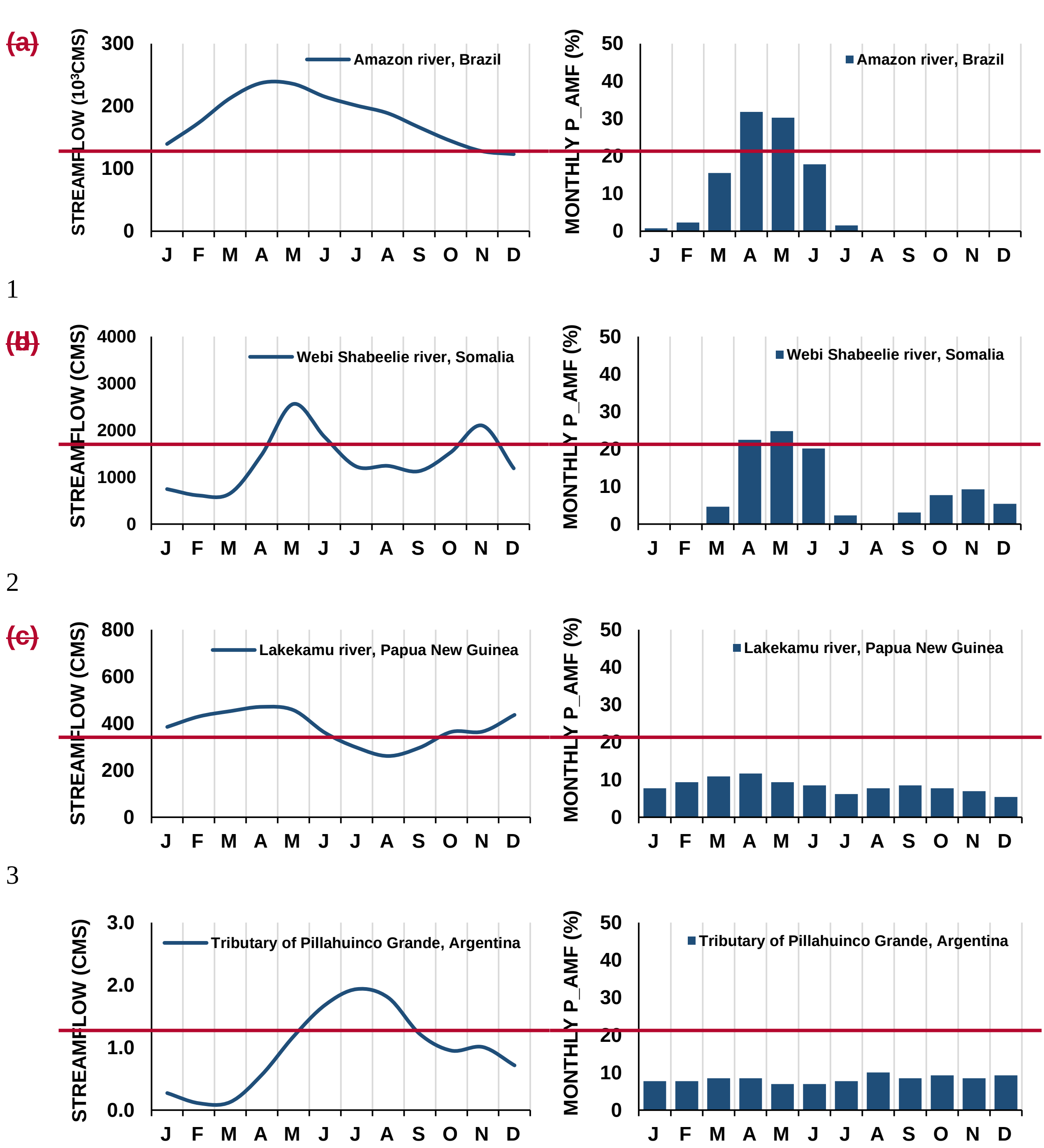
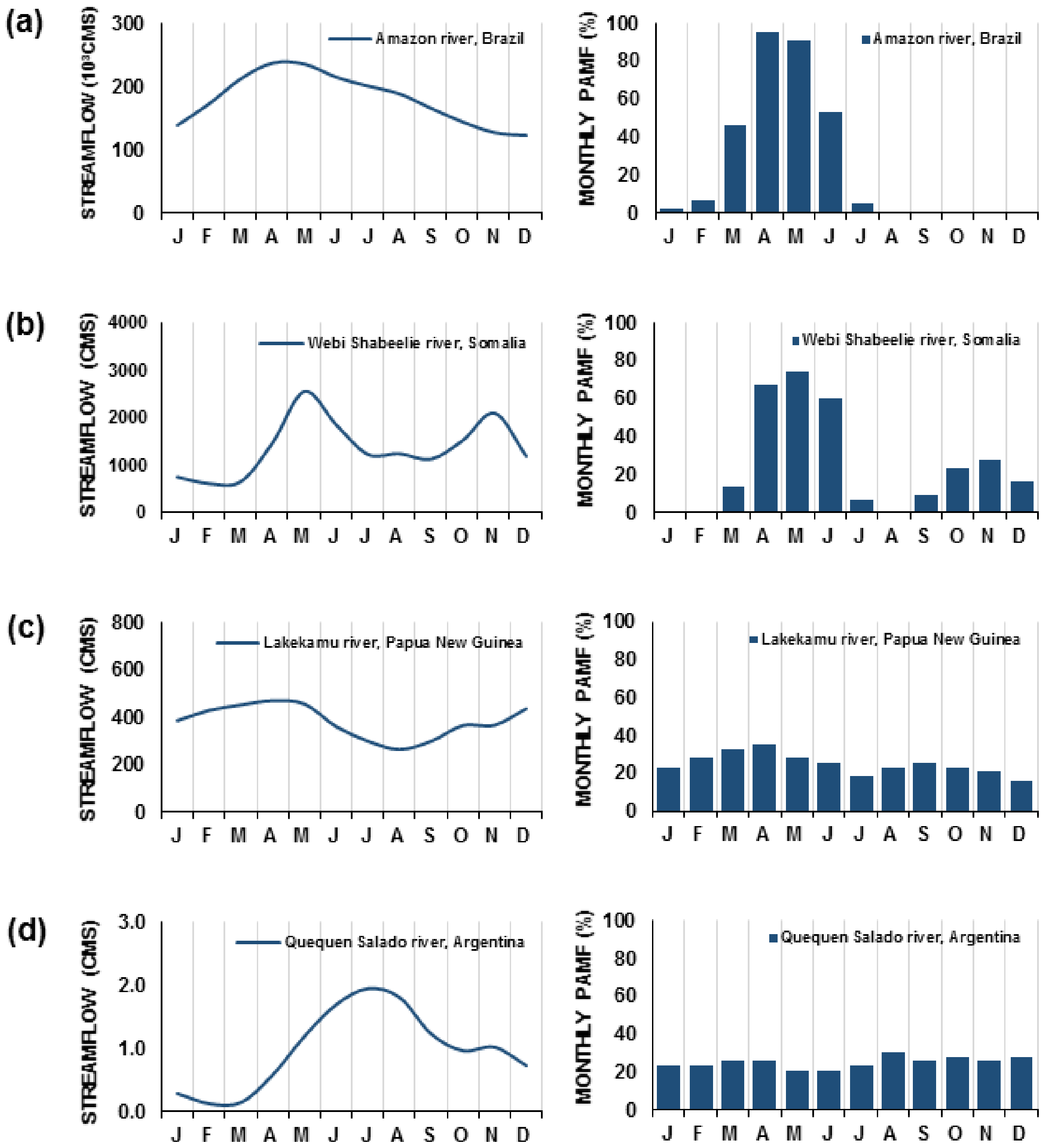


Figure 10. ~~Figure 11.~~ Archive of major flood events globally from the Dartmouth Flood Observatory (DFO) over 1985-2008.

1


(a)
STREAMFLOW (10³CMS)
Amazon river, Brazil
MONTHLY P_AMF (%)
Amazon river, Brazil
(b)
STREAMFLOW (CMS)
Webi Shabeelie river, Somalia
MONTHLY P_AMF (%)
Webi Shabeelie river, Somalia
(c)
STREAMFLOW (CMS)
Lakekamu river, Papua New Guinea
MONTHLY P_AMF (%)
Lakekamu river, Papua New Guinea
STREAMFLOW (CMS)
Tributary of Pillahuinco Grande, Argentina
MONTHLY P_AMF (%)
Tributary of Pillahuinco Grande, Argentina
J F M A M J J A S O N D



~~Figure 12.~~ Figure 11. Model-based streamflow climatology (left) and corresponding monthly ~~P_{AMF}~~ PAMF (right.) Types and locations are: a) uni-modal streamflow ~~-~~ – At Bom Lugar, Amazon river, Brazil, b) bimodal streamflow ~~-~~ – At Saacow, Webi Shabeelie river, Somalia, c) constant streamflow ~~-~~ – At Terapo Mission, Lakekamu river, Papua New Guinea and d) low-flow ~~– Tributary of Pillahuinco Grande~~ – At La Sortija, Quequen Salado river, Argentina.

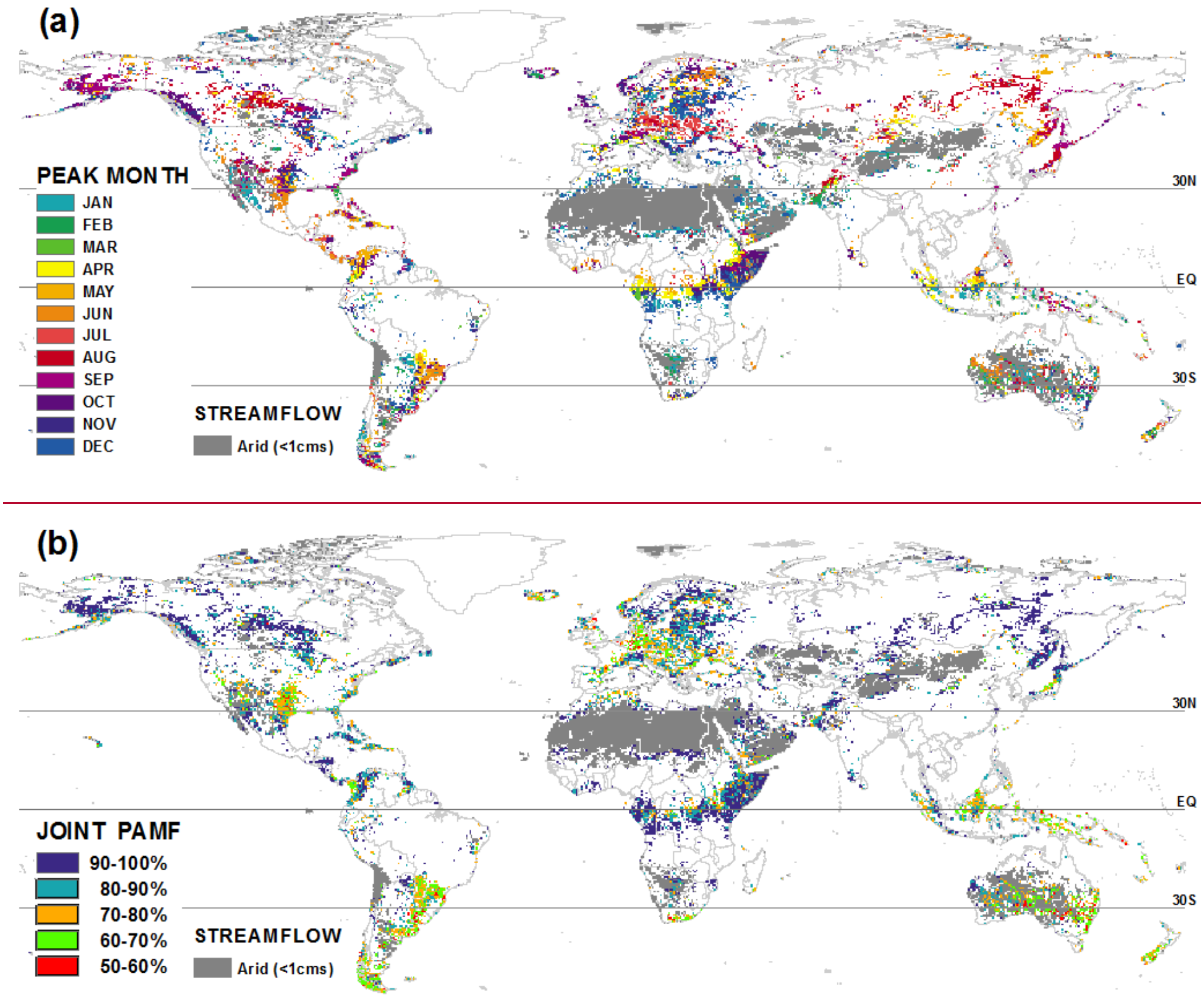
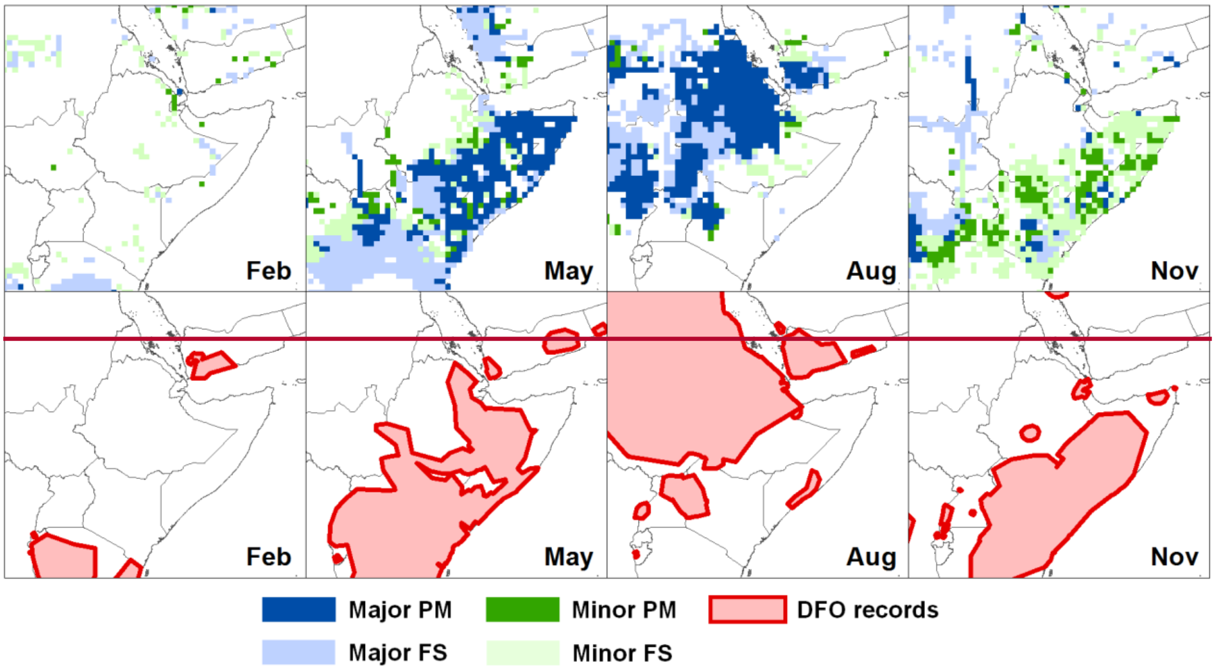


Figure 12. (a) Minor Peak Month (PM) for flooding as defined at detected grid cells and (b) joint PAMFs of major and minor PMs at corresponding cells.


Feb
May
Aug
Nov
Feb
May
Aug
Nov
Major PM
Minor PM
DFO records
Major FS
Minor FS

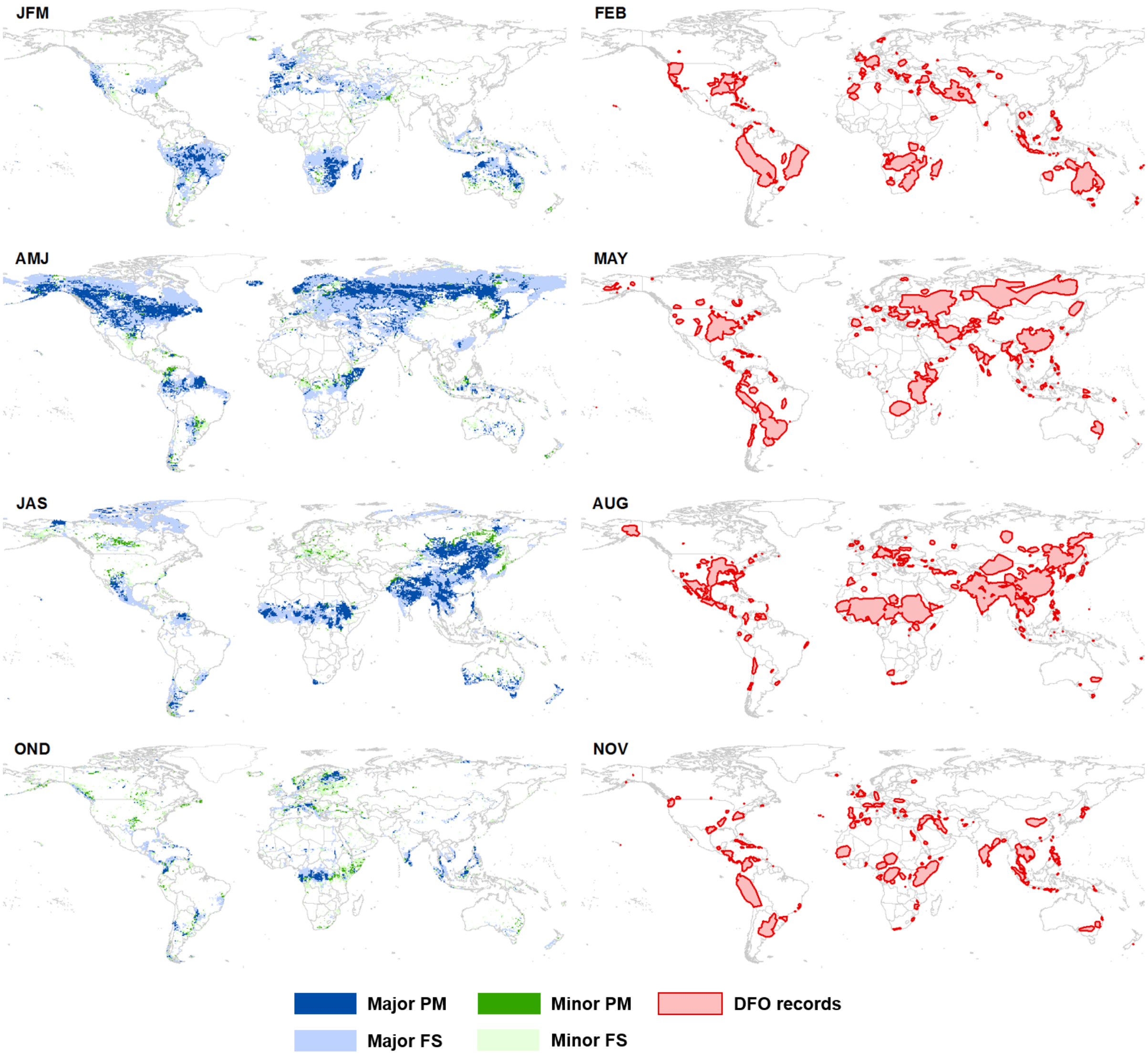

JFM
FEB
AMJ
MAY
JAS
AUG
OND
NOV
Major PM
Minor PM
DFO records
Major FS
Minor FS

Figure 13. ~~East Africa's monthly total flood seasons (above~~Defined major FS and minor FS where joint PAMF is greater than 60% (left); peak month of major and minor ~~flood seasons~~FSs (dense color) and pre- and post-month of ~~prior FS~~major and ~~pre-month of next FS~~minor FSs (light color.) Monthly accumulated actual flood records (DFO) during 1958-2008 (~~below~~right.)