

1 **Defining High-flow Seasons using Temporal Streamflow**

2 **Patterns from a Global Model**

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1 **Abstract**

2 Globally, flood catastrophes lead all natural hazards in terms of impacts on society, causing
3 billions of dollars of damages annually. Here, a novel approach to defining high-flow seasons
4 (3-month) globally is presented by identifying temporal patterns of streamflow. The main
5 high-flow season is identified using a volume-based threshold technique and the PCR-
6 GLOBWB model. In comparison with observations, 40% (50%) of locations at a station (sub-
7 basin) scale have identical peak months and 81% (89%) are within 1 month, indicating fair
8 agreement between modeled and observed high-flow seasons. Minor high-flow seasons are
9 also defined for bi-modal flow regimes. Identified major and minor high-flow seasons
10 together are found to well represent actual flood records from the Dartmouth Flood
11 Observatory, further substantiating the model’s ability to reproduce the appropriate high-flow
12 season. These high spatial-resolution high-flow seasons and associated performance metrics
13 allow for an improve understanding of temporal characterization of streamflow and flood
14 potential, causation, and management. This is especially attractive for regions with limited
15 observations and/or little capacity to develop early warning flood systems.

1 **1 Introduction**

2 Flood disasters rank as one of the most destructive natural hazards in terms of economic
3 damage, causing billions of dollars of damage each year (Munich Re, 2012). These flood
4 damages have risen starkly over the past half-century given the rapid increase in global
5 exposure (Bouwer, 2011; UNISDR, 2011; Visser et al., 2014). To specifically address flood
6 disasters from a global perspective, understanding of global-scale flood processes and
7 streamflow variability is important (Dettinger and Diaz, 2000; Ward et al., 2014). In recent
8 decades, studies have investigated global-scale streamflow characteristics using observed
9 streamflow from around the world (Beck et al., 2013; McMahon, 1992; McMahon et al.,
10 2007; Peel et al., 2001, 2004; Poff et al., 2006; Probst and Tardy, 1987) and modeled
11 streamflow from global hydrological models (Beck et al., 2015; van Dijk et al., 2013; McCabe
12 and Wolock, 2008; Milly et al., 2005; Ward et al., 2013, 2014) to investigate ungauged and
13 poorly gauged basins (Fekete and Vörösmarty, 2007). Despite this broad attention on annual
14 streamflow and its connections to global climate processes and precursors, there has been
15 relatively little attention paid to the intra-annual timing of streamflow, emphasizing the need
16 for analysis of seasonal streamflow patterns to further improve understanding of large-scale
17 hydrology and atmospheric behaviors on the main (flood) streamflow season globally
18 (Dettinger and Diaz, 2000). Moreover, better assessment of streamflow timing and seasonality
19 is important for addressing frequency and trend analyses, flood protection and preparedness,
20 climate-related changes, and other hydrological applications that possess important sub-
21 annual characteristics (Burn and Arnell, 1993; Burn and Hag Elnur, 2002; Cunderlik and
22 Ouarda, 2009; Hodgkins et al., 2003). This motivates further investigation of intra-annual
23 temporal streamflow patterns globally.

24 Only a small number of studies have investigated global-scale seasonality and temporal
25 patterns of streamflow, with minimal focus on objective streamflow timing. Haines et al.
26 (1988) cluster 969 world rivers into 15 categories based on seasonality and average monthly
27 streamflow data, and present one of the first maps providing a global classification. Burn and
28 Arnell (1993) aggregate 200 streamflow stations into 44 similar climatic regions and
29 subsequently combine these into 13 groups using hierarchical clustering based on similarity of
30 the annual maximum flow index, providing spatial and temporal coincidences of flood
31 response. Dettinger and Diaz (2000) aggregate 1345 sites into 10 clusters based on seasonality

1 using climatological fractional monthly flows (CFMFs) to identify peak months and linkages
2 with large-scale climate drivers.

3 In general, these studies define high streamflow or flood seasons subjectively based on the
4 relationship between dominant streamflow amplitude patterns and large-scale climate
5 drivers/patterns, and delineate large-scale homogeneous regions correspondingly. Defining
6 high flow season timing is essentially a bi-product of these analyses, and may be problematic
7 due to varying seasonal patterns (e.g. bi-modal distribution, constant or low flow areas, etc.)
8 not captured at the large-scale delineation. There is also typically no distinguishment between
9 minor and high flow seasons. In some cases, these minor seasons (e.g. resulting from bi-
10 modal precipitation distribution) can produce high flow or flood conditions, and are thus of
11 interest to identify. Here we identify high-flow seasons by capturing annual peak timing using
12 a volumetric technique at the cell and sub-basin scale, presenting an approach focused on
13 streamflow temporal patterns rather than pattern of amplitude. The new measure of Peak
14 Month (PM) and High-flow Season (HS) coupled with the model grid scale provides much
15 higher resolution peak timings globally than previously presented (often at large basin scale or
16 subcontinental scale). The performance measure introduced here, which is Percentage of
17 Annual Maximum Flow (PAMF), is also a new contribution relating the models ability to
18 capture high flow season timing. These advantages are also helpful for identifying less-
19 dominant but important seasons (minor high-flow seasons) that possess similar characteristics
20 to the high flow season (e.g. bi-modal annual cycle), another unique contribution of this work.
21 This leads to better temporal characterization and understanding of flood potential, causation,
22 and management, particularly in ungauged or limited-gauged basins.

23

24 **2 Data description**

25 **2.1 Streamflow stations**

26 Daily streamflow observations utilized in this study are from the Global Runoff Data Centre
27 ([GRDC, 2007](#)), specifically those, stations located along the global hydrology model's
28 drainage network. Since station records that are missing even short periods may effect how a
29 high-flow season is defined, we have excluded years with any daily missing values. In this
30 study, a minimum of 20 hydrological years is required for a station to be retained, leaving,
31 691 stations from all continents except Antarctica, with upstream basin areas ranging from

1 9,539 to 4,680,000 km² and periods of record between 20 - 43 years across 1958 - 2000
2 (Figure 1). Although this criteria is admittedly quite strict (no missing 20-year daily data),
3 including stations with missing records does not add a significant number. These stations are
4 mostly located on large-rivers; annual streamflow of 75% of stations is larger than 100
5 m³/sec, 35% of stations are larger than 500 m³/sec, 20% of stations are larger than 1,000
6 m³/sec and 5% of stations are larger than 5,000 m³/sec.

7 **2.2 PCR-GLOBWB**

8 In this study, we evaluate simulations of daily streamflow over the period 1958-2000 taken
9 from [Ward et al. \(2013\)](#), carried out using PCR-GLOBWB (PCRaster GLOBal Water
10 Balance), a global hydrological model with a 0.5° x 0.5° resolution ([Van Beek and Bierkens,](#)
11 [2009](#); [Van Beek et al., 2011](#)). Although the PCR-GLOBWB model is not calibrated, and
12 simulations may contain biases and uncertainty at coarse spatial resolution, the long time-
13 series of streamflow provided globally has been deemed sufficient to estimate long-term flow
14 characteristics with spatial consistency ([Winsemius et al., 2013](#)). Additionally, this model has
15 been validated in previous studies in terms of streamflow ([Van Beek et al., 2011](#)) and
16 terrestrial water storage ([Wada et al., 2011](#)) at stations along major rivers in the world. The
17 model's extreme discharges are also evaluated by [Ward et al. \(2013\)](#) with fair to good
18 performance at stations with large drainage area ($\geq 125,000$ km²), corresponding to 24% of
19 GRDC stations used in this study, excepting overestimation in several arid regions. Note that
20 for the simulations used in this study, the maximum storage within the river channel is based
21 on geomorphological laws that do not account for existing flood protection measures such as
22 dikes and levees.

23 For the simulations used in this study, the PCR-GLOBWB model was forced with daily
24 meteorological data from the WATCH (Water and Global Change) project ([Weedon et al.,](#)
25 [2011](#)), namely precipitation, temperature, and global radiation data. These data are available
26 at the same resolution as the hydrological model (0.5° x 0.5°). The WATCH forcing data were
27 originally derived from the ERA-40 reanalysis product ([Uppala et al., 2005](#)), and were
28 subjected to a number of corrections including elevation, precipitation gauges, time-scale
29 adjustments of daily values to reflect monthly observations, and varying atmospheric aerosol-
30 loading. It is possible that this may have some minor effect on streamflow simulation, likely

1 providing more realistic outcomes. Full details of corrections are described in [Weedon et al.](#)
2 [\(2011\)](#).

3

4 **3 Defining high-flow seasons**

5 To identify spatial and temporal patterns of dominant streamflow uniformly, we design a
6 fixed time window for representing high-flow seasons globally. Here we define major high-
7 flow seasons as the 3-month period most likely to contain dominant streamflow and the
8 annual maximum flow. The central month is referred to as the Peak Month (PM) and the full
9 3-month period is referred to as the High-flow Season (HS). Specifically, we define PM first,
10 and then define HS as the period also containing the month before and after the PM. This
11 approach is performed for both observed (station) and simulated (model) streamflow to gauge
12 performance.

13 **3.1 Methodology for defining grid-cell scale high-flow seasons**

14 In the last few decades, a number of studies have investigated the timing of peak flows in the
15 context of analyzing flood seasonality, frequency and trends. Generally, two main properties
16 are emphasized regarding flood timing: peak volume and peak timing. Considering peak
17 volume, the occurrence dates are commonly recorded for a fixed-time period or specific
18 amount of peak volume, often in the context of trend analysis. For examples, [Hodgkins and](#)
19 [Dudley \(2006\)](#) use winter-spring center of volume (WSCV) dates to analyze trends in
20 snowmelt-induced floods, and [Burn \(2008\)](#) uses percentiles of annual streamflow volume
21 dates as indicators of flood timing, also for trend analysis. For peak timing, two sampling
22 methods are frequently applied in hydrology. The first and most common is the annual-
23 maximum (AM) method, which samples the largest streamflow in each year. The second
24 method is the peaks-over-threshold (POT) method ([Smith, 1984, 1987; Todorovic and](#)
25 [Zelenhasic, 1970](#)), in which all distinct, independent dominant peak flows greater than a fixed
26 threshold are counted. In contrast to the AM method, POT can capture multiple large
27 independent floods within a single year, including the annual maximum flow, but may not
28 capture the annual maximum flow in years in which streamflow is less than the pre-defined
29 threshold; this threshold can either be defined based on a specific average number of floods or
30 a specific mean exceedance level over the entire period ([Cunderlik et al., 2004a; Institute of](#)
31 [Hydrology, 1999; Lang et al., 1999](#)). The PM selected, therefore, is dependent on the peak

1 properties (volume, timing) considered. For a local study, selecting the PM can be based on
2 well-defined climatic or hydrologic characteristics (e.g. rainy season, snow-melt, etc.),
3 however no single global method can be uniformly applied to define the PM everywhere.
4 Thus, to define the HS, and specifically the PM, globally, both peak volume and peak timing
5 aspects need to be considered (Javelle et al. 2003). To do this, we adopt a Volume-Based
6 Threshold (VBT) technique. This technique is similar to a streamflow volume-based
7 technique in terms of capturing the days (Julian dates) when streamflow exceeds the pre-
8 defined threshold (percentile of flows) and associated volume (Burn, 2008). The major
9 difference, however, is that the VBT applies the threshold over the entire time-series
10 (available record) concurrently instead of on a year-by-year basis. In other words, for the 95th
11 percentile, instead of annually calculating the 95th percentile, it is calculated using the entire
12 period of record. The common volume-based technique thus records events every year
13 surpassing the threshold, however for the VBT approach, every year need not have a peak
14 above the threshold. This approach emphasizes capturing the key peaks across the entire
15 available time-series (as in a peak over threshold approach). VBT thus contains both volume
16 and timing characteristics for defining the Peak Month (PM). Here, the month containing the
17 greatest number of occurrences over the specified percentage of flows across all years (1958-
18 2000) is defined as the PM, and subsequently the HS is designated as the period containing
19 the PM plus the month before and after the PM. Figure 2 provides an example based on seven
20 years of synthetic streamflow with the volumetric threshold set at the top 5% of flows; the
21 number of days surpassing the 5% threshold is listed for each month. In this example, August
22 has the largest number of days over the threshold (105 days), thus August is defined as PM
23 and July-September is defined as HS.

24 To evaluate the defined HS objectively, by evaluating the number of annual maximum flows
25 captured, we develop a simple evaluating statistic called the Percentage of Annual Maximum
26 Flow (PAMF). PAMF is computed as shown in Eq. 1:

$$27 \quad PAMF(i) = \frac{\sum_{j=i-1}^{i+1} n_{AMF}(j)}{\sum_{k=1}^{12} n_{AMF}(k)}, \quad 1 \leq i \leq 12 \quad (1)$$

28 where $n_{AMF}(i)$ denotes the number of annual maximum flows that occur in month i across
29 the full record. In Eq. (1), when i is 1 (Jan), $i - 1$ in the summation is 12 (Dec), and when i is
30 12 (Dec), $i + 1$ is 1 (Jan). Here the PAMF provides the percentage of annual maximum flows
31 occurring in the defined HS across the evaluation period. The PAMF is relatively simple, yet

1 provides clear indication of how well PM selected represents the occurrence of annual peaks
2 across the time-series. For example, a high PAMF indicates that the HS is highly likely to
3 contain the annual maximum flood each year. In contrast, a low PAMF indicates that the
4 timing of the annual maximum flow is more likely to vary temporally, and may be a result of
5 bimodal seasonality, consistently high or low streamflow throughout the year, streamflow
6 regulated by infrastructure or natural variation. In this study, we subjectively classify HS
7 PAMF values as: high = 80-100%, moderate = 60-80%, low = 40-60% and poor = 0-40%.
8 The PAMF is calculated for both the observed streamflow at the selected 691 GRDC stations
9 and the simulated streamflow at the associated 691 grid locations.

10 The VBT technique is compared with the common volume-based technique and POT
11 technique to gauge performance. Four volume-based durations, namely V01%, V03%, V05%
12 and V10% and three POT techniques averaging 1, 2, and 3 peaks per year (POT1, POT2 and
13 POT3, respectively) are selected. For the V01% technique, the HS is simply centered on the
14 PM containing the largest number of occurrences of the top 1% of annual streamflow volume
15 across the total years available. The V03%, V05% and V10% techniques are similar to the
16 V01% approach, respectively using 3%, 5% and 10% of annual streamflow volume.
17 Comparatively, techniques with a shorter time component (1-3% of annual volume) favor
18 identifying the PM by peak timing, since the top 1-4 days of streamflow tend to be located near
19 the peak, while techniques with longer time components (5-10% of annual volume) favor
20 identifying the PM based on duration and peak volume, since the top 19-33 days of
21 streamflow tend to be located near the volumetric centroid of the hydrograph, rather than the
22 peak, if they differ. The VBT technique is an attempt to bridge these two criteria. For the POT
23 techniques, independence criteria is applied to avoid counting multiple peaks from the same
24 event ([Institute of Hydrology, 1999](#)). For example, two peaks must be separated by at least
25 three-times the average rising time to peak, and minimum flow between two peaks must be
26 less than two-thirds of the higher one of the two peaks. More details of independence criteria
27 are described in [Lang et al. \(1999\)](#).

28 An analysis examining sensitivity of selected threshold levels for the VBT technique is also
29 undertaken. Performance of thresholds representing 1%, 3%, 5% and 10% exceedance across
30 the entire period of record, named VBT1%, VBT3%, VBT5% and VBT10%, respectively, are
31 compared.

1 To compare techniques and thresholds, the PMs are defined at the 691 selected stations and
2 associated model grids. The locations where the PMs differ (by at least one technique) are of
3 most interest. This occurs at 61% of stations and 54% of associated grids. Cross-correlations
4 of PM between the four common volume-based techniques clearly indicate the tendency of
5 the defined PM to shift from peak timing dominated to peak volume dominated as the time
6 component increases (Table 1). Correlation between VBT techniques and volume-based
7 techniques are quite similar and consistent (0.82-0.86 and 0.84-0.86 for observed and
8 simulated streamflow, using VBT5%; Table 1), preliminarily indicating some success in
9 capturing both timing and volume properties, while correlation between the VBT techniques
10 and POT are less strong (0.78-0.81 and 0.79-0.83 for observed and simulated streamflow,
11 respectively, using VBT5%; Table 1). The PAMF is also useful for comparing techniques,
12 such that the technique having the highest average PAMF typically contains more annual
13 maximum flow events in their defined HSs. The VBT5% is superior to other VBT and POT
14 techniques for both observed and modeled streamflow, having the highest PAMF values,
15 however the volume-based techniques indicate similar or even slightly better performance
16 than VBT5% (Table 2). This is not unexpected as the volume-based techniques are designed
17 to capture annual peak flows on a year-by-year basis, whereas the POT and VBT record
18 significant peaks across the full time-series, and may not capture annual peaks in some years
19 in which that peak is small relative to all peaks throughout the available record. Thus VBT
20 tends to select PMs that contain the most significant peaks overall, and subsequently have the
21 highest potential for capturing probable flood seasons for flood-prone basins, a desirable
22 outcome for this study. To illustrate this in the context of the PAMF, if all years are ranked for
23 each location based on the annual peak flow, and the top 50% (half) are retained, the PAMF
24 actually favors the VBT approach, surpassing the volume-based approach by 5-6% for PMs
25 and 2-3% for HSs.

26 Finally, techniques may be evaluated by comparing the temporal difference (number of
27 months) between model-based and observed PMs; closer is clearly superior. The VBT3% and
28 VBT5% techniques produce the greatest degree of similarity between model-based and
29 observed PMs (81% of stations having ± 1 month difference; Table 3). Overall, the VBT
30 technique demonstrates superior performance as compared with the POT techniques by all
31 comparisons. The VBT technique is also on par or slightly superior to the common volume-
32 based technique, especially considering the 5% threshold; thus, the remainder of the analysis
33 is carried out utilizing the VBT5% technique only.

3.2 Methodology for defining sub-basin scale high-flow seasons

In addition to evaluating the HS at the 691 grid cells based on model outputs, the PM and HS 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 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 m³/s are significantly modulated by dams (Lehner et al., 2011), often significantly attenuating flow hydrographs and flood volumes (twenty percent of GRDC stations fall into this category). 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 PM, the maximum 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 PAMF values are compared, and the month having the higher average PAMF is defined as the PM.
- If there is a tie between months and equivalent average PAMF values, the month having the higher average annual streamflow is defined as the PM.

1 The sub-basin's PM is defined based on the occurrence of station or grid-level PMs rather
2 than the PAMF values to diminish results being skewed by biased simulations or varying
3 climate effects in small parts of the sub-basin. When there are an equal number of occurrences
4 for different PMs, the average PAMF values are used to determine which PM is selected. In
5 this case, the effect of stations downstream of reservoirs will be minimized given their
6 typically low average PAMF values, assuming operational rules relatively evenly distribute
7 the annual flow across all months; however, if operational rules instead concentrate releases to
8 a few months, PAMF values may actually be high. This procedure is applied for both stations
9 (observations) and corresponding grid cells (model) in each sub-basin. To illustrate, consider
10 the 6 GRDC stations in the Zambezi River Basin (Figure 3). For most of the stations, the
11 observed PM is defined as a month later than the model-based PM (Table 4), an apparent bias
12 in the model. The PAMF of STA06 observations is noticeably lower than for other stations
13 (36%; Table 4) given its location downstream of the Itezhi-Tezhi dam (STA05) (Figure 3).
14 Otherwise, PAMF values are consistently high across all stations. March is the PM identified
15 most often, thus the final sub-basin PM selected is March.

16 In contrast, the model-based simulated streamflow produces a high PAMF at STA06 (97%),
17 as the Itezhi-Tezhi dam is not represented in the simulations used for this study, and
18 subsequently does not account for modulated streamflow. Across other stations, the PAMF is
19 also high, however an equal number of stations select February and March. In this case,
20 February is selected as the final basin PM given its higher average PAMF value (96% vs.
21 91%).

22 By this approach, all 691 GRDC stations are grouped into 223 sub-basins to define the PM
23 (Figure 6); 58% of sub-basins are defined by a single station, only 7.6% (observations) and
24 8.1% (model) of sub-basins have ties when defining PMs, and only one sub-basin has a tie
25 between PMs and average PAMF values.

26

27 **4 Verification of selected high-flow seasons**

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

4.1 Observed versus modeled high-flow seasons

Ideally the model-based and observed GRDC stations have fully or partially overlapping HS periods. If so, this builds confidence in interpreting HSs at locations where no observed data are available. 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). In the southeastern United States, GRDC stations express relatively lower PAMF values for observations (40-60%) than model outputs (60-80%), due to the high level of managed infrastructure. In the central-southern United States and Europe, low PAMF values are computed for both observations and modeled output (Figure 5) with notable temporal differences (Figure 4 (c)). For observations, this is attributable, at least in part, to reservoirs and dams along the Mississippi, Missouri and Danube rivers. Additionally, relatively constant streamflow patterns are identified in both observations and modeled output, consistent with previous studies reporting these flow regimes as uniform or perpetually wet (Burn and Arnell, 1993; Dettinger and Diaz, 2000; Haines et al., 1988). Minor high-flow seasons may also play a role. Model biases also effect PM selection; for Northwestern North America, PMs for many points are defined on average one month earlier than with observations, producing moderate PAMF values (60% and higher). In Northern Europe, especially South Finland, this becomes much more pronounced, with large differences between PMs from observations and the model, on the order of 4-months (Figure 4(c), 6(c), and 8(a)). In western and northern Australia, PMs are modeled 1-month later on average than observations excepting with two occurrences in the west (5-month difference) due to both observed and modeled low-flow conditions. Such low-flow regimes are also apparent in southeastern Australia, causing large differences between PMs (4-5 months). The differences in PMs between observations and modeled outputs are also compared at the continental scale (Figure 7). In North America, 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 (e.g. HS; Figure 7). In Asia 65% of stations and 70% of sub-basins have identical PMs, growing to 90% of stations and 92% of sub-basins with ± 1 month temporal difference (Figure 7). In central Russia, a large difference between PMs (± 3 months) are attributable to reservoirs on the Yenisei and Angara rivers and model bias (Figure 4 (c)). In Africa, 48% of stations and 60% of sub-basins produce identical PMs (Figure 7), 30% of stations and 27% of sub-basins are modeled 1-month earlier, and 7.4% of stations and 6.7% of sub-basins are modeled 1-month later than observation (Figure 7). In

1 South America, with only 5 stations, 40% have the same month, 40% are modeled 1-month
2 earlier and 20% of stations are modeled 2-months earlier than observations.

3 Comparing observations and modeled output globally, 40% of the locations share the same
4 PM. The model's bias is one of main reasons for this moderate performance; other important
5 contributors include minor high-flow seasons, perpetually wet or dry regions, and
6 anthropogenic effects such as reservoir regulation. Considering a difference of ± 1 month, this
7 jumps to 81%, and 91% for ± 2 months (Figure 7). From a sub-basin perspective, the
8 similarities are even stronger (50% identical PM, 88% ± 1 month and 92% ± 2 month),
9 indicating a relatively high level of agreement. For locations having dissimilar PMs ($\geq \pm 3$
10 months, 9% of locations and 8% of sub-basins), a substantial portion are located downstream
11 of reservoirs directly, such as STA06 in the Zambezi example (Table 4), or are low-flow (dry)
12 or constant-flow locations, both producing exceedingly low PAMF values. Differences in
13 PMs are not unexpected for low-flow and constant-flow locations, given the propensity for the
14 annual streamflow maximum to potentially occur in a wide number of months. Overall,
15 however, as more than 80% of both stations and sub-basins have similar PMs (± 1 month), it
16 appears that the global water balance model performs appropriately well in defining high-flow
17 seasons globally at locations where observations are available.

18 This may be subsequently extended to defining PMs and PAMF at all grid cells (Figure 8).
19 Generally, low and poor PAMF values (0-60%) indicate a naturally unstable annual maximum
20 flow (no clear high-flow season), which occurs in cases of constant-flow, low-flow, bi-modal
21 flow and regulated flow. All cases, except regulated flow, are simulated within the PCR-
22 GLOBWB simulations used, thus the cell-based PAMF values (Figure 8 (b)) can provide a
23 sense of confidence for the defined PM (Figure 8 (a)). Examples of low-flow regions include
24 the central United States and Australia having low PAMF regional values (Figure 8 (b)). Bi-
25 modal regions, such as much of East Africa and Southern South America with their two rainy
26 seasons, and constant-flow regions, such as Europe, also indicate low PAMF values (Figure 8
27 (b)). These flow regimes are further investigated as minor HS in section 5.

28 **4.2 Modeled high-flow seasons versus actual flood records**

29 Model-based PMs may also be verified (subjectively) by surveying historic flood records.
30 One such source is the Dartmouth Flood Observatory (DFO), a large, publically accessible
31 repository of major flood events globally over 1985-2008, based on media and governmental
32 reports and instrumental and remote sensing sources. Delineations of affected areas are best

1 estimates (Brakenridge, 2011). The DFO records provide start time, end time and duration of
2 each flooding event, as defined by the report or source, and represented as occurrence (start
3 month (Figure 9). DFO flood events and grid cell based PMs (Figure 8 (a)) may be compared
4 outright, however their characteristics differ slightly. The DFO covers 1985-2008 while the
5 model represents 1958-2000. Also, the model-based PM represents the month most likely for
6 a flood to occur; the DFO is simply a reporting of when the event did occur, regardless of
7 whether it fell in the expected high-flow season or not. Nevertheless, model-based PMs and
8 historic flood records illustrate similarity (compare Figures 8 (a) and 9), particularly when
9 both the major and minor high flow seasons are considered, further indicating merit in the
10 ability of the proposed approach to identify the PM. Consistently, regions with high model-
11 based PAMF (80-100%), such as Eastern South America, Central Africa and Central Asia,
12 tend to agree well with DFO records, while poor or less than poor PAMF (0-60%) regions,
13 such as Central North America, Europe, and East Africa, tend not to be in agreement with
14 DFO records. In these low PAMF regions, however, DFO records also illustrate floods
15 occurring sporadically throughout the year, further supporting accordance between cell-based
16 PAMF and DFO records (Figures 8 (b) and 9).

17

18 **5 Defining minor high-flow seasons**

19 In some climatic regions, there is no one single, well-defined flood season. For example, East
20 Africa has two rainy seasons, the major season from June to September and the minor season
21 from January to April/May. These two seasons are induced by northward and southward shifts
22 of the inter-tropical convergence zone (ITCZ) (Seleshi and Zanke, 2004). This bi-modal East
23 African pattern allows for potential flooding in either season. In Canada, as another example,
24 the dominant spring snowmelt season (Mar-May) and fall rainy season (Aug-Oct) allow for
25 flood occurrences in either period (Cunderlik and Ouarda, 2009).

26 Previous studies have investigated techniques to differentiate seasonality from uni-, bi- and
27 multi-modal streamflow climatologies and evaluate trends in timing and magnitude of
28 streamflow, including the POT method, directional statistics method, and relative flood
29 frequency method (Cunderlik and Ouarda, 2009; Cunderlik et al., 2004a). These methods may
30 perform well at the local (case-specific) scale to define minor high-flow seasons, however
31 applying them uniformly at the global scale can be problematic, given spatial heterogeneity.
32 Additionally, even though bimodal streamflow climatology may be detected, the magnitude of

1 streamflow in the minor season may or may not be negligible in regards to flooding potential
2 as compared with the major season.

3 To detect noteworthy minor high-flow seasons globally, we classify streamflow regimes by
4 climatology and monthly PAMF value, calculated using Eq. (1) at each month (Figure 10).
5 Classifications include unimodal, bimodal, constant, and low-flow. The unimodal streamflow
6 climatology has high values of PAMF around the PM; the bi-modal classification is
7 represented by two peaks of PAMF (and may therefore contain a minor season); both constant
8 and low-flow classifications represent low values of PAMF between months. Distinguishing
9 between bi-modal and other classifications is nontrivial. For example, initial inspection of the
10 constant streamflow classification (both climatology and monthly PAMF, Figure 10 (c)) could
11 be mistaken for a non-dominant bi-modal distribution. We adopt the following criteria to
12 differentiate bi-modal streamflow from uni-modal, constant, and low-flow conditions.

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

22 A *potential* minor PM is identified by a secondary peak in the monthly PAMF rather than the
23 magnitude or shape of streamflow. A minor HS is not defined when a major PM's PAMF is
24 greater than 80% (minimum of 35 out of 43 annual maximums), indicating a robust uni-modal
25 streamflow character (Figure 10 (a)). The sum of both major and minor PM's PAMF (joint
26 PAMF) is used to determine the likelihood that one of the HSs contains the annual maximum
27 flow; a high value of the joint PAMFs (80-100%) indicates strong likelihood (Figure 10 (b)),
28 moderate values (60-80%) imply moderate likelihood, with some probability of being
29 classified as constant streamflow (Figure 10 (c)); low values (40-60%) are likely constant or
30 low streamflow (Figure 10 (d)). Minor HSs are similar to major HSs, containing the minor
31 PM and the month before and after. Minor HSs are evident in the tropics and sub-tropics and
32 are spatially consistent with bi-modal rainfall regimes discovered by Wang (1994) (Figure

1 11). Examples include East Africa (second rainy season in winter) and Canada (rainfall-
2 dominated runoff in autumn) both having high joint PAMF values (80-100%). Additional
3 examples include the major HS (NDJ) and minor HS (MAM) in Central Africa consistent
4 with the latitudinal movement of the ITCZ, intra-Americas' major HS (ASON) and minor HS
5 (AMJJ) (Chen and Taylor, 2002), and coastal regions of British Columbia in Canada and
6 southern Alaska's minor HS (SOND) due to wintertime migration of the Aleutian low from
7 the central north Pacific (Figure 11). Distinct runoff process controlled by different climate
8 and hydrology systems can induce a bi-modal peak within a large-scale basin, such as the
9 upstream sections of the Yenisey and Lena river systems in Russia where the major HS
10 (AMJ) is dominated by snowmelt and the minor HS (JAS) is spurred on by the Asian
11 monsoon. The same mechanism produces minor HSs around the extents of the Asian summer
12 monsoon (90-100% of sum of PAMFs) (Figure 8 (b) and 11). Moderate minor HSs include,
13 for example, the southern United States' (Texas and Oklahoma) bi-modal rainfall pattern
14 (AMJ and SON) and in the southwestern United States (Arizona) where the summertime
15 major HS (JJA) is produced by the North American monsoon and the wintertime minor HS
16 (DJF) is affected by the regional large-scale low pressure system (Woodhouse, 1997).
17 Southeastern Brazil's summertime major HS (NDJF) and post-summer minor HS (AMJ) are
18 dominated by formation and migration of the South Atlantic Convergence Zone (Herdies,
19 2002; Lima and Satyamurty, 2010). In central and eastern Europe, the major HS (FMAM) and
20 minor HS (JJA) are defined as moderate (60-80% of joint PAMF values for central Europe
21 and 70%-90% for eastern Europe), indicating that a minor HS is not overly pronounced; for
22 northeastern Europe the major HS (MAM) and minor HS (NDJ) contain high joint PAMF
23 values (80%-100%).

24 For the major HS and minor HS with joint PAMF values exceeding 60% (Figure 12), flood
25 records (DFO) occurring over more than one month are counted in each month based on the
26 reported duration. Although one distinct flood event may dominate a monthly DFO record,
27 strong similarity is evident between the HSs and monthly flood records (Figure 12). Minor
28 HSs with high PAMF values corresponding well with observed DFO flood records include
29 East Africa (bi-modal streamflow), the intra-Americas, and Northern Asia; only a few
30 reported flood records occur in the minor HSs in high latitudes.

31

6 Conclusions and Discussion

In this study, a novel approach to defining high-flow seasons globally is presented by identifying temporal patterns of streamflow objectively. Simulations of daily streamflow from the PCR-GLOBWB model are evaluated to define the dominant and minor high-flow seasons globally. In order to consider both peak volume and peak timing, a volume-based threshold technique is applied to define the high-flow season and is subsequently evaluated by the PAMF. To verify model defined high-flow seasons, we compare with observations at both station and sub-basin scales. 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, thus well capturing high flow seasons. When considering anthropogenic effects and bi-modal or perpetually wet/dry flow regions, these results indicate fair agreement between modeled and observed high-flow seasons. Regions expressing bi-modal streamflow climatology are also defined to illustrate potential for noteworthy secondary (minor) high-flow seasons. Model defined major and minor high-flow seasons are additionally found to represent actual flood records from the Dartmouth Flood Observatory, further substantiating the models ability to reproduce the appropriate high-flow season.

Large-scale temporal phenomena associated with the defined major and minor high-flow 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 high-flow 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 high-flow seasons. Specifically, the defined PM (Figure 8 (a)) 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 8 (b)) to represent the reliability of the defined PM. This can provide a clear sense of whether the identified high-flow season is pronounced or vague. The identification of minor high-flow 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 high-flow seasons are also consistent with DFO flood records both spatially and temporally, further substantiating their appropriateness.

1 Although biased simulations may theoretically contribute to a misidentified high-flow season,
2 the global hydrological model's acceptable ability to define high-flow seasons is highlighted
3 in this study. The global hydrological model's ability to define major and minor high-flow
4 seasons at high resolution is highlighted in this study. Although results indicate relatively
5 positive performance overall, regional performance varies spatially. This is advantageous for
6 many reasons, including hydrologic assessment in ungauged and poorly gauged basins and
7 also for investigating flood season timing within large basins having diverse physical
8 processes, for example, how the PM may shift along long rivers (e.g. Congo River) or basins
9 with both snowmelt and rain-dominated processes. These spatially heterogeneous high-flow
10 seasons at high resolution have the potential to better characterize streamflow regimes than
11 previous studies (e.g. [Dettinger and Diaz, 2000](#); [Haines et al., 1988](#)). Additional analysis to
12 include upstream management and regulations is required to further classify global
13 streamflow regimes and major high-flow seasons (or the elimination of them) for specific
14 subbasin-level hydrologic applications.

15

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13

1 Table 1. Cross-correlations of Peak Month (PM) at locations where the PMs differ by at least one classification technique (occurs at 61% of
 2 stations and 54% of associated grids).

Classification Technique		VBT1%	VBT3%	VBT5%	VBT10%	V01%	V03%	V05%	V10%	POT1	POT2	POT3
Observed	VBT1%	1.00										
	VBT3%	0.90	1.00									
	VBT5%	0.85	0.94	1.00								
	VBT10%	0.79	0.86	0.91	1.00							
	V01%	0.82	0.82	0.82	0.81	1.00						
	V03%	0.81	0.84	0.83	0.84	0.89	1.00					
	V05%	0.81	0.85	0.86	0.85	0.86	0.92	1.00				
	V10%	0.80	0.84	0.85	0.87	0.83	0.88	0.96	1.00			
	POT1	0.78	0.78	0.78	0.74	0.76	0.77	0.76	0.74	1.00		
	POT2	0.74	0.78	0.78	0.78	0.80	0.80	0.82	0.81	0.81	1.00	
POT3	0.77	0.81	0.81	0.80	0.80	0.81	0.83	0.81	0.86	0.93	1.00	
Simulated	VBT1%	1.00										
	VBT3%	0.87	1.00									
	VBT5%	0.83	0.95	1.00								
	VBT10%	0.80	0.88	0.90	1.00							
	V01%	0.86	0.85	0.84	0.84	1.00						
	V03%	0.87	0.86	0.85	0.83	0.92	1.00					
	V05%	0.87	0.88	0.85	0.84	0.90	0.97	1.00				
	V10%	0.82	0.87	0.86	0.85	0.83	0.89	0.92	1.00			
	POT1	0.80	0.83	0.83	0.81	0.83	0.86	0.86	0.82	1.00		
	POT2	0.78	0.81	0.80	0.79	0.79	0.83	0.83	0.82	0.92	1.00	
POT3	0.80	0.81	0.79	0.80	0.80	0.83	0.84	0.81	0.92	0.95	1.00	

3

1 Table 2. Average PAMF of each classification technique for modeled and observed where stations having different PMs.

Section	VBT1%	VBT3%	VBT5%	VBT10%	V01%	V03%	V05%	V10%	POT1	POT2	POT3
Observed	60.8%	61.7%	62.0%	62.0%	63.4%	63.6%	63.0%	62.5%	60.8%	59.1%	60.6%
Simulated	63.5%	64.5%	64.7%	63.5%	65.1%	64.8%	64.9%	64.1%	63.1%	60.3%	61.9%

2

1 Table 3. Percentage of stations according to the difference in PMs between modeled and observed streamflow at each classification technique.

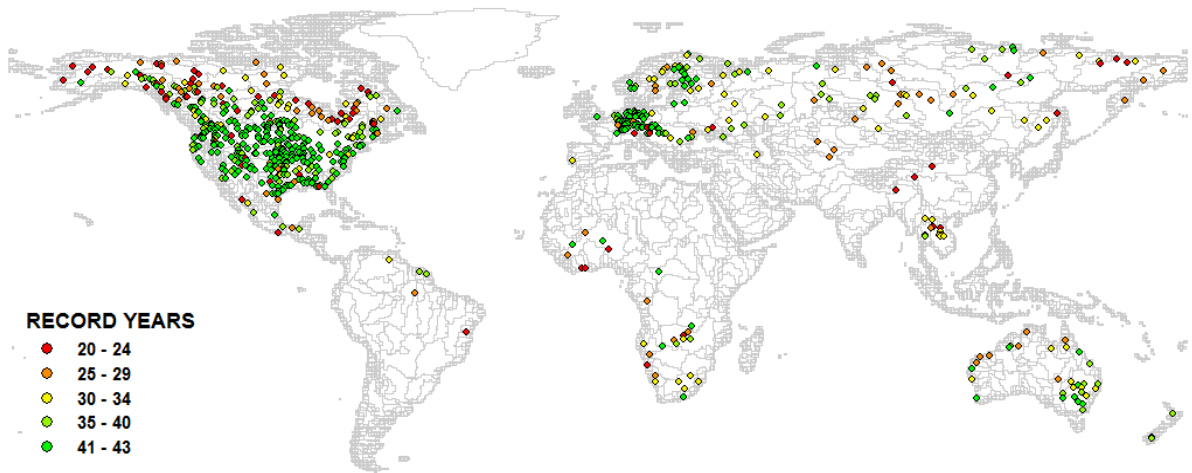
Difference in PMs	VBT1%	VBT3%	VBT5%	VBT10%	V01%	V03%	V05%	V10%	POT1	POT2	POT3
Same	39%	39%	40%	42%	38%	39%	40%	42%	38%	36%	38%
$\leq \pm 1$ month	80%	81%	81%	80%	78%	79%	79%	79%	75%	75%	77%
$\leq \pm 2$ month	90%	91%	91%	90%	89%	90%	89%	89%	87%	87%	88%
$\leq \pm 3$ month	94%	95%	95%	95%	94%	95%	95%	95%	93%	93%	94%

2

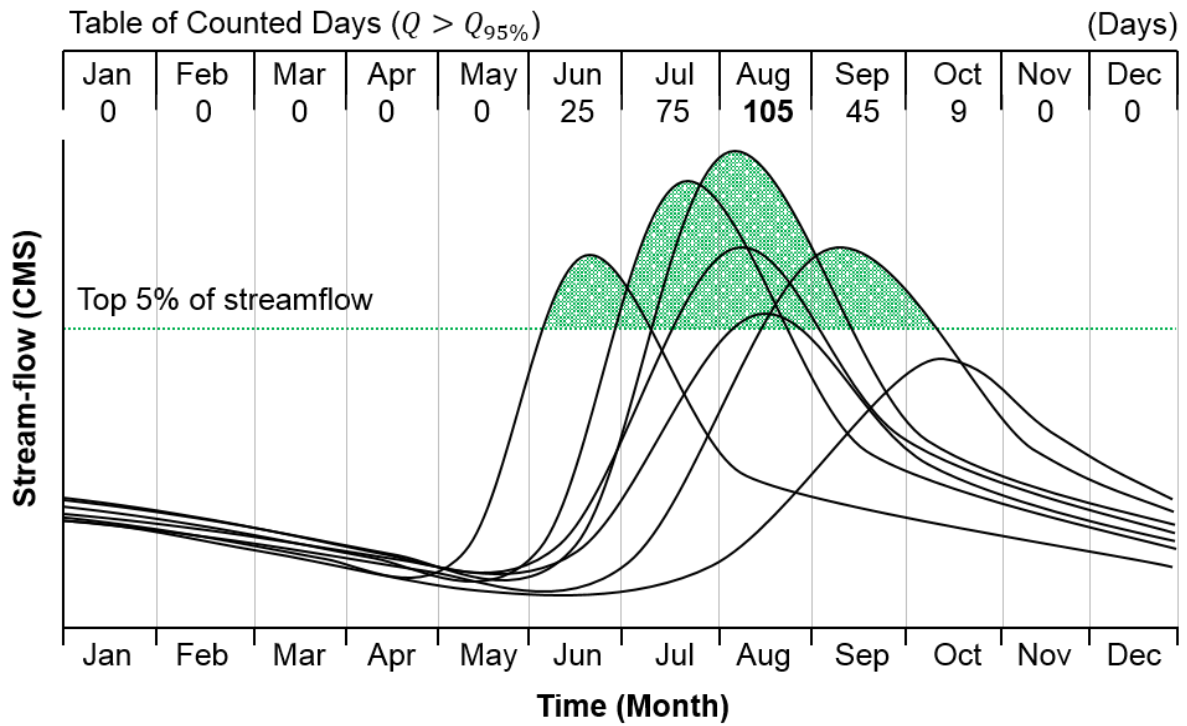
1 Table 4. Comparison of Peak Month (PM) for flooding and calculated P_{AMF} at 6 GRDC stations in the Zambezi River Basin.

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)	PAMF (%)	PM (month)	PAMF (%)	PM (month)	PAMF (%)	PM (month)	PAMF (%)	PM (month)	PAMF (%)	PM (month)	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

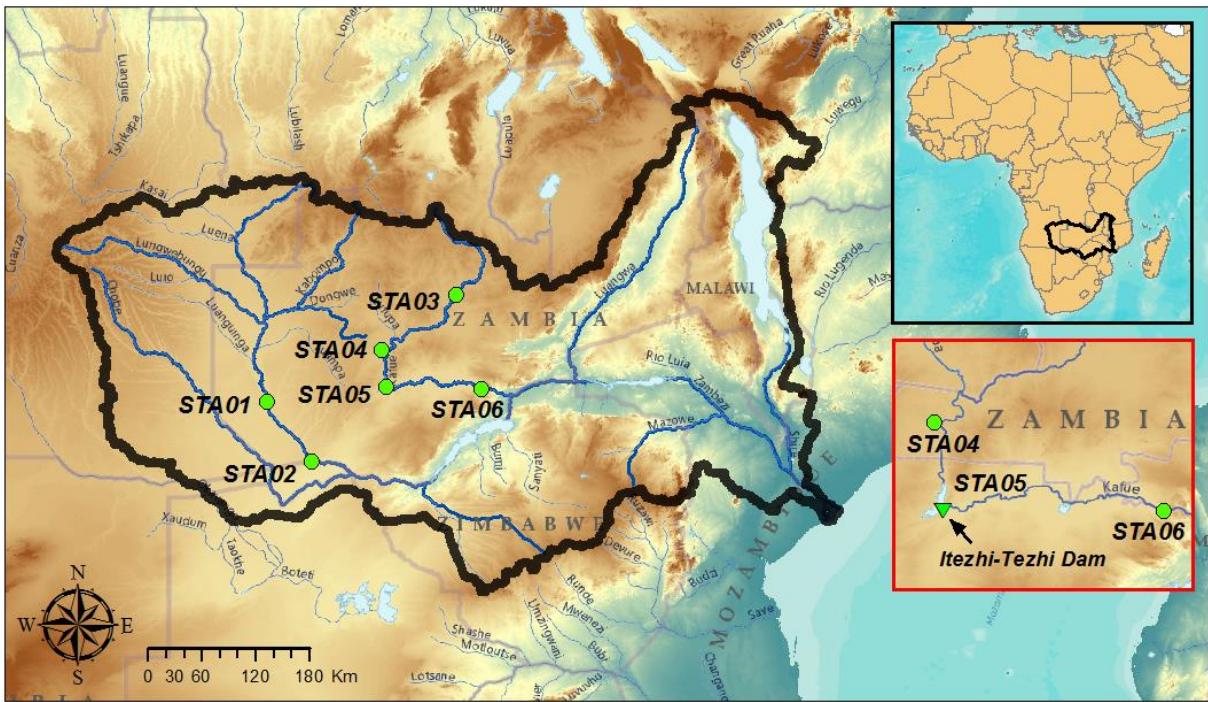
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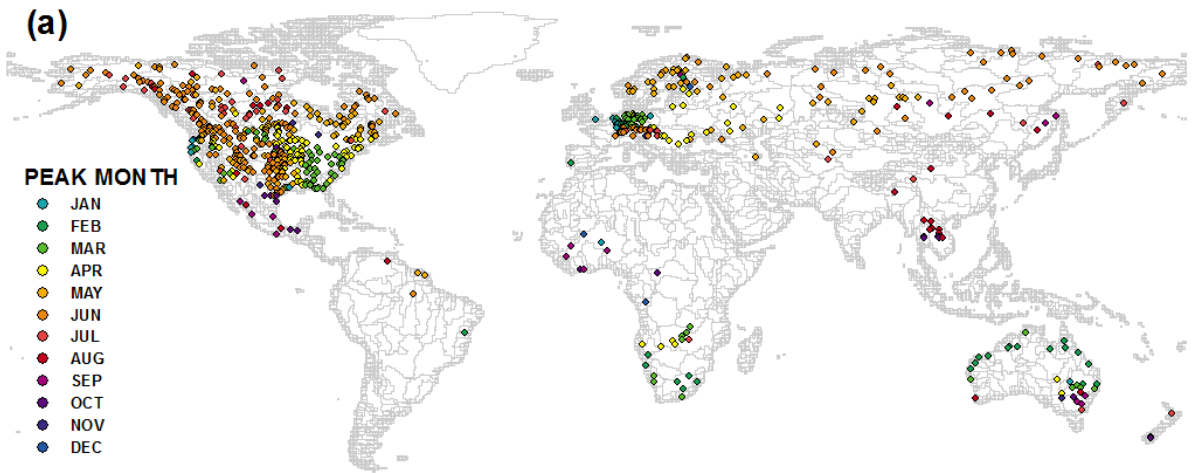
1
2 Figure 1. Location of 691 selected GRDC stations with corresponding number of years per
3 station. Background polygons are world sub-basins based on 30' drainage direction maps
4 ([Döll and Lehner, 2002](#)) with separation of large basins ([Ward et al., 2014](#)).



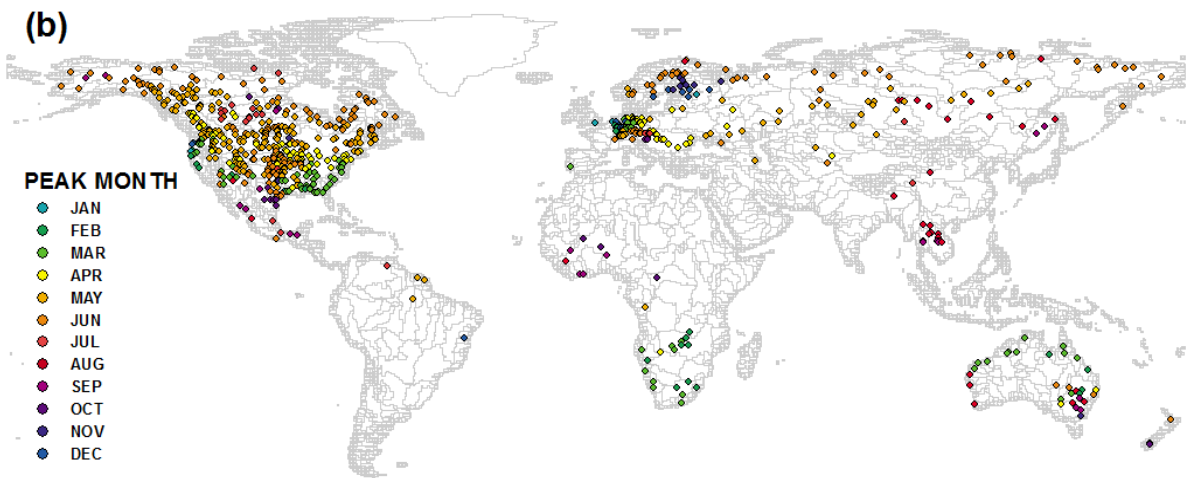
- 1
- 2 Figure 2. Seven years of synthetic streamflow data. Dotted line represents the 5% streamflow threshold. Numbers indicates the total days above the threshold for each month.
- 3



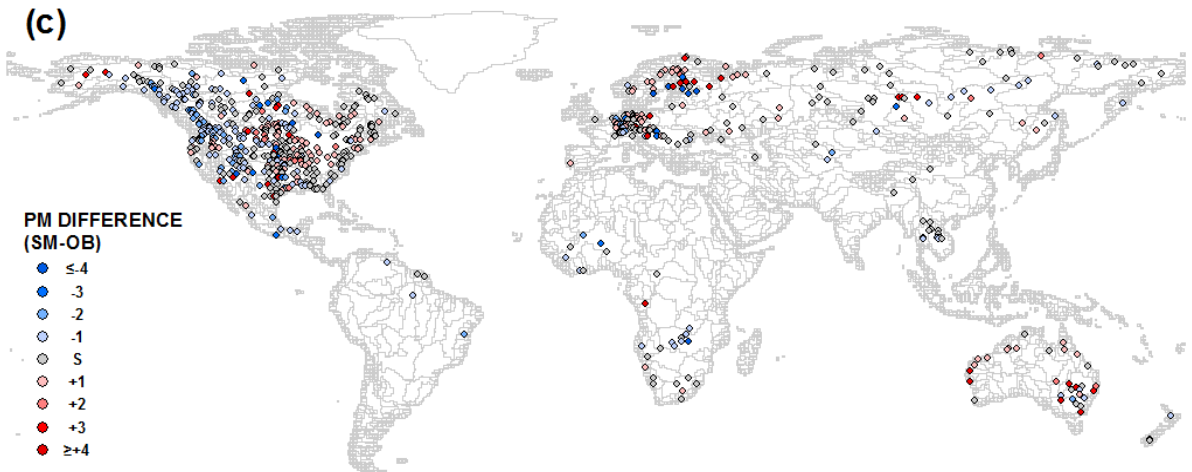
1
 2 Figure 3. Map of Zambezi River Basin; the solid black line delineates the basin and the green
 3 points are the 6 GRDC stations (STA01-06), with STA06 downstream of the Itezhi-Tezhi dam
 4 (STA05).



1

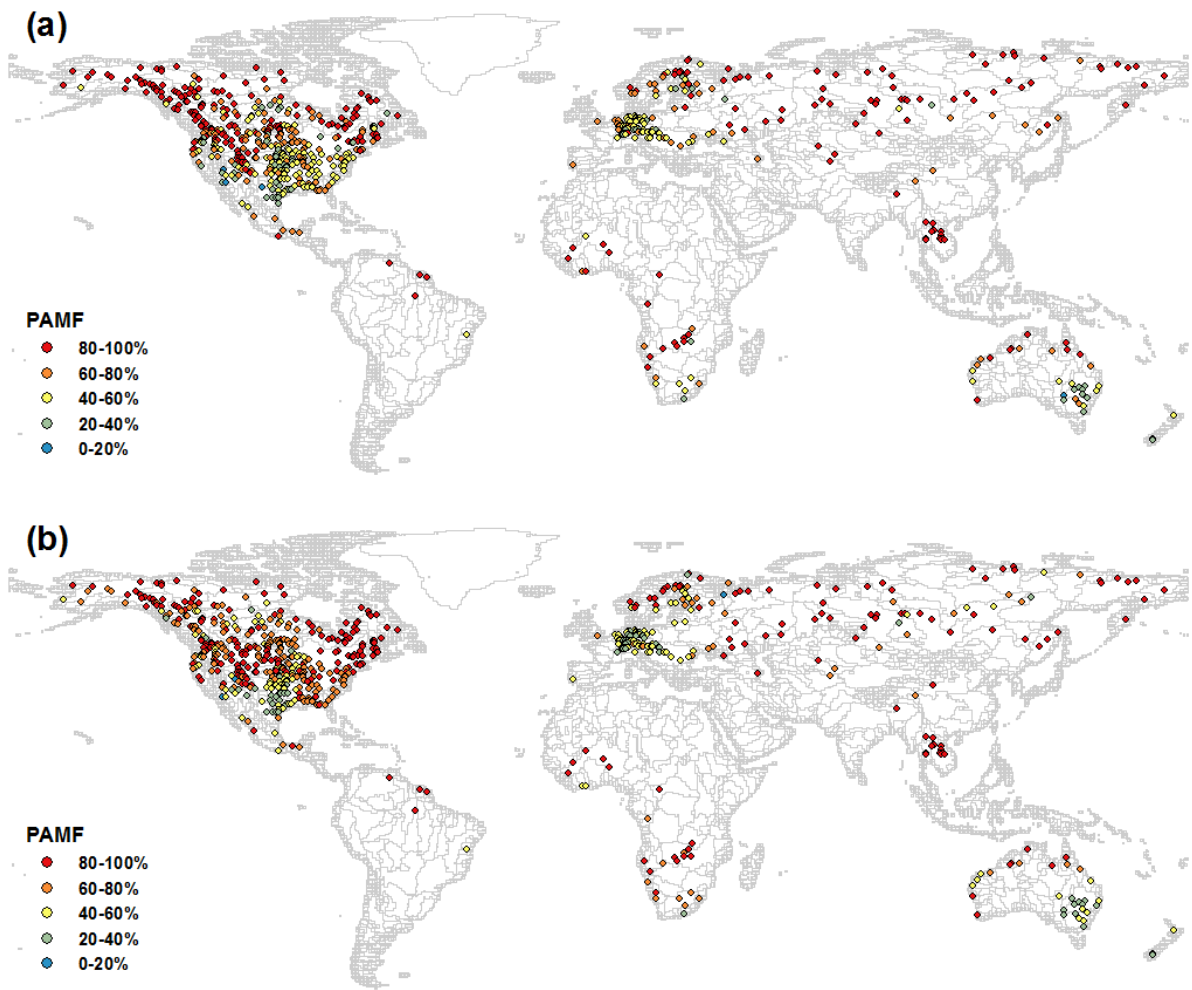


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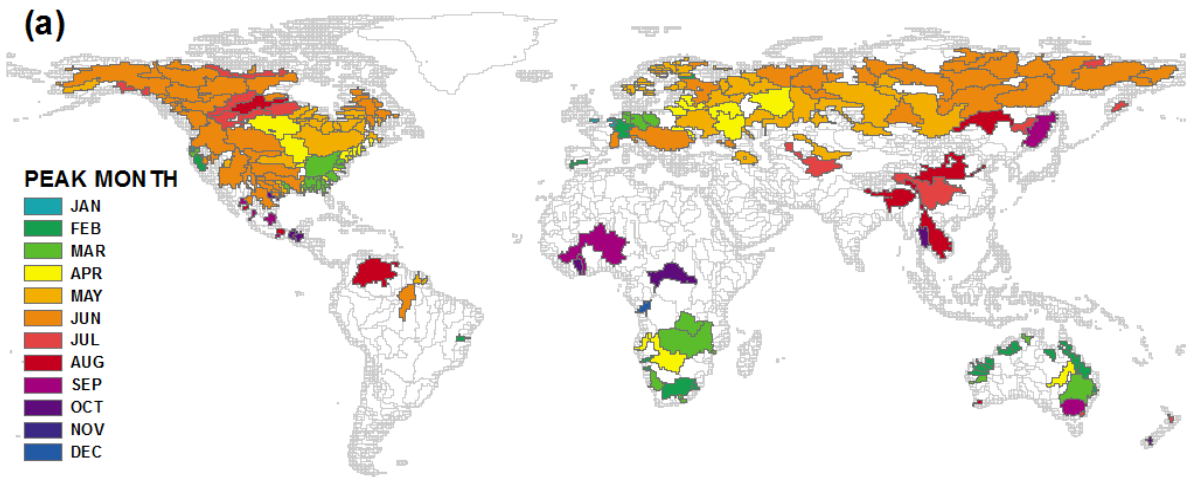


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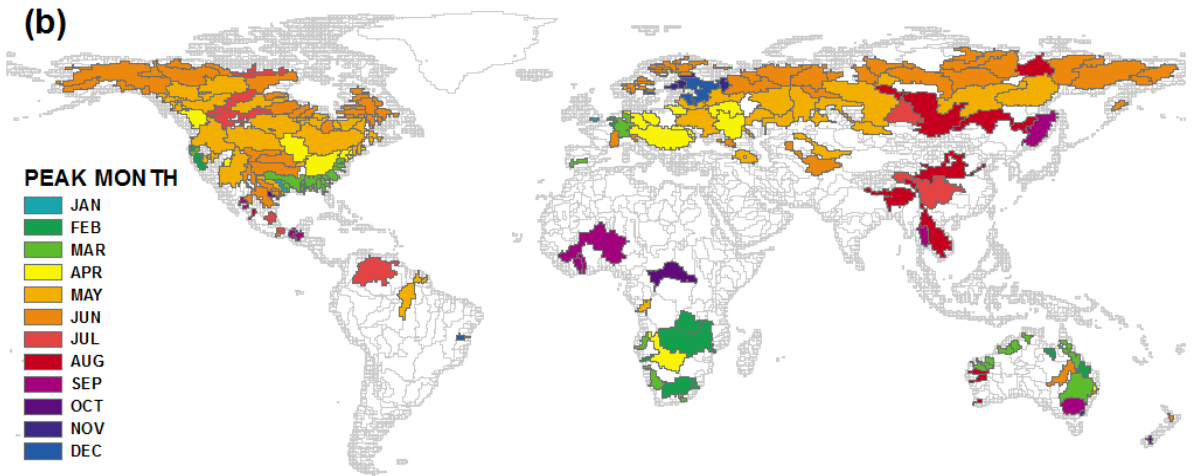
4 Figure 4. Peak Month (PM) for flooding as defined by (a) 691 GRDC observation stations, (b)
 5 simulated streamflow at associated locations and (c) Temporal difference in PM between
 6 observations and simulation (simulation-observation, in number of months; negative
 7 (positive) value indicates that the simulated PM is earlier (later) than the observed PM).



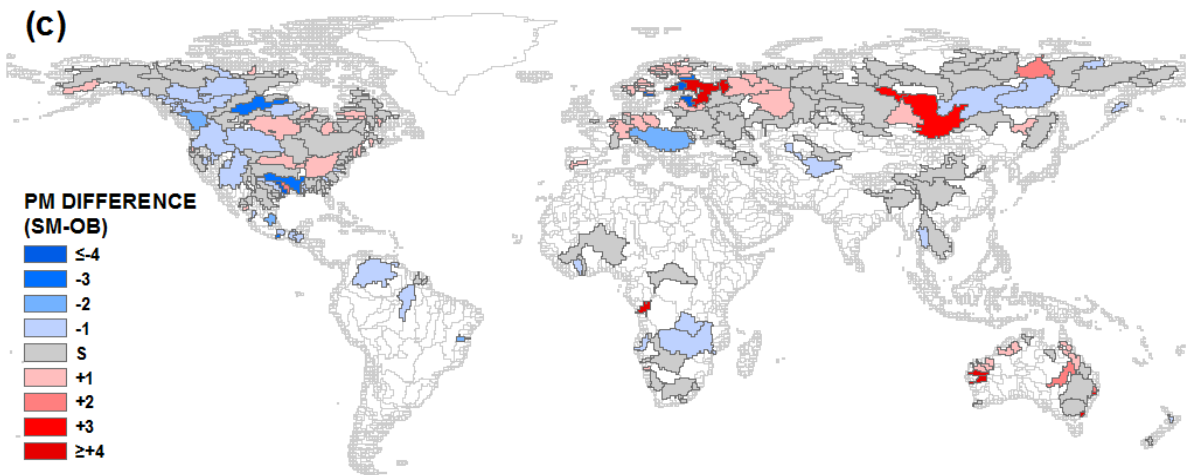
2
 3 Figure 5. Calculated Percentage of Annual Maximum Flow (PAMF) values for (a) 691 GRDC
 4 observation stations, and (b) simulated streamflow at associated locations; subjectively
 5 classified as high = 80-100%, moderate = 60-80%, low = 40-60%, and poor = 0-40%.



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4 Figure 6. Peak Month (PM) for flooding by sub-basin as defined by (a) 691 GRDC
 5 observation stations, (b) simulated streamflow at associated sub-basins and (c) Temporal
 6 difference in PM between observations and simulation (simulation-observation, in number of
 7 months; negative (positive) value indicates that the simulated PM is earlier (later) than the
 8 observed PM).

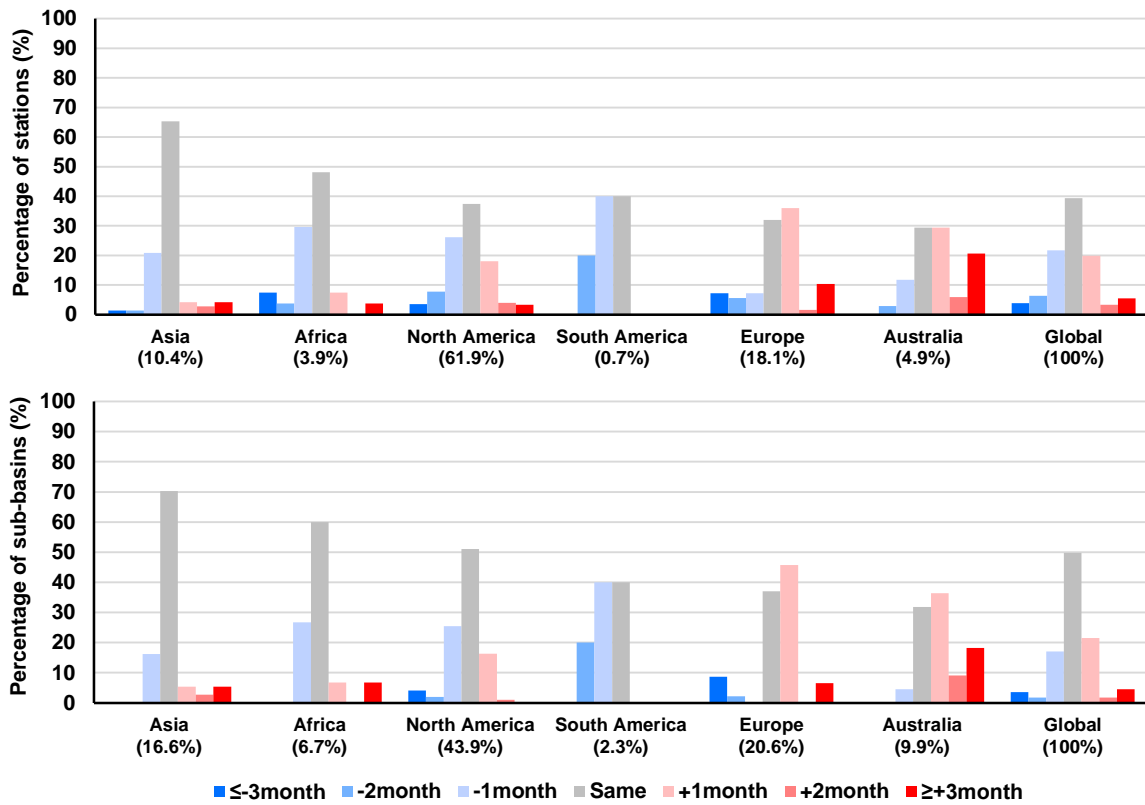
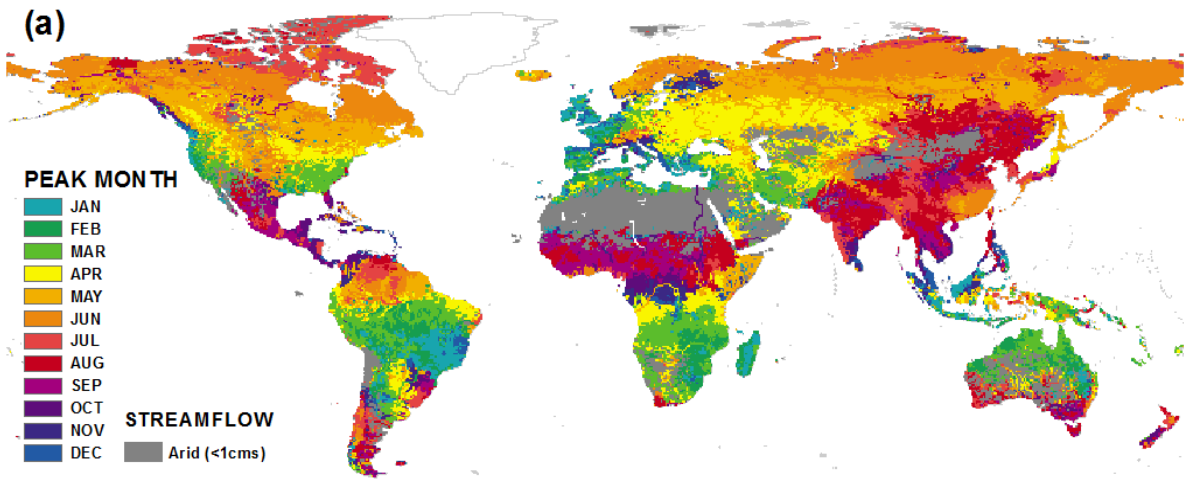
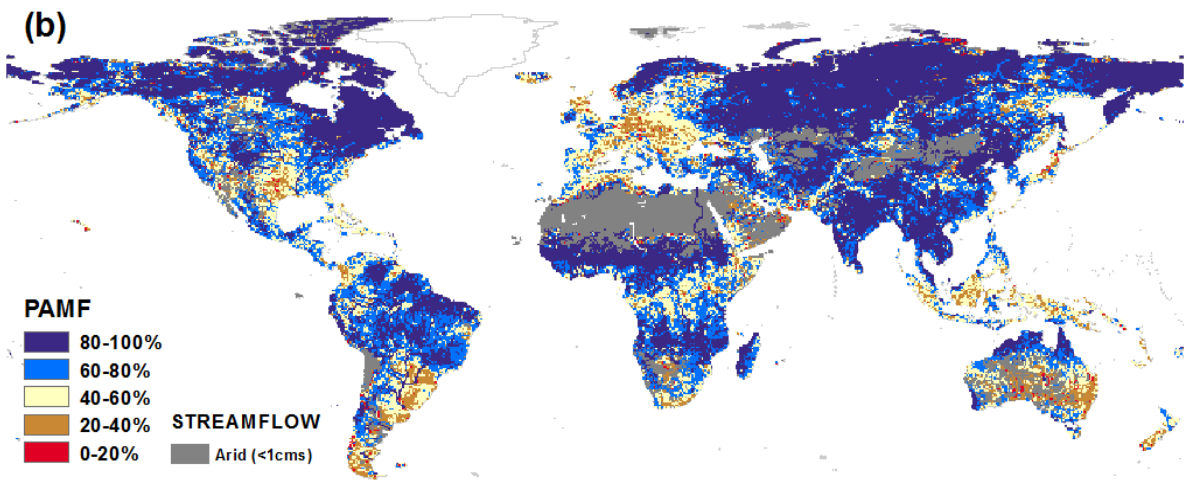


Figure 7. Percentage of stations (above) and sub-basins (below) according to temporal difference of PM between observations and model outputs (SM-OB, number of months) in each continent.



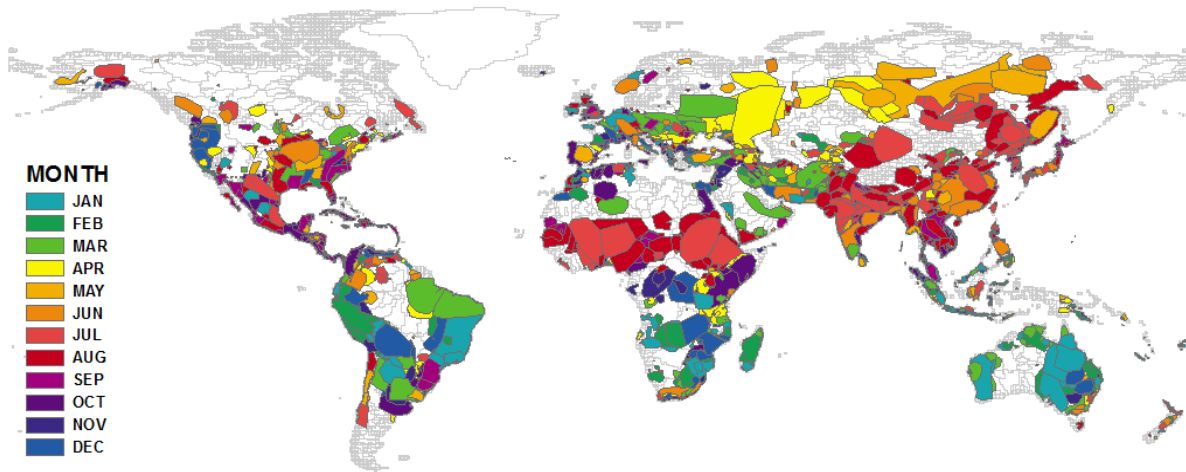
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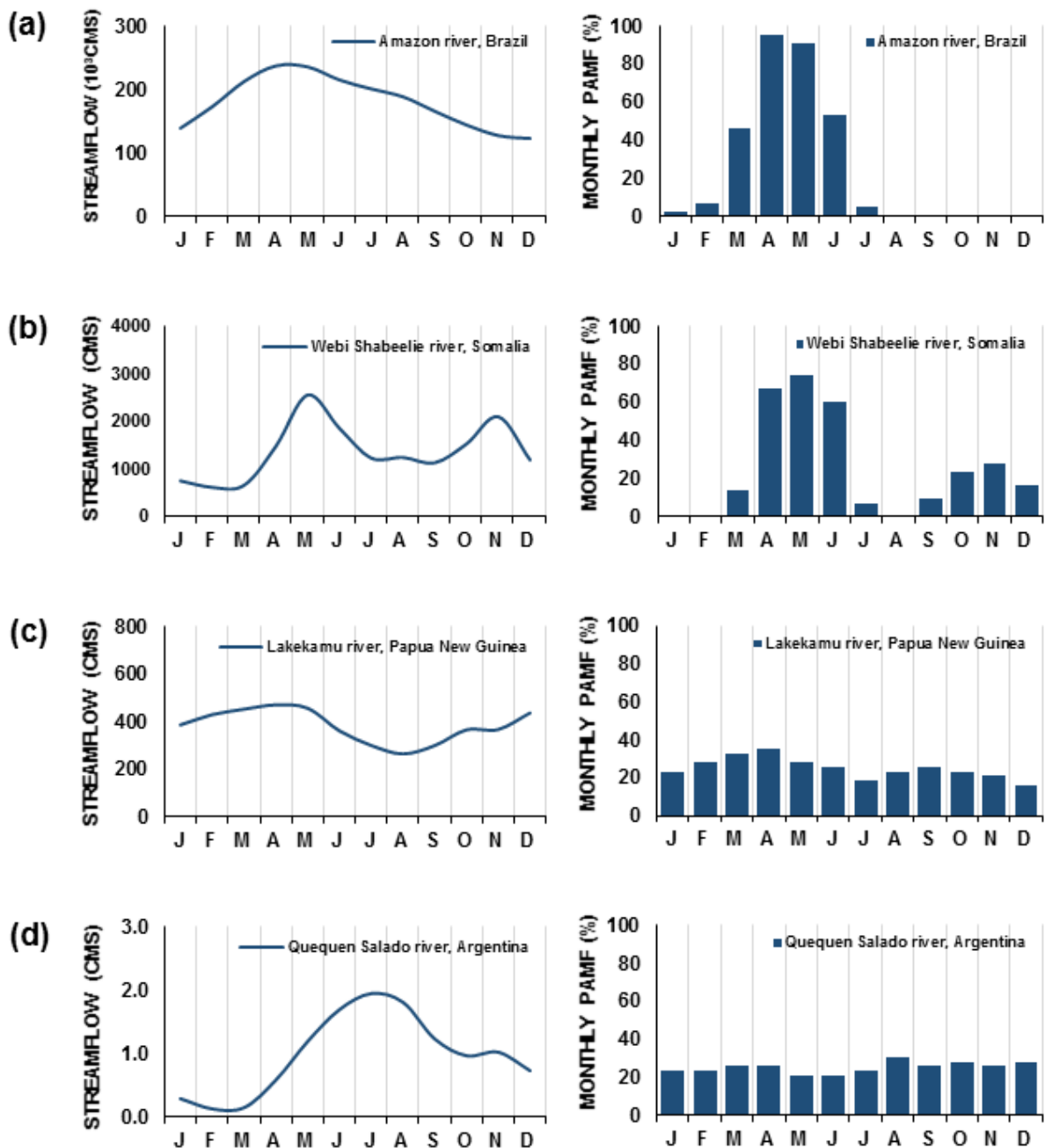
2

3 Figure 8. (a) Peak Month (PM) as defined at all modeled grid cells (b) Calculated Percentage
 4 of Annual Maximum Flow (PAMF) values for at all modeled grid cells; subjectively
 5 classified as high = 80-100%, moderate = 60-80%, low = 40-60% and poor = 0-40%.

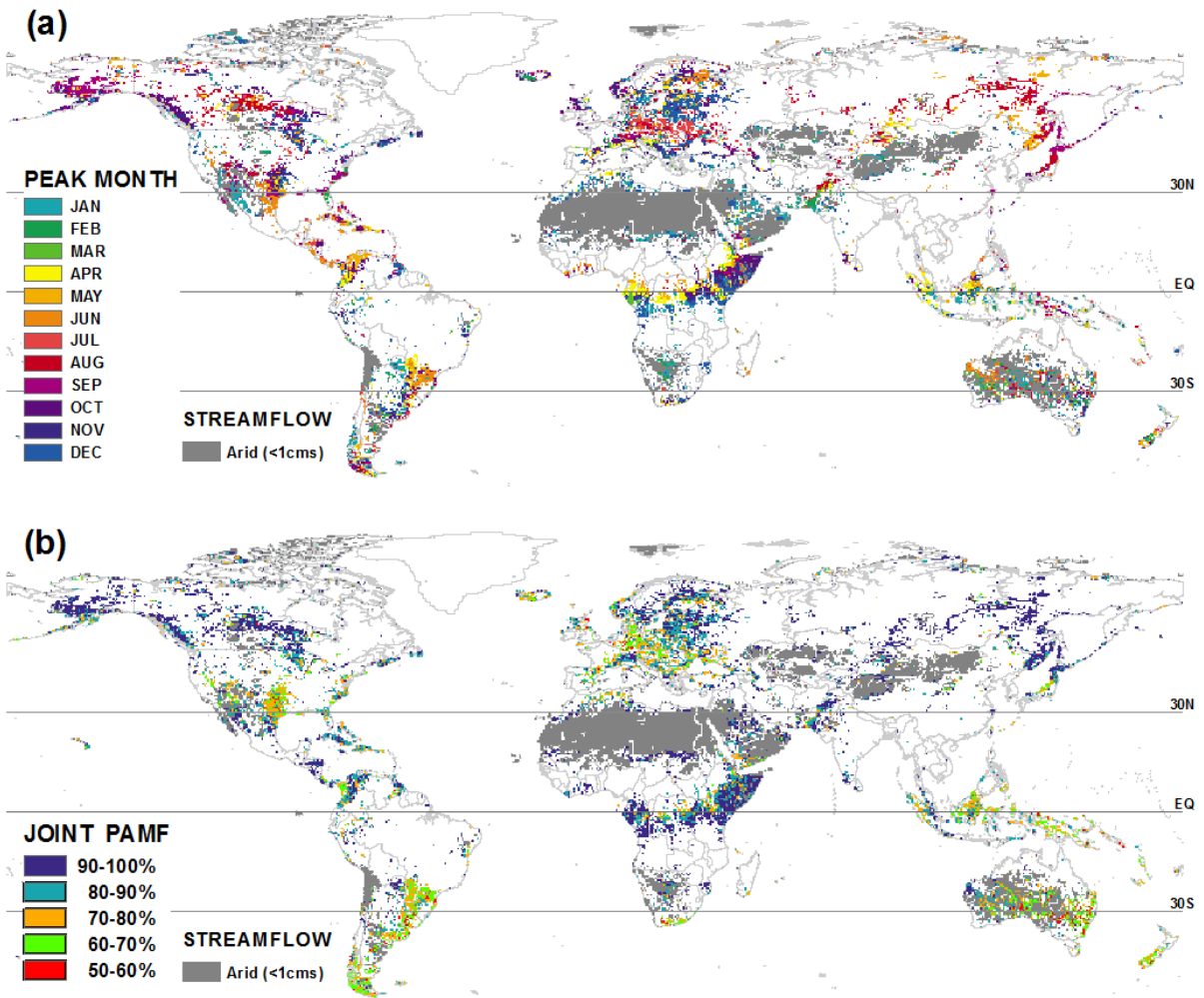
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2 Figure 9. Occurrence (start) months of 3,486 events from 'Global Active Archive of Large
3 Flood Events' from the Dartmouth Flood Observatory (DFO) over 1985-2008 ([Brakenridge,](#)
4 [2011](#)); polygons indicate the estimated spatial extent, colors represent the start month, with
5 most recent events in time layered on top.



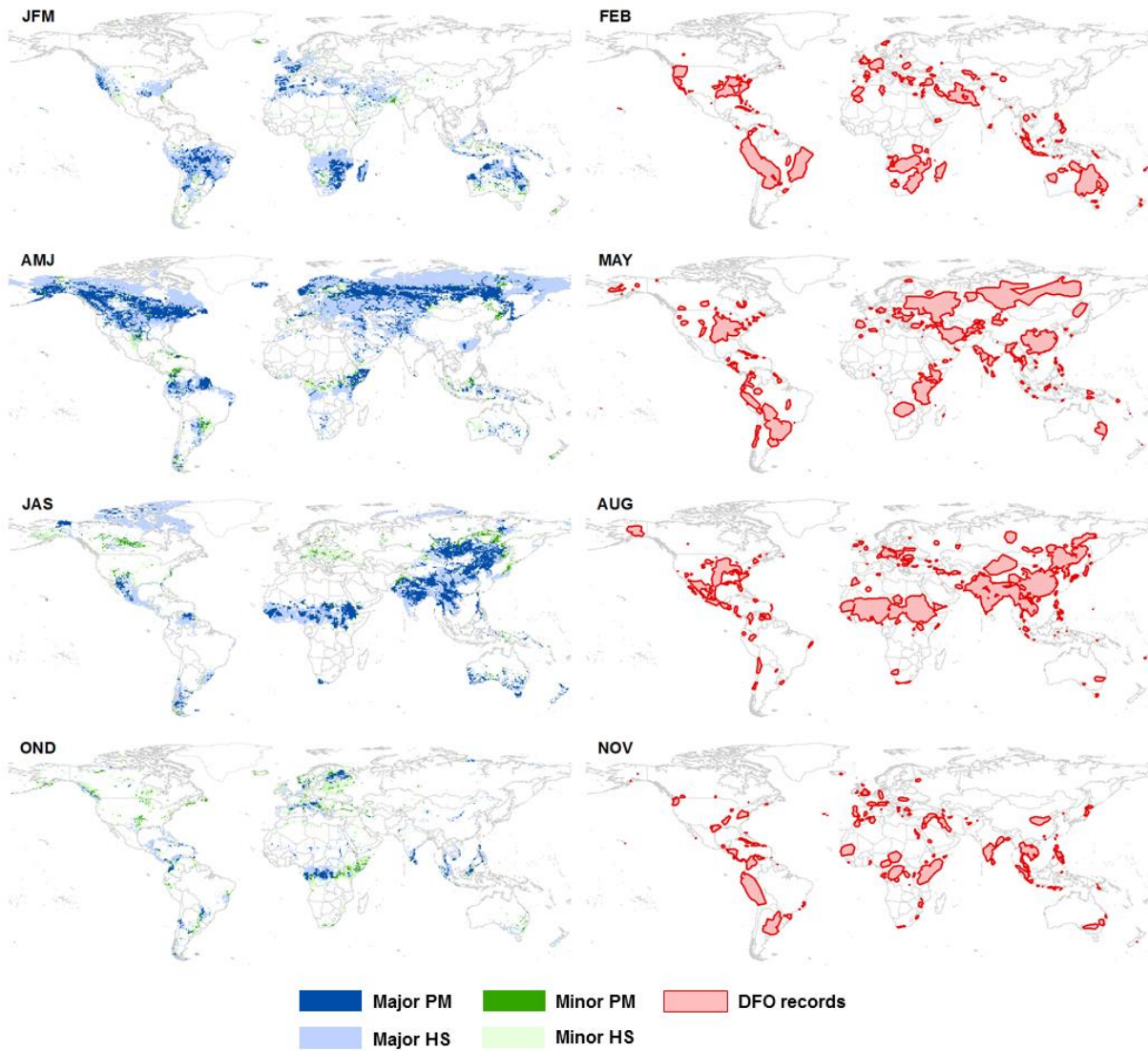
1
2 Figure 10. Model-based streamflow climatology (left) and corresponding monthly PAMF
3 (right). Types and locations are: a) uni-modal streamflow – At Bom Lugar, Amazon river,
4 Brazil, b) bimodal streamflow – At Saacow, Webi Shabeelie river, Somalia, c) constant
5 streamflow – At Terapo Mission, Lakekamu river, Papua New Guinea and d) low-flow – At
6 La Sortija, Quequen Salado river, Argentina.



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3 Figure 11. (a) Minor Peak Month (PM) for flooding as defined at detected grid cells and (b)
 4 joint PAMFs of major and minor PMs at corresponding cells; subjectively classified as high =
 5 80-100%, moderate = 60-80%, and low = 40-60%.



1
 2 Figure 12. Defined major HS and minor HS where joint PAMF is greater than 60% (left);
 3 peak month of major and minor HSs (dense color) and pre- and post-month of major and
 4 minor HSs (light color). Monthly accumulated actual flood records (DFO) during 1958-2008
 5 (right).