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Recent Trends in Frequency and Duration of Global Floods

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Abstract. Frequency and duration of flood events are analyzed using Dartmouth Flood Observatory's (DFO) global flood database to detect significant trends and regime shifts during 1985-2015 at global and latitudinal scales. Three classes of flood duration (i.e. short: 1-7, moderate: 8-20, and long: 21 days and above) are also considered for this analysis. The non-parametric Mann-Kendall trend test and Pettitt change-point analysis are used to evaluate three hypotheses (H1, H2, and H3) addressing potential monotonic trends and regime shifts in flood frequency, moments of the duration, and the frequency of a specific flood duration type. The results show that long duration flood frequency has increased across most spatial scales with significant change-point observed in the 2000s. In the tropics, floods have increased four-fold since the 2000s. This increase is 2.5 fold in the north mid-latitudes. There is no monotonic trend in the frequency of short duration floods across all global and latitudinal scales. There is also a significant increasing trend in the annual median and tails of flood durations globally and in each latitudinal belt. The possible causes of these trends are analyzed using a Generalized Linear Model framework and also discussed qualitatively. This analysis provides the framework for understanding simultaneously changing climate and socioeconomic conditions and how they relate to the frequency and persistence in the organization of global and local dynamical systems that cause hydrologic extremes.

1 Introduction

Higher levels of spatiotemporal vulnerabilities to climate-related extreme events are becoming a "new normal" in both developing and developed countries. At the same time, there is rapidly growing population, assets and expanding residential/commercial sectors that are susceptible to damages due to extremes (Mirza, 2003; Thomalla et al., 2006; Hallegatte et al., 2013; Singh and Zommers, 2014). Recent studies by Di Baldassarre et al. (2010) and Vogel et al. (2011) in Africa and the United States showed that there had been a considerable change in the flood frequency and magnitude in regions which have undergone intense urbanization. While the fatalities from the flood events have substantially decreased in recent decades mainly due to improved flood early warning systems and better flood control infrastructure, statistics still point out that more people are (in)directly being affected by the flood events (EM-DAT, 2016). These impacts include various deteriorations of social services, economic disruptions and health-related consequences of population displacement (i.e. disturbances in food supply chain, under nutrition, water/vector-borne diseases, and being injured, displaced or left homeless) (Schultz, 2006; Milojevic et al., 2011; Lowe et al., 2013). A recent example was the unusual increase in bacillary dysentery risk in Baise (Guangxi Province, China) during the years 2004 to 2012 due to frequent occurrences of flood events during the period (see more details in Liu et al. (2017)). Similar examples of the impact of recurrent events can be drawn from recent Thailand floods that caused severe supply chain disruptions (Ziegler et al., 2012; Haraguchi and Lall, 2015; Promchote et al., 2016). This research on long duration floods has gained much interest in the recent times (Robertson et al., 2011; Nakamura et al., 2013; Ward et al., 2015; Najibi et al., 2017). An important issue in this context is whether we understand the nature, i.e. the frequency and recent trends and the physical causes of such recurrent floods that may be associated with repeated rainfall into the region. Understanding these trends can help in better management of flood control infrastructure and global supply chain.

Global and near-daily observations from the Earth's surface are now available using the satellite microwave sensors (passive/active) which can be employed to measure the changes of water surfaces (e.g. river discharge and watershed runoff) (Brakenridge et al., 2007). The utilization of such information with even limited ground-based discharge data can allow mapping of the inundation extents caused by flood events at many locations around the world. This has particular advantage in understanding the flood impacts in developing nations where there is lack of sufficient in-situ measurements (Brakenridge et al., 2007; Van Dijk et al., 2016; Brakenridge et al., 2016). In this study, we provide a first global scale analysis of the recent trends in the frequency and the probability distribution of the duration of floods observed around the world from these satellites. 31 years (from 1985 to 2015) of global flood data are now available which makes it possible to perform a variety of statistical analyses. The frequency of floods and its statistics can vary substantially, depending on the geomorphological features and climate-related factors such as flash floods, long-rain floods, short-rain floods, rain-on-snow floods, and snowmelt floods (Merz and Blöschl, 2003). Till date, little is known about the possible temporal changes in the probability distribution of flood duration at global and latitudinal scales. This led us to exploring the global active archive of flood events to address these four questions:

1. How has the annual frequency of floods changed at the global scale and various latitudinal belts during the last three decades?
2. How has the probability distribution of flood duration (i.e. the moments and extreme values) changed at the global scale and various latitudinal belts during the last three decades?
3. Can the changes (if any) in the frequency and the probability distribution be attributed to changes in specific flood classes, i.e. short, moderate or long duration and to multi-scale climate and atmospheric factors?
4. Which countries are most susceptible to short, moderate and long duration floods?

We tried to address each question using a formal hypothesis testing framework and mainly focused on detecting changes in the frequency and probability distribution of floods globally, along with attributing them to potential causal factors. We consider that floods (especially the long duration floods) are caused by a systematic organization of the global and local dynamical systems. Understanding the temporal trends (regime like behavior) will help us to understand better, the frequency and persistence in the organization of these dynamical systems. This will ultimately lead to an exploration of the predictability of such states using the Lyapunov exponents (Abarbanel and Lall, 1996; Karamperidou et al., 2014; Perdigão and Blöschl, 2015). Together, the characterization of the trends and the predictability of these extremes will allow us to better understand the potential implications of climate change, and also of whether or not a regional persistent flood regime is likely to end or continue.

Section 2 provides the details on global flood data, hypotheses and employed methodology for this study. In Section 3, we present the results of the hypothesis tests. In Section 4, we discuss the potential causes through a quantitative and qualitative verification of observed trends using a Generalized Linear Modeling framework and extensive supporting literature. Finally, in Section 5, we present the conclusions of the study.

2 Data, Hypotheses, and Methodology

2.1 Global active archive of flood events: Dartmouth Flood Observatory (DFO)

A comprehensive record of flood events is available in Dartmouth Flood Observatory (DFO) which was initially founded in 1993 at Dartmouth College, NH, United States. In 2010, the observatory moved to the Community Surface Dynamics Modeling System (CSDMS) (http://csdms.colorado.edu/) as a division of Institute of Arctic and Alpine Research (INSTAAR) at University of Colorado, CO, United States (Brakenridge, 2010). Information in this archive is based on the instrumental measurements, and remote sensing sensors, in addition to the official reported flood details by the news agencies and governmental statements (Brakenridge et al., 2016). However, DFO mostly takes advantage of orbital remote sensing sensors to identify, measure and monitor the global flood events by

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gathering globally consistent information on surface water changes, in particular since 1999. Specifically, DFO utilizes the MODIS (Moderate-resolution Imaging Spectroradiometer) sensors (approximately 250-m pixels) for flood detection and satellite microwave data such as AMSR-E (Advanced Microwave Scanning Radiometer for EOS -Earth Observation System- from Global Change Observation Mission-Water (GCOM-W)) for measuring the river discharge in addition to available surface discharge observations. The discharge values and runoff coefficients are then calculated from the Water Balance Model (WBM) embedded with the specific soil type, surface gradient, and permeability, and land use/land cover (LULC) characteristics.

The remote sensing and model outputs are employed to frequently map the potential land surface's inundation extents. Then, an archive flood number is assigned if a) that is unusually "large" compared to the typical annual high water and previously mapped water-land extents, and/or b) if there are large damages caused to structures, extensive land inundation, and fatalities (Brakenridge et al., 2016).

The dataset covers the land flood events at global scale starting from January 1, 1985 to present (any recent flood event is immediately going to be added to the data archive). Here, we considered 31 years of global flood events from January 1, 1985 to December 31, 2015. This comprehensive dataset includes adequate information typically on the location of a flood event (longitude, latitude, and name of country), flood begin/end date, and flood duration.

2.2 Aggregating floods on the basis of the latitudinal belts

The flood events are spatially aggregated to five climate zones - mid-latitudes (Northern hemisphere: 35 ºN-55 ºN and Southern hemisphere: 35 ºS-55 ºS), subtropics (Northern hemisphere: 23.5 ºN-35 ºN and Southern hemisphere: 23.5 ºS-35 ºS) and tropics (23.5 ºS to 23.5 ºN), as suggested by Env (2016). This aggregation along the latitudinal belts will yield more consistency given its relation to the global circulation dynamics, temperature variabilities and precipitation patterns (Gabler et al., 2008). Fig. 1 represents the schematic of the five climate zones. We also show four countries (USA, China, India, and Thailand) that have high flood frequency.

FIGURE 1

Next, for each latitudinal belt, the total number of flood events per year (calendar year from January 1 to December 31), the duration of these floods and location (name of country) are processed. This procedure is formulated as follows:

$$F_C^{t,r} = \text{Total number of flood event(s) in latitudinal belt r and year t} \quad (1)$$

$$\boldsymbol{F_D^{t,r}} = \text{Duration(s) of flood event(s) in latitudinal belt r and year t } [\mathrm{day(s)}] \quad (2)$$

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$$\boldsymbol{F_L^{t,r}} = \text{Location(s) of flood event(s) in latitudinal belt r and year t [name of country(ies)]} \quad (3)$$

where F_C indicates the flood counts (frequency), $\mathbf{F_D}$ indicates the distribution of flood duration, and $\mathbf{F_L}$ indicates the distribution of flood location. The superscripts r and t denote the latitudinal belt (r= {global, tropics, mid-latitudes (N and S), subtropics (N and S)}), and year (t= {1985, 1986,. . . , 2015}).

In addition, the number of floods in each latitudinal belt are also categorized in terms of *duration*. We denote the short duration flood as $F_{C_\mathrm{S}}^{t,r}$ if the duration is between 1 and 7 days; moderate duration floods as $F_{C_\mathrm{M}}^{t,r}$ if the duration is between 8 and 21 days; and long duration floods as $F_{C_\mathrm{L}}^{t,r}$ if the duration is greater than 21 days. These categories are also consistent with the DFO's flood classification (Brakenridge, 2010). The subscripts S, M and L stand for *Short*, *Moderate* and *Long* duration flood event, and the rest of variables appeared here are already introduced in Equation 1-3.

2.3 ENSO and NCEP/NCAR reanalysis data

To investigate the association of large-scale ocean-atmospheric signals with the trends in the flood data, 31-year anomalies of El Niño–Southern Oscillation (ENSO) are calculated from the monthly time series of Niño 3.4. These values are originally related to the sea surface temperature of an averaged area bounded in 5 ºS-5 ºN and 170 ºW-120 ºW from HadISST1 dataset (Rayner et al., 2003). Furthermore, yearly geopotential height (GPH) and precipitable water content (PWC) are aggregated from the monthly GPH (at 500-mb level) and PWC values from January 1985 to December 2015 respectively. These data are obtained from the NCEP/NCAR reanalysis database (Kalnay et al., 1996; Kistler et al., 2001) with 2.5°×2.5° spatial resolution provided by the Earth System Research Laboratory in Physical Sciences Division of National Oceanic and Atmospheric Administration (NOAA) (https://www.esrl.noaa.gov/psd/). Given that our analysis is at different latitudinal scales, we further aggregated the yearly GPH and PWC data to get a separate time series for global scale and each latitudinal belt (i.e. tropics, subtropics (N), subtropics (S), mid-latitudes (N), and mid-latitudes (S)).

2.4 Hypotheses

Most of the global precipitation studies indicate that there is an increase in recent patterns of precipitation and extreme rainfall intensities (Solomon, 2007; Zhou et al., 2013). Consequently, our goal here is to investigate whether we see a significant trend and noticeable regime shifts in the frequency and duration of floods. The main hypotheses (**H1**, **H2**, and **H3**) and the evaluation procedure are presented in Table 1. We begin our investigation with H1, the hypothesis that there is no monotonic trend in the annual frequency of the flood events. We test this hypothesis using the Mann-Kendall trend test (Mann, 1945). With H2, we are exploring whether there is a change in the probability distribution of the flood duration over time. We test this hypothesis by applying the Mann-Kendall

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trend test on the three resistance moments, median, median absolute deviation, and skewness of the annual distribution of flood duration as well as extreme flood durations. Hypothesis H3 is defined to take into account, the changes in the patterns of flood frequencies for each category, short, moderate and long duration floods.

TABLE 1

3 Results

3.1 Addressing H1: Trends in the annual frequency of flood events

Mann-Kendall (MK) test (Equation A1-A3) is applied to each time series of F_C (i.e. global, tropics, mid-latitudes (N), mid-latitudes (S), subtropics (N) and subtropics (S)) for detection of monotonic trends. The MK test is based on ranks and assumes no underlying probability distribution for the data (Helsel and Hirsch, 1992). The test statistic is based on the pairwise comparison between the values and is independent of the distribution of the original series. The magnitude of the slope of the trend is estimated using the method of Sen, the median of the pairwise slopes between the elements of the series (Sen, 1968). Statistical significance is evaluated at a 5% significance level (i.e. the probability of incorrectly rejecting the null hypothesis). Besides, a test for possible regime change in the distribution of F_C time series is accomplished through the change-point analysis based on nonparametric Pettitt method, given by Equation B1. Figure 2 presents the F_C time series for the global scale and the five latitudinal zones. A LOESS (LOcal regrESSion) curve (shown only if the trend is significant) and the location of change-point is also indicated. The detailed statistics derived from the trend and change-point analyses are given in Table 2.

FIGURE 2

TABLE 2

A total of 4311 flood events occurred during last three decades worldwide. The outputs of MK test on the annual frequency of global floods indicate that there is a statistically significant monotonic trend with τ (Kendall correlation coefficient between F_C and time) and β (robust Sen Slope) values of 0.26 and 2.12, respectively. A total of 2020 events (out of 4311 flood events) occurred across the tropics. The hypothesis that there is no trend in the frequency of floods in the tropics is also rejected. This is also the case for both subtropics (S) and mid-latitudes (S). The hypothesis that there is no monotonic trend in the annual frequency of flood events could not be rejected for subtopics (N) and mid-latitudes (N). Change-point analysis of these data indicates that for all regions (except the subtropics (N) region), significant change occurred between the years 1995 to 2001, as explicitly annotated in the F_C time series in Figure 2.

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- **H1**: The frequency of flood events has increased at the global scale, tropics, subtropics (S), and mid-latitudes (S). Furthermore, a significant change is detected between the years 1995 and 2001 with a maximum number of flood events occurring around the year 2005 across all spatial scales.

3.2 Addressing H2: Trends in distribution of flood durations

In addition to the frequency of flood events, we attempt to take into account, a set of the "resistant measures" to detect any significant monotonic trend and change-point in the probability distribution of flood duration over the years. This evaluation strategy investigates for the existence of a trend in the moments of the distribution of flood duration. Four indicators are selected because of their scale-invariant characteristics suitable for such asymmetrical distributions. For each of the six spatial scales (global, tropics, mid-latitudes (N), mid-latitudes (S), subtropics (N), subtropics (S)), we derived four sets of time series. These include the median, median absolute deviation (MAD), resistant skewness, and the 90th percentile of the flood durations per year. Note that the sample sizes each year may differ. For instance, the total number of floods in 1985 at the global scale is 69. We compute the median, MAD, skewness and the 90th percentile of the durations of these 69 events. The trend and change-point detection analyses are performed on time series of each moment indicator. The following four subsections elaborate this further.

3.2.1 Trends in median of flood durations

From Figure 3, we can see that there is a monotonic trend in the median of the flood durations at all spatial scales. In Table 3, we present the statistics of the tests along with showing whether they are statistically significant. For example, the median of flood durations at a global scale has increased steadily from 4 days in the year 1985 to 10 days in the year 2015. The change-point analysis shows that there is a significant change-point year in 2004 for the global scales and the tropics.

FIGURE 3

TABLE 3

3.2.2 Trends in Median Absolute Deviation (MAD) of flood durations

We use the Median Absolute Deviation (MAD) of flood durations per year as a measure of the deviation from the central tendency. The MAD is a robust measure to quantify the within-year variation of flood durations. It is resistant to the influences of outliers (Hampel, 1974). Contrary to the standard deviation (SD) -which is affected by non-normality of probability distribution and extremely high/low values- the presence of outliers does not change the MAD value (Leys et al., 2013). MAD is computed as follows:

$$\boldsymbol{F}_{\boldsymbol{D}_{\boldsymbol{MAD}}}^{\boldsymbol{t,r}} = median\left(\|\boldsymbol{F_D}^{t,r} - F_{D_{Median}}^{t,r}\|\right) \quad (4)$$

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where t, r, and $\boldsymbol{F_D}^{\boldsymbol{t,r}}$ are the same variables defined already by Equation 2 and $F^{t,r}_{D_{Median}}$ is defined in Section 3.2.1.

FIGURE 4

TABLE 4

The MK test and change-point analyses are performed on the MAD of flood durations at different global and latitudinal scales and presented in Figure 4 and Table 4. The output statistics acknowledge the existence of significant increasing trends in MAD at global, tropics and subtropics (N) with the change-point year detected in years 2002 and 2003 for global and tropical floods, respectively. It is worth mentioning that the MAD of flood durations increased from 2-3 days in the year 1985 to around 5 days in 2015.

3.2.3 Trends in resistant skewness of flood durations

The presence of outliers amongst the variables will generate a large and possibly misleading measure of skewness (Helsel and Hirsch, 1992). Instead, the resistant skewness is a more robust measure for capturing the asymmetrical/symmetrical properties in the data. It is defined to be as:

$$F^{t,r}_{D_{rSkewness}} = \frac{\left(F^{t,r}_{D_{0.75}} - F^{t,r}_{D_{Median}}\right) - \left(F^{t,r}_{D_{Median}} - F^{t,r}_{D_{0.25}}\right)}{\left(F^{t,r}_{D_{0.75}} - F^{t,r}_{D_{0.25}}\right)} \tag{5}$$

where $F^{t,r}_{D_{rSkewness}}$ defines the resistant skewness of flood durations, r and t are the same variables previously given in Equation 2, and also $F^{t,r}_{D_{0.25}}$ and $F^{t,r}_{D_{0.75}}$ refer to 25$^{\text{th}}$ and 75$^{\text{th}}$ percentiles of flood durations for each year and specified latitudinal belt.

The resistant skewness of flood durations is calculated using Equation 5 and presented in Figure 5. As before, MK trend test and change-point analysis are applied to the time series of resistant skewness of flood durations. As Table 5 indicates, the pattern of resistant skewness of flood durations has changed before/after the year 2002 across the globe and tropics. Moreover, there is a statistically significant increasing skewness at the global scale, tropics, subtropics (S) and mid-latitudes (S). Considering Figure 5 and Table 5, it can be seen that the yearly asymmetrical/symmetrical behavior of distribution of flood durations has considerably changed during the recent three decades (approximately from 5 to 8). Conversely, there is no significant trend in the skewness of flood durations in subtropics (N) and mid-latitudes (N).

FIGURE 5

TABLE 5

3.2.4 Trends in 90$^{\text{th}}$ percentile of flood durations

Finally, we test for monotonic trend in the extreme values (expressed here as 90$^{\text{th}}$ percentile) of flood durations. This measure also serves as a surrogate for extremely long duration flood events each year.

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By definition, the 90th percentile of flood durations ($F^{t,r}_{D_{90}}$) is the value in which only 10 percent of entire flood durations in that year had a greater value in the latitudinal belt r and year t. Figure 6 and Table 6 present the summary of MK test and the change-point analysis on the 90th percentile of flood durations.

FIGURE 6

TABLE 6

The magnitude of long duration floods has substantially changed over the recent three decades at the global scale, tropics, mid-latitudes (N and S) and subtropics (S), as presented in Table 6. The null hypothesis that there is no monotonic trend in the tails is rejected in all scales, except the sub-tropics (N). Furthermore, we find that the magnitude of the long duration flood events is more than 30 days in the 2000s, whereas they were less than 20 days in the 1980s and 1990s. The output of change-point analysis suggests that this change in the behavior of the tails occurred in the year 2002 on the global scale, tropics, and mid-latitudes (N).

The highlights of trend and change-point analysis presented in Figures 3 to 6 and Tables 3 to 6 are outlined below:

- **H2**: The median of flood durations has increased in all spatial scales. There is also an increasing monotonic trend in MAD of flood duration distributions across the globe, tropics, and subtropics (N). We also see an increase in the resistant skewness of flood duration distributions around the globe, tropics, subtropics (S) and mid-latitudes (S). For the extreme flood durations (i.e., 90th percentile), we see an increasing trend in all spatial scales (except subtropics (N)) over past three decades.

3.3 Addressing H3: Trends in frequency of short, moderate and long duration flood events

Given that we find statistically significant trends in the tails of the distribution (magnitude of the long duration floods), we were interested in exploring whether there would be a trend in the frequency of the long duration floods as well. This conundrum led us to perform the MK test and the change-point analysis on long duration flood frequency ($F_{C_{\text{L}}}$) for tropics, subtropics, and mid-latitudes. In addition, we also performed these tests on short duration flood frequency ($F_{C_{\text{S}}}$) and moderate duration flood frequency ($F_{C_{\text{M}}}$). Results are presented in Table 7. As it can be seen from Table 7, there is no monotonic trend in the frequency of short duration flood events occurring across all spatial scales. This indicates that the number of short duration floods has not changed over the last three decades worldwide. However, this phenomenon is not true for moderate and long duration floods. In fact, the frequency of both moderate and long duration floods has increased in the tropics. These findings are consistent with the results from H2. There is also an increasing trend in moderate duration floods at the subtropics (S) and long duration floods at the mid-latitudes (N).

TABLE 7

For the long duration flood events in tropics, the total number of events has increased from 60 before 2000 to 249 after 2000. Similarly, the total number of events in the mid-latitudes has increased from 27 to 70 post-2000. In other words, long duration flood events occurred during recent 15 years are four times more than before the year 2000. The increase across the mid-latitudes (N) is around 2.5 times pre and post 2000. Table 8 shows the outputs of change-point assessment on observed trend in flood durational classes (i.e. Table 7).

TABLE 8

In summary:

- **H3**: Frequency of moderate and long duration flood classes has changed recently, but remain unchanged for the short duration floods in all the latitudinal belts. The annual frequencies of moderate and long duration flood events have increased across the tropics and mid-latitudes (N) (on the scale of 4 and 2.5 events per year, respectively) over last three decades.

3.4 Country scale vulnerability analysis to short, moderate and long duration flood events

Next, we explored the country scale vulnerability to short, moderate and long duration floods. There were 4311 flood events that occurred from 1985 to 2015 around the world. According to Table 2 and Table 7, globally the total number of short, moderate and long duration flood events were 2508 (≈59%), 1151 (≈27%), and 560 (≈13%), respectively. In addition to specifying the spatial scale by considering the latitudinal belts, we carry out the proportional flood frequencies at the country level for different flood duration classes. First, we excluded any countries which had less than 31 flood events (i.e. a combination of all duration classes) to ensure that we investigate only those counties that have at least one flood pear year. This screening resulted in 28 countries with minimum 31 flood events during last three decades. Then, the fraction of flood frequencies for each country and duration class -short, moderate and long- is calculated. Figure 7 (a) presents these fractions for the 28 countries. The size of the circle indicates the total number of events. For instance, the red color circle seen at the low end of the figure is presenting the data for Colombia. The total number of floods for Colombia over the 31 years is 44 events. 66% of these floods are short duration floods, 2% of these are moderate duration floods and 32% (indicated by the value of the color) are long duration floods.

FIGURE 7

Also shown in Figure 7 (b) are the time series of the long duration floods for India, China, USA, and Thailand. These are the countries ranked highest for long duration floods. To elaborate on Figure 7, we address some statistics from top four countries with highest long duration flood frequencies that might not necessary be corresponded to large fractions in short and moderate flood duration classes.

In total, 226 flood events occurred across India in which around 43, 32, and 25% of them were short, moderate and long duration events, respectively. In the U.S., short, moderate and long duration flood events account for 66, 26, and 8% of 388 flood events that occurred in last three decades. However, the fraction of long duration flood events is much higher for Thailand (30% of total flood events). In China, although half of the flood events were from short duration class (i.e., 50%), still 34 and 16% of flood events were related to moderate and long duration flood classes. Here, we presented a simple overview of the vulnerability profile for different countries. It can directly help inform and improve the flood warning systems tailored to various types and resource management during post-disaster responses. Furthermore, with increasing globalization, countries are now interdependent through supply chain networks to achieve streamlined production and overall cost reductions. A country level understanding of the exposure to different types of floods can help better predict the vulnerable nodes that might cause a systemic network failure. It can also provide the necessary analysis for pricing and portfolio risk management for agencies that insure and hedge against the flood losses.

4 Discussion

The trends in frequency and the distribution of the floods (prominent in long duration floods) may be related to several causes ranging from erroneous/inaccurate flood data from DFO, changing climate and atmospheric patterns, and socioeconomic contributions such as increased exposure to the flood events. We attempt to explain these possibilities in the following three sections:

4.1 Are the DFO flood archive data inaccurate?

The answer is negative. The flood archive data provided by DFO are being collected from different methods of observations and validations since 1985 (see the summary of methods in Brakenridge et al. (2005)). They have improved their flood detection methods by including MODIS products since 1999. MODIS products contain surface inundation information based on vertically and horizontally polarized backscatters acquired remotely from radiances change between water, land and vegetation-covered surfaces (Brakenridge et al., 2007). One has to acknowledge, however, that there could be some uncertainties as a result of this since surface may also be interpreted as water in the presence of clouds, cloud shadows, and mountainous terrain (Brakenridge et al., 1998). Besides, there are more flood warning systems and facilities, transmitting instruments, reporting networks, and communications nowadays at different levels of social and governmental divisions that DFO is using to provide more comprehensive flood information. We also specifically focused on robust measures for the trend analysis to remove the effect of any outliers that may be seen in the data.

4.2 Have the patterns of climate, atmospheric dynamics and regional hydrologic conditions changed recently?

The answer is positive. The frequency of heavy precipitation events has increased at global scales (Groisman et al., 2005; Zhou et al., 2013; Liu and Zipser, 2015). For example, using daily precipitation observations from the Global Historical Climatology Network (GHCN) dataset, Alexander et al. (2006) showed that the distributions of precipitation indices in 1979–2003 period are significantly different from the 1901–1950 period with a tendency towards wetter conditions. Solomon (2007), in fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), discussed that the annual precipitation intensity has increased over high-latitude regions during the periods 1901 to 2005, except the southwest of the United States, northwestern Mexico, and the Baja Peninsula. This report also highlights the increasing contribution of extreme rainfall events to the total precipitations across the Europe and United States which mostly happened during the last three decades of the 20th century. Westra et al. (2013) tested 8326 land-based rainfall stations (with at least 30 years of record from 1900 to 2009) and found that the annual maximum daily precipitation has significantly increased for more than two-thirds of these stations at the global scale.

Theoretical studies also discussed that mean global precipitation intensity increased by 1–3% (conditional on available energy budgets) in proportion to the 1ºC increasing rate of surface air temperature. Trenberth (1999), Trenberth et al. (2003), Trenberth (2011), Schiermeier (2011), and Glur et al. (2013) among others have also argued that an increase in air temperature will increase the atmospheric water-holding capacity (Clausius-Clapeyron relationship) leading to more intense and frequent precipitation events. Hence, fluctuating precipitation regimes would interrupt the current balances of components within the hydrological cycle and human activities (Doherty et al., 2000; Dentener et al., 2006). Consequently, warmer and wetter atmosphere is likely to intensify the global water cycle that ultimately will result in more frequent and larger flood events.

The space-time distribution of precipitation regimes is potentially related to the large-scale ocean-atmosphere circulations (Portmann et al., 2009; Yu et al., 2016; Najibi et al., 2017) driven by the natural climatic variability (Trenberth et al., 2007; Zappa et al., 2015). Natural climate variability often causes periods of increasing extremes (flood rich cycle) or decreasing extreme events (flood poor cycle) depending on the phase of the climate (Merz et al., 2014; Hall et al., 2014; Blöschl et al., 2015; Bates, 2016). In addition to the current conditions, climate models also indicate more drastic changes related to the regional hydrology in the future (Few, 2003; Prein et al., 2016). For instance, an increased duration of winter precipitation regime is expected across the U.S. Northeast, and Midwest, which ultimately would cause early spring floods as the snowpack simultaneously melts (Meyer and Weigel, 2010). Conversely, convective thunderstorms with large precipitation intensity are projected to occur more often during the summer months in the future.

In an effort to investigate any significant relationship between the observed trend in flood data and recent changes in the atmospheric circulation patterns, we initially considered the variability of GPH

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and PWC over time at global and each latitudinal belt from 1985 to 2015. Figure 8 represents the 31 years annual variation of GPH and PWC.

FIGURE 8

Generally, GPH and PWC values have tended to increase recently. For instance, a 4% increasing rate in PWC can be observed at global scale during the last 15 years (from 25.65 in 2000 to 26.6 $kg.m^{-2}$ in 2015). This value is around 5.5% in the tropics. An increasing GPH trend indicates that more cyclonic circulations will occur in mid-lower troposphere (Wang and Zhou, 2005), which in turns can generate more clouds and several widespread rainfall events. Furthermore, an increasing trend in the floods can be attributed to natural climate variability (quasi-periodic nature) that leads to persistent wet or dry regimes. For all the cases where the no trend hypothesis is rejected, we explore Generalized Linear Models (Dobson and Barnett, 2008) with these climate indicators as predictors to explain the trends. Our proposition is that the detected time trend is due to cyclical climate influences (large-scale ocean-atmospheric interactions as observed from ENSO) or changes in the synoptic scale patterns in the regional atmosphere (as seen from PWC and GPH), or some combination thereof. The corresponding residual time-trend analysis from the models explains whether the long-term natural variability and/or changing regional atmospheric patterns dominates the trends. The time series (1985 - 2015) of Fc, $F_{D_{Median}}$, and $F_{D_{90}}$ in each spatial scale where we see a trend is informed by the climate covariates as:

$$F_C = a + b_1 PWC + b_2 GPH + b_3 ENSO + b_4 PWC \times GPH \quad (6)$$

$$F_{D_{Median}} = a + b_1 PWC + b_2 GPH + b_3 ENSO + b_4 PWC \times GPH \quad (7)$$

$$F_{D_{90}} = a + b_1 PWC + b_2 GPH + b_3 ENSO + b_4 PWC \times GPH \quad (8)$$

where a, b_1, b_2, b_3, b_4 are the GLM's coefficients. We then obtain the residuals of the models. The residuals represent the values for Fc, $F_{D_{Median}}$, and $F_{D_{90}}$ after adjusting for exogenous variables. In other words, they reveal the variability beyond what could be caused by the exogenous climate factors. Hence, the analysis of the time trends in the residuals will help to discern any unexplained trend after accounting for the trend due to climate modulation.

The detailed information on the GLMs including the formula, statistically significant coefficients (at 5% significance level), and MK test's outputs on the residuals are shown in Table 9.

TABLE 9

For Fc and $F_{D_{90}}$, a Poisson distribution is considered as the link function to satisfy the natural distribution of flood data time series. Based on the observed trend in Fc, $F_{D_{Median}}$, and $F_{D_{90}}$, and the GLM outputs, the most important remarks from Table 9 are given below:

1. PWC, GPH, ENSO and interaction of PWC with GPH (i.e., PWC×GPH) are significant at global scale and the tropics. The residual trend does not show any significant trend indicating that the trend we originally observed may be due in part to these climate variables. Ward et al. (2016) and Emerton et al. (2017) have previously demonstrated the role of ENSO in modulating global floods. Our results corroborate with theirs along with showing the synoptic scale variables that also modulate the floods. Further, we find no significant relation with Fc variability in southern subtropics and mid-latitudes. The trend in these latitudes is unexplained.
2. Observed trend in $F_{D_{Median}}$ at global and mid-latitude (N) scales cannot be explained with the selected predictors at 5% significance level. Conversely, ENSO shows to be a potential driver of $F_{D_{Median}}$ across the tropics and mid-latitudes (S). The residuals of fitted GLM over the tropics and sub-tropics (N) are indicating a trend leading to the hypothesis that there should be one or a set of unexplained factor(s) that might drive the observed trend in $F_{D_{Median}}$, in addition to the climate modulation.
3. In mid-latitudes (N), extreme flood duration values (i.e. $F_{D_{90}}$) can be explained with PWC, GPH, and their joined interaction. These predictors plus ENSO are able to explain the trends across the subtropics (S). In a similar fashion, ENSO also plays a significant role in driving extreme flood duration across the mid-latitudes (S).

In summary, we have approached the explanation of trend in an exploratory spirit and formulated models based on known theoretical arguments. We see that trends in the tropics and southern hemisphere can be largely attributed to ENSO, and the interaction of PWC with GPH is the main explanatory variable for trends in the subtropic (N and S) and mid-latitudes (N). Furthermore, we emphasize that the time series (both observed variables and exogenous variables) may have substantial autocorrelation structure that may manifest as apparent trends in limited data. Detection of autocorrelation before ascribing trends is important. While we did not explicitly test out an autocorrelated model, we investigated for any structured autocorrelation in the residuals after accounting for the exogenous variables and found none. Further, we did not examine the effect of lagged dependence of the climate variables here. One can develop models where an appropriate lag can be chosen based on the model performance. While we have only demonstrated a generalized linear model framework, one can also explore the non-parametric models.

4.3 Have the exposures of residential/industrial sectors to flood events increased recently?

The answer is positive. The number of people, residential, industrial properties and assets exposed to the flood events have drastically increased (Bouwer, 2011; Jongman et al., 2012; Kundzewicz et al., 2014). The type of vulnerability to the flood risk is mostly connected to the country scale development and its environmental characteristics (Peduzzi et al., 2009). While exposure of people to floods is the main concern in developing countries, exposure of assets and properties to floods is the vital

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concern for the developed countries (Jongman et al., 2012). Recently, many residential and industrial infrastructures have moved to flat and cheap lands of floodplains. The nature of geomorphological features of land has been modified to embrace these new developments. Hirabayashi et al. (2013) and Stevens et al. (2016) have recently indicated that the increase in the reporting of floods can be linked to the increase in the land use development in the floodplains.

5 Conclusions

A global assessment of flood events is performed here focusing on flood frequencies and duration characteristics in different global/latitudinal/country scales from the year 1985 to 2015. The comprehensive assessment of frequencies of flood events and characteristic of probability distribution of flood durations presented here is the very first large-scale study of 'actual' flood events worldwide focusing on understanding temporal changes over the last three decades.

It was verified here that the frequency of flood events increased at the global scale, tropics, subtropics (S), and mid-latitudes (S) with a significant change detected in early 2000s. Selected metrics of the flood duration showed a monotonic increasing trend for the median (in all spatial scales), MAD (across the globe, tropics, and subtropics (N)), resistant skewness (across the globe, tropics, subtropics (S) and mid-latitudes (S)), and extremes (all spatial scales except subtropics (N)). More importantly, we find that the frequency of moderate and long duration floods has increased recently, but remain unchanged for the short duration floods in all spatial scales. The trends in the tropics and southern hemisphere can be largely attributed to ENSO. The interaction of PWC with GPH is the main explanatory variable for trends in the subtropic (N and S) and mid-latitudes (N). We summarize our trend and change-point analyses in Table 10 and present an overall review below.

TABLE 10

- The frequency of flood events has increased; change-points were detected between the years 1995 and 2001; the year 2005 is recognized as the year with the maximum number of flood occurrences across all spatial scales.
- There is a statistically significant trend in the moments of the flood duration at the global scale, tropics, subtropics, and mid-latitudes; the extreme floods post-2000 is more than 30 days as opposed to less than 20 days in the 1980s and 1990s.
- The yearly number of moderate and long duration flood occurrences increased (from before to after the 2000s) by a factor of 4 and 2.5 events per year across the tropics and mid-latitudes (N) respectively.
- There was no monotonic trend observed in the frequencies of short duration floods (i.e. flood duration of 1 to 7 days) across all the spatial scales.

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- The increase in frequency of long duration floods during recent years are related to persistent patterns in hydrologic components, climate teleconnections and atmospheric circulation conditions as reported here and in some climate-informed flood studies (e.g., Lu and Lall (2016), Najibi et al. (2017)).

While this study explores the trends in the frequency and duration of global floods, especially the long duration floods, it is necessary to investigate the cause-effect mechanism of these trends conditional to different space-time scales. Understanding the hierarchical layers of Earth system dynamics connected to the global flood events will provide us with comprehensive information and realization that can be translated to better define the multi-scale flood risk management and damage control strategies.

Appendix A: Non-parametric trend test

The nonparametric rank-based Mann-Kendall (MK) test is widely applied to detect the monotonic trend (i.e. a gradual change over time with consistency in direction) in climatic or environmental time series (Mann, 1945; Kendall, 1948). It is an appropriate approach to be employed for that type of variables that exhibit skewness around the general relationship (Helsel and Hirsch, 1992). The MK's null hypothesis (H_0) is that there is no monotonic trend (i.e. $-Z_{1-\frac{\alpha}{2}} \leq Z_{\mathrm{MK}} \leq Z_{1-\frac{\alpha}{2}}$) (Hirsch, 1992), while a failure to reject H0 does not confirm the lack of trend in time series. In fact, the provided data are not sufficient to conclude that a trend might be existing, bounded to that specified level of confidence (Meals et al., 2011). The MK test is based on the S statistic as the sum of integers given in the form of the following configuration as:

$$S = \sum_{p=1}^{T-1} \sum_{q=p+1}^{T} \mathrm{Sign}\left(y_q - y_p\right); \text{ where } \mathrm{Sign}\left(y_q - y_p\right) = \begin{cases} +1 & \text{if } \left(y_q - y_p\right) > 0 \\ 0 & \text{if } \left(y_q - y_p\right) = 0 \\ -1 & \text{if } \left(y_q - y_p\right) < 0 \end{cases} \tag{A1}$$

Also,

$$Z_{\mathrm{MK}} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \tag{A2}$$

where T is the total number of observations, y_q and y_p are respectively the data values in the time series p and q (p>q). Hence, three cases can be associated with the S value derived from Equation A1 (Helsel and Hirsch, 1992) as:

1. It is a large positive number: an upward trend is observed since the later-measured values tend to be larger than earlier ones,

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2. It is a large negative number: a downward trend is indicated since the later values tend to be smaller than earlier ones,

3. It is an absolute small number: no trend is indicated.

Further, the Kendall's *Tau* (τ) nonparametric correlation coefficient and Sen's slope (β) (i.e. rate of consistent change) (Sen, 1968) can be computed as:

$$\tau = \frac{S}{\frac{T(T-1)}{2}} \text{ ; and } \beta = median\{\frac{y_q - y_p}{x_q - x_p}\}, p = 1,2,...,T-1 \text{ and } q = 2,3,...,T \tag{A3}$$

where Kendall's Tau (τ) value is between -1 and +1 (similar to correlation coefficient in linear regression analysis).

Appendix B: Non-parametric change-point test

In addition to the MK test, we also attempt to identify the point of change in the regimes of each time series. To do so, the nonparametric Pettitt method which is essentially based on the Mann-Whitney U-test is utilized to identify the location of single and significant change-point (i.e. year number) over the time series (Pettitt, 1979). The null hypothesis (H_0) here is the entire observations are following one or more distributions featuring the same location parameter. The corresponding statistical equation is mentioned below:

$$K_T = max(U_{t,T}) \text{ ; where } U_{t,T} = \sum_{p=1}^{t} \sum_{q=t+1}^{T} \text{Sign}(Y_p - Y_q), p = 1,2,...,T-1 \text{ and } q = 2,3,...,T \tag{B1}$$

where the $Sign$ function embedded in Equation B1 is previously defined in Equation A1. The change-point for the time series is occurring at K_T if it is statistically significant (p-values of the two-tailed test at significance level $\alpha \leq 0.05$).

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References

Environmental Literacy Council, https://enviroliteracy.org/, (Accessed on 06/12/2015), 2016.

Abarbanel, H. D. and Lall, U.: Nonlinear dynamics of the Great Salt Lake: system identification and prediction, Climate Dynamics, 12, 287–297, 1996.

Alexander, L., Zhang, X., Peterson, T., Caesar, J., Gleason, B., Klein Tank, A., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., et al.: Global observed changes in daily climate extremes of temperature and precipitation, Journal of Geophysical Research: Atmospheres, 111, 2006.

Bates, P.: Flooding: what is normal?, Science in Parliament, 73, 25–26, 2016.

Blöschl, G., Gaál, L., Hall, J., Kiss, A., Komma, J., Nester, T., Parajka, J., Perdigão, R. A., Plavcová, L., Rogger, M., et al.: Increasing river floods: fiction or reality?, Wiley Interdisciplinary Reviews: Water, 2, 329–344, 2015.

Bouwer, L. M.: Have disaster losses increased due to anthropogenic climate change?, Bulletin of the American Meteorological Society, 92, 39–46, 2011.

Brakenridge, G., Tracy, B., and Knox, J.: Orbital SAR remote sensing of a river flood wave, International Journal of Remote Sensing, 19, 1439–1445, 1998.

Brakenridge, G., Syvitski, J., Niebuhr, E., Overeem, I., Higgins, S., Kettner, A., and Prades, L.: Design with nature: Causation and avoidance of catastrophic flooding, Myanmar, Earth-Science Reviews, 2016.

Brakenridge, G. R.: Global active archive of large flood events, Dartmouth Flood Observatory, University of Colorado. Available online: http://floodobservatory. colorado. edu/index. html (accessed on 10 September 2014), 2010.

Brakenridge, G. R., Nghiem, S. V., Anderson, E., and Chien, S.: Space-based measurement of river runoff, Eos, Transactions, American Geophysical Union, 86, 185–188, 2005.

Brakenridge, G. R., Nghiem, S. V., Anderson, E., and Mic, R.: Orbital microwave measurement of river discharge and ice status, Water Resources Research, 43, 2007.

Dentener, F., Stevenson, D., Ellingsen, K. v., Van Noije, T., Schultz, M., Amann, M., Atherton, C., Bell, N., Bergmann, D., Bey, I., et al.: The global atmospheric environment for the next generation, Environmental Science & Technology, 40, 3586–3594, 2006.

Di Baldassarre, G., Montanari, A., Lins, H., Koutsoyiannis, D., Brandimarte, L., and Blöschl, G.: Flood fatalities in Africa: from diagnosis to mitigation, Geophysical Research Letters, 37, 2010.

Dobson, A. J. and Barnett, A.: An introduction to generalized linear models, CRC press, 2008.

Doherty, R., Kutzbach, J., Foley, J., and Pollard, D.: Fully coupled climate/dynamical vegetation model simulations over Northern Africa during the mid-Holocene, Climate Dynamics, 16, 561–573, 2000.

EM-DAT, C.: The OFDA/CRED International Disaster Database. Universite Catholique de Louvain, Brussels, Belgium, 2016.

Emerton, R., Cloke, H., Stephens, E., Zsoter, E., Woolnough, S., and Pappenberger, F.: Complex picture for likelihood of ENSO-driven flood hazard, Nature Communications, 8, 2017.

Few, R.: Flooding, vulnerability and coping strategies: local responses to a global threat, Progress in Development Studies, 3, 43–58, 2003.

Gabler, R. E., Petersen, J. F., Trapasso, L., and Sack, D.: Physical geography, Nelson Education, 2008.

Glur, L., Wirth, S. B., Büntgen, U., Gilli, A., Haug, G. H., Schär, C., Beer, J., and Anselmetti, F. S.: Frequent floods in the European Alps coincide with cooler periods of the past 2500 years, Scientific reports, 3, 2770, 2013.

Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T. R., Hegerl, G. C., and Razuvaev, V. N.: Trends in intense precipitation in the climate record, Journal of climate, 18, 1326–1350, 2005.

Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., Kjeldsen, T., Kriauciuniene, J., Kundzewicz, Z., Lang, M., et al.: Understanding flood regime changes in Europe: A state of the art assessment, Hydrology and Earth System Sciences, 18, 2735–2772, 2014.

Hallegatte, S., Green, C., Nicholls, R. J., and Corfee-Morlot, J.: Future flood losses in major coastal cities, Nature Climate Change, 3, 802–806, doi:10.1038/nclimate1979, https://doi.org/10.1038%2Fnclimate1979, 2013.

Hampel, F. R.: The influence curve and its role in robust estimation, Journal of the American Statistical Association, 69, 383–393, 1974.

Haraguchi, M. and Lall, U.: Flood risks and impacts: A case study of Thailand's floods in 2011 and research questions for supply chain decision making, International Journal of Disaster Risk Reduction, 14, 256–272, 2015.

Helsel, D. R. and Hirsch, R. M.: Statistical methods in water resources, vol. 49, Elsevier, 1992.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., and Kanae, S.: Global flood risk under climate change, Nature Climate Change, 3, 816–821, 2013.

Hirsch, R.: Statistical Methods in Water Resources. Studies in Environmental Science, Elsevier Science & Technology, 1992.

Jongman, B., Ward, P. J., and Aerts, J. C.: Global exposure to river and coastal flooding: Long term trends and changes, Global Environmental Change, 22, 823–835, 2012.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., et al.: The NCEP/NCAR 40-year reanalysis project, Bulletin of the American meteorological Society, 77, 437–471, 1996.

Karamperidou, C., Cane, M. A., Lall, U., and Wittenberg, A. T.: Intrinsic modulation of ENSO predictability viewed through a local Lyapunov lens, Climate dynamics, 42, 253–270, 2014.

Kendall, M. G.: Rank correlation methods., 1948.

Kistler, R., Collins, W., Saha, S., White, G., Woollen, J., Kalnay, E., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., et al.: The NCEP–NCAR 50–year reanalysis: Monthly means CD–ROM and documentation, Bulletin of the American Meteorological society, 82, 247–267, 2001.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., et al.: Flood risk and climate change: global and regional perspectives, Hydrological Sciences Journal, 59, 1–28, 2014.

Leys, C., Ley, C., Klein, O., Bernard, P., and Licata, L.: Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median, Journal of Experimental Social Psychology, 49, 764–766, 2013.

Liu, C. and Zipser, E. J.: The global distribution of largest, deepest, and most intense precipitation systems, Geophysical Research Letters, 42, 3591–3595, 2015.

Liu, X., Liu, Z., Zhang, Y., and Jiang, B.: The Effects of Floods on the Incidence of Bacillary Dysentery in Baise (Guangxi Province, China) from 2004 to 2012, International Journal of Environmental Research and Public Health, 14, 179, 2017.

Lowe, D., Ebi, K. L., and Forsberg, B.: Factors increasing vulnerability to health effects before, during and after floods, International journal of environmental research and public health, 10, 7015–7067, 2013.

Lu, M. and Lall, U.: Tropical Moisture Exports, Extreme Precipitation and Floods in Northeast US, Hydrol. Earth Syst. Sci, pp. 1–40, 2016.

Mann, H. B.: Nonparametric tests against trend, Econometrica: Journal of the Econometric Society, pp. 245–259, 1945.

Meals, D., Spooner, J., Dressing, S., and Harcum, J.: Statistical analysis for monotonic trends, Tech Notes, 6, 23, 2011.

Merz, B., Aerts, J., Arnbjerg-Nielsen, K., Baldi, M., Becker, A., Bichet, A., Blöschl, G., Bouwer, L., Brauer, A., Cioffi, F., et al.: Floods and climate: emerging perspectives for flood risk assessment and management, Natural Hazards and Earth System Sciences, 14, 1921, 2014.

Merz, R. and Blöschl, G.: A process typology of regional floods, Water Resources Research, 39, 2003.

Meyer, M. D. and Weigel, B.: Climate change and transportation engineering: Preparing for a sustainable future, Journal of Transportation Engineering, 137, 393–403, 2010.

Milojevic, A., Armstrong, B., Kovats, S., Butler, B., Hayes, E., Leonardi, G., Murray, V., and Wilkinson, P.: Long-term effects of flooding on mortality in England and Wales, 1994-2005: controlled interrupted time-series analysis, Environmental Health, 10, 11, 2011.

Mirza, M. M. Q.: Climate change and extreme weather events: can developing countries adapt?, Climate policy, 3, 233–248, 2003.

Najibi, N., Devineni, N., and Lu, M.: Hydroclimate drivers and atmospheric teleconnections of long duration floods: An application to large reservoirs in the Missouri River Basin, Advances in Water Resources, 100, 153–167, 2017.

Nakamura, J., Lall, U., Kushnir, Y., Robertson, A. W., and Seager, R.: Dynamical structure of extreme floods in the US Midwest and the United Kingdom, Journal of Hydrometeorology, 14, 485–504, 2013.

Peduzzi, P., Dao, H., Herold, C., and Mouton, F.: Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index, Natural Hazards and Earth System Sciences, 9, 1149–1159, 2009.

Perdigão, R. and Blöschl, G.: Dynamics of the flood response to slow-fast landscape-climate feedbacks, Proceedings of the International Association of Hydrological Sciences, 370, 125–130, 2015.

Pettitt, A.: A non-parametric approach to the change-point problem, Applied statistics, pp. 126–135, 1979.

Portmann, R. W., Solomon, S., and Hegerl, G. C.: Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States, Proceedings of the National Academy of Sciences, 106, 7324–7329, 2009.

Prein, A. F., Rasmussen, R. M., Ikeda, K., Liu, C., Clark, M. P., and Holland, G. J.: The future intensification of hourly precipitation extremes, Nature Climate Change, 2016.

Promchote, P., Simon Wang, S.-Y., and Johnson, P. G.: The 2011 great flood in Thailand: Climate diagnostics and Implications from climate change, Journal of Climate, 29, 367–379, 2016.

Rayner, N., Parker, D. E., Horton, E., Folland, C., Alexander, L., Rowell, D., Kent, E., and Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, Journal of Geophysical Research: Atmospheres, 108, 2003.

Robertson, A. W., Kushnir, Y., Lall, U., and Nakamura, J.: On the connection between low-frequency modulation of large-scale weather regimes and springtime extreme flooding over the midwest of the United States, Science and Technology Infusion Climate Bulletin. Fort Worth, TX, USA, pp. 150–152, 2011.

Schiermeier, Q.: Increased flood risk linked to global warming: likelihood of extreme rainfall may have been doubled by rising greenhouse-gas levels, Nature, 470, 316–317, 2011.

Schultz, B.: Flood management under rapid urbanisation and industrialisation in flood-prone areas: a need for serious consideration, Irrigation and drainage, 55, 2006.

Sen, P. K.: Estimates of the regression coefficient based on Kendall's tau, Journal of the American Statistical Association, 63, 1379–1389, 1968.

Singh, A. and Zommers, Z., eds.: Reducing Disaster: Early Warning Systems For Climate Change, Springer Netherlands, doi:10.1007/978-94-017-8598-3, https://doi.org/10.1007%2F978-94-017-8598-3, 2014.

Solomon, S.: Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC, vol. 4, Cambridge University Press, 2007.

Stevens, A. J., Clarke, D., and Nicholls, R. J.: Trends in reported flooding in the UK: 1884–2013, Hydrological Sciences Journal, 61, 50–63, 2016.

Thomalla, F., Downing, T., Spanger-Siegfried, E., Han, G., and Rockström, J.: Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation, Disasters, 30, 39–48, 2006.

Trenberth, K. E.: Atmospheric moisture recycling: Role of advection and local evaporation, Journal of Climate, 12, 1368–1381, 1999.

Trenberth, K. E.: Changes in precipitation with climate change, Climate Research, 47, 123–138, 2011.

Trenberth, K. E., Dai, A., Rasmussen, R. M., and Parsons, D. B.: The changing character of precipitation, Bulletin of the American Meteorological Society, 84, 1205–1217, 2003.

Trenberth, K. E., Smith, L., Qian, T., Dai, A., and Fasullo, J.: Estimates of the global water budget and its annual cycle using observational and model data, Journal of Hydrometeorology, 8, 758–769, 2007.

Van Dijk, A. I., Brakenridge, G. R., Kettner, A. J., Beck, H. E., De Groeve, T., and Schellekens, J.: River gauging at global scale using optical and passive microwave remote sensing, Water Resources Research, 52, 6404–6418, 2016.

Vogel, R. M., Yaindl, C., and Walter, M.: Nonstationarity: flood magnification and recurrence reduction factors in the United States1, 2011.

Wang, Y. and Zhou, L.: Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation, Geophysical Research Letters, 32, 2005.

Ward, P., Kummu, M., and Lall, U.: Flood frequencies and durations and their response to El Niño Southern Oscillation: Global analysis, Journal of Hydrology, 539, 358–378, 2016.

Ward, P. J., Jongman, B., Salamon, P., Simpson, A., Bates, P., De Groeve, T., Muis, S., De Perez, E. C., Rudari, R., Trigg, M. A., et al.: Usefulness and limitations of global flood risk models, Nature Climate Change, 5, 712–715, 2015.

Westra, S., Alexander, L. V., and Zwiers, F. W.: Global increasing trends in annual maximum daily precipitation, Journal of Climate, 26, 3904–3918, 2013.

Yu, L., Zhong, S., Pei, L., Bian, X., and Heilman, W. E.: Contribution of large-scale circulation anomalies to changes in extreme precipitation frequency in the United States, Environmental Research Letters, 11, 044 003, 2016.

Zappa, G., Hawcroft, M. K., Shaffrey, L., Black, E., and Brayshaw, D. J.: Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models, Climate Dynamics, 45, 1727–1738, 2015.

Zhou, Y., Lau, W. K., and Liu, C.: Rain characteristics and large-scale environments of precipitation objects with extreme rain volumes from TRMM observations, Journal of Geophysical Research: Atmospheres, 118, 9673–9689, 2013.

Ziegler, A. D., Lim, H. S., Tantasarin, C., Jachowski, N. R., and Wasson, R.: Floods, false hope, and the future, Hydrological Processes, 26, 1748–1750, 2012.

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Figure 1. Spatial segmentation to assign the global flood events (1985 to 2015) into different latitudinal belts; Mid-latitudes (N): 55 ºN-35 ºN, Subtropics (N): 35 ºN-23.5 ºN, Tropics (N): 23.5 ºS-23.5 ºN, Subtropics (S): 35 ºS-23.5 ºS, and Mid-latitudes (S): 55 ºS-35 ºS; (N) and (S) indicate Northern and Southern hemisphere, respectively; the four rounded rectangles shows United States of America (USA), China, India and Thailand.

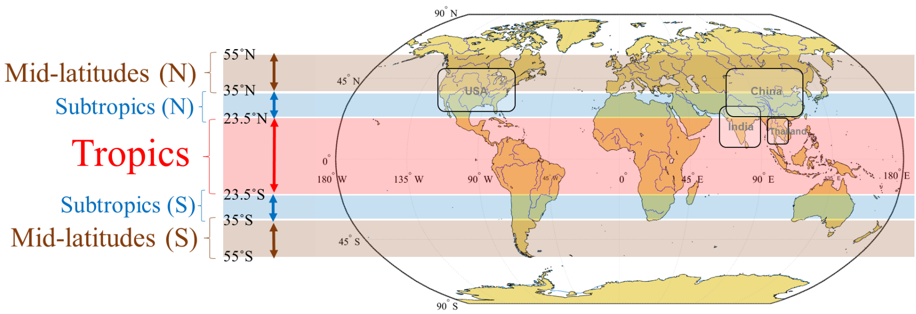

Figure 2. Frequency of flood events at global scale and each latitudinal belt (i.e. Tropics, Subtropics (N), Subtropics (S), Mid-latitudes (N), and Mid-latitudes (S)); the location of change-point is presented by a triangle and vertical solid-line; LOESS curve fitting is shown for the time-series where a significant trend on number of flood events is observed (light gray colored dashed-line refer to upper and lower confidence interval).

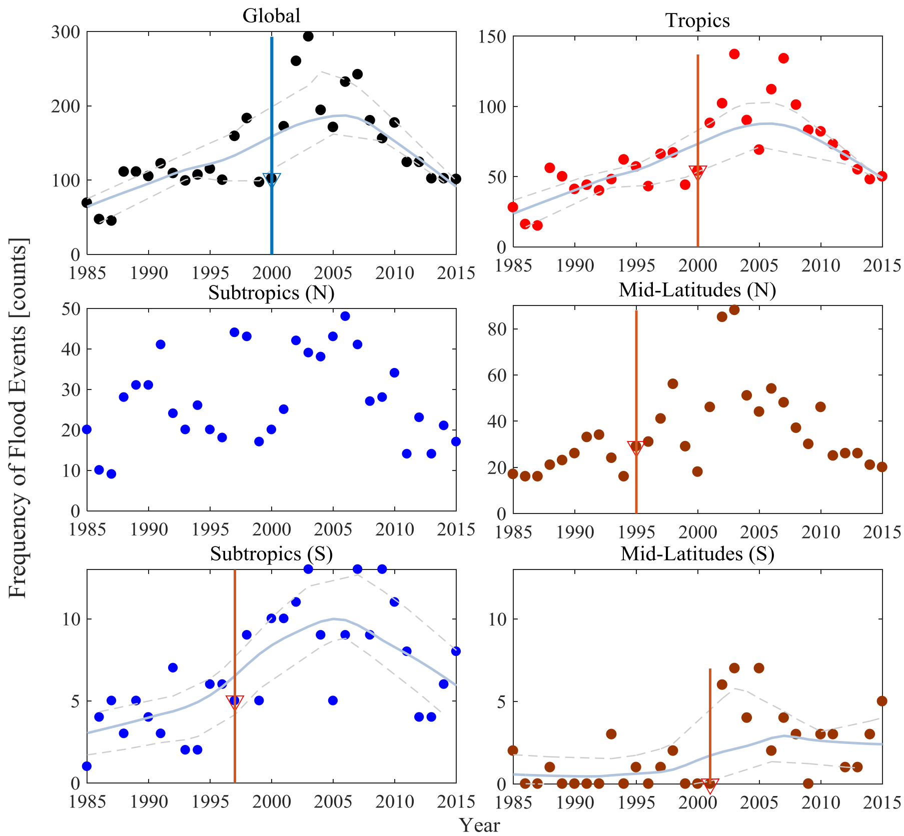

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Figure 3. Same as Figure 2 but for Median of flood durations.

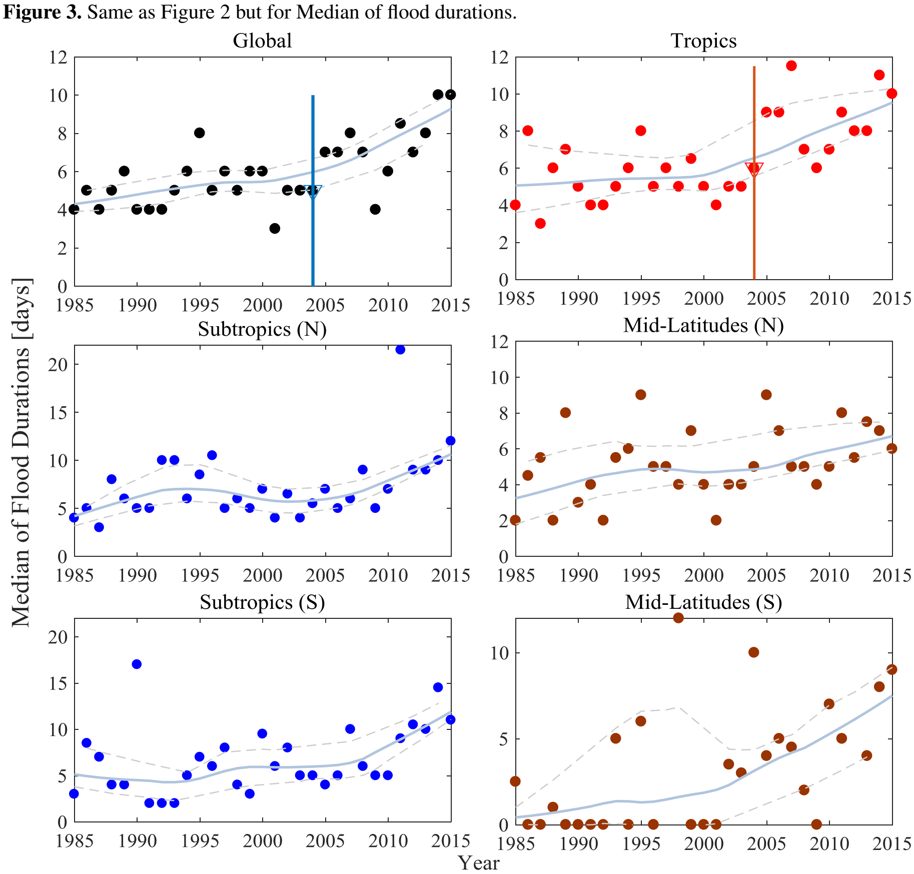

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Figure 4. Same as Figure 2 but for Median Absolute Deviation (MAD) of flood durations.

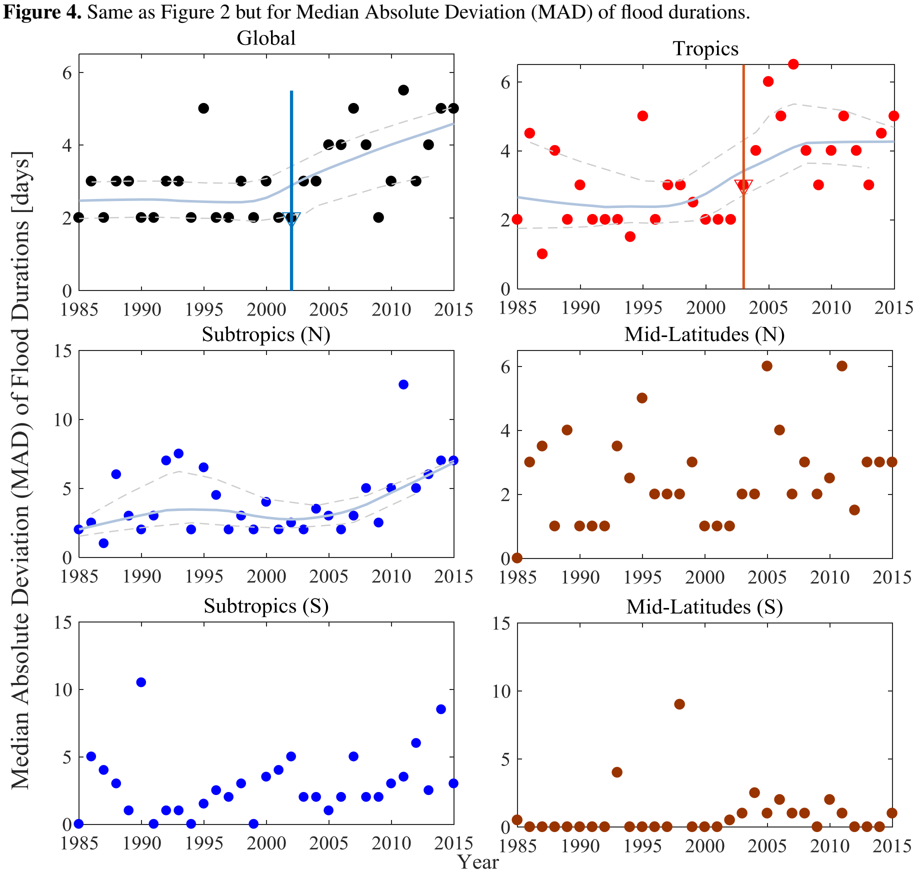

Figure 5. Same as Figure 2 but for Skewness of flood durations.

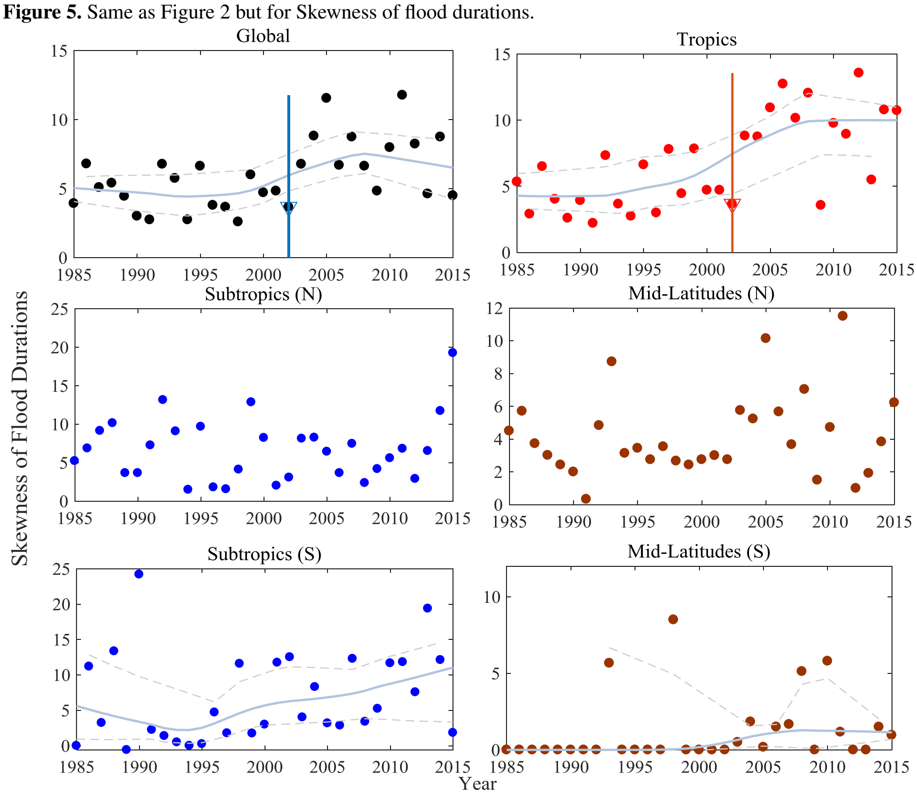

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Figure 6. Same as Figure 2 but for the 90th percentile of flood durations.

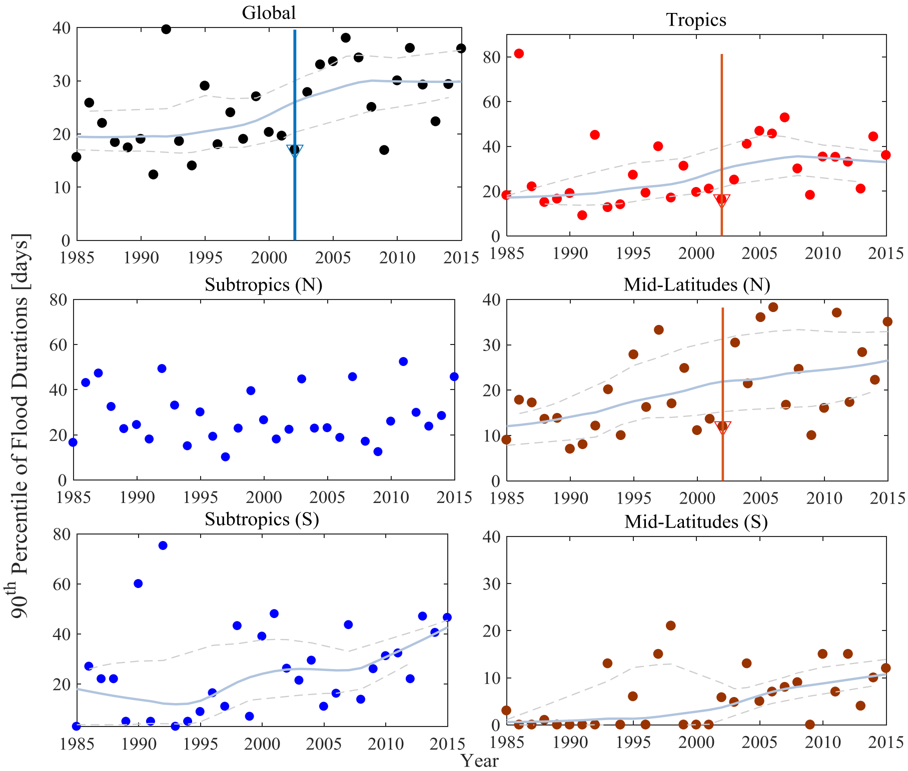

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Figure 7. (a) Relative frequency of short (< 7 days), moderate (8 to 21 days) and long duration (> 21 days) floods for those countries with at least 31 events from 1985 to 2015; **(b)** Time series of frequency of long duration (> 21 days) flood events for top 4 countries (i.e. India, China, the U.S., and Thailand) with maximum number of long duration flood events; LOESS curve fitting is applied on each time-series of country-based long flood durations; light gray colored dashed-line refer to upper and lower confidence interval.

(a)

(b)

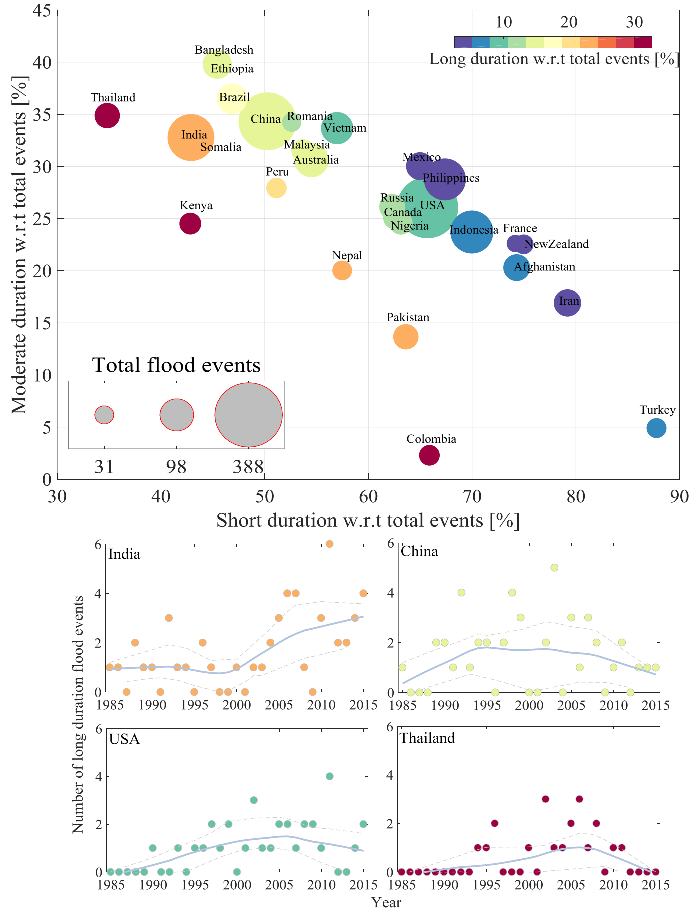

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Figure 8. Annual variations of Geopotential Height (GPH) at 500-mb level and Precipitable Water Content (PWC) at global scale and each latitudinal belt (i.e. Tropics, Subtropics (N), Subtropics (S), Mid-latitudes (N), and Mid-latitudes (S)); blue and orange colored lines refer to PWC $[kg.m^{-2}]$ and GPH $[m]$, respectively.

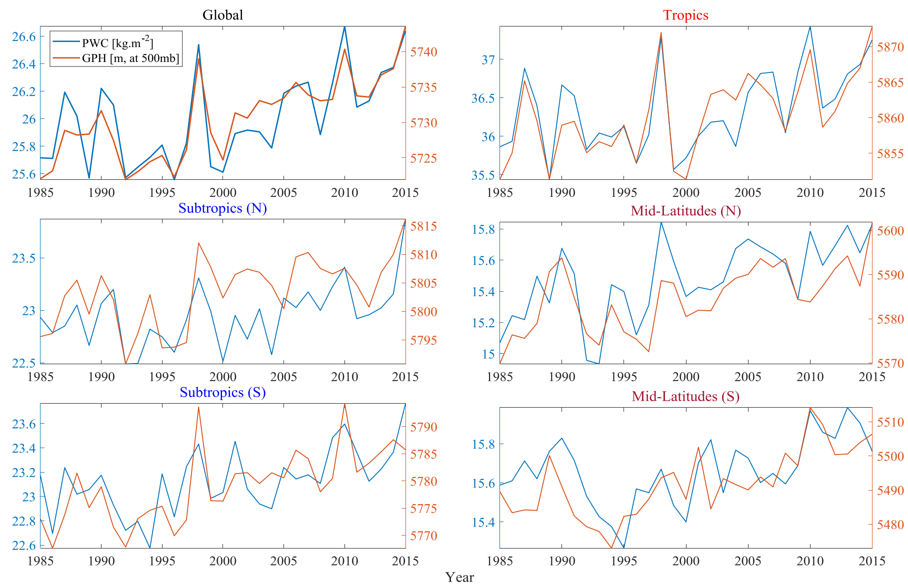

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Table 1. Proposed hypotheses and evaluation approach.

	Hypothesis	Evaluation Strategy
H1	There is no monotonic trend in the annual frequency of flood events globally and in different latitudinal belts.	Non-parametric Mann-Kendall trend test is applied on the annual time series of flood counts ($F_C^{t,r}$).
H2	There is no monotonic trend in the distribution of flood duration globally and in different latitudinal belts.	Non-parametric Mann-Kendall trend test is applied on the annual time series of median, median absolute deviation, resistant skewness, and 90th percentile of flood duration's distributions ($\boldsymbol{F_D}^{t,r}$).
H3	There is no monotonic trend in the annual frequency of short, moderate and long duration flood events in different latitudinal belts.	Non-parametric Mann-Kendall trend test is applied on the annual time series of short, moderate and long duration flood events ($Fc_S^{t,r}$, $Fc_M^{t,r}$, $Fc_L^{t,r}$).

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Table 2. Summary of Trend (Mann-Kendall Test with significance level $\alpha = 0.05$) and Change-Point analysis (Pettitt Test with significance level $\alpha = 0.05$) on frequencies (occurrences) of flood events at global scale and over 5 latitudinal belts.

Spatial Scale	Frequency of Flood Events (1985 − 2015)					
	Trend Analysis					
	Total flood events	Maximum number of events per year	Kendall's Tau	Sen's slope	*p*-value (two tailed test)	Trend
Global	4311	293	0.26	2.12	0.0429	✓
Mid-Latitudes (North)	1077	88	0.22	0.5	0.086	×
Subtropics (North)	856	48	0.032	0.048	0.8115	×
Tropics	2020	137	0.4	1.74	0.0016	✓
Subtropics (South)	210	13	0.366	0.22	0.0038	✓
Mid-Latitudes (South)	59	7	0.327	0.083	0.0077	✓

Spatial Scale	**Change-Point Analysis**			
	K_T	*p*-value (two tailed test)	Change-Point year	Change-Point
Global	162	0.012	2000	✓
Mid-Latitudes (North)	144	0.035	1995	✓
Subtropics (North)	85	0.4885	2010	×
Tropics	198	0.00095	2000	✓
Subtropics (South)	184	0.0027	1997	✓
Mid-Latitudes (South)	189	0.0019	2001	✓

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Table 3. Summary of Trend (Mann-Kendall Test with significance level $\alpha = 0.05$) and Change-Point analysis (Pettitt Test with significance level $\alpha = 0.05$) based on median of flood durations at global scale and over 5 latitudinal belts.

Spatial Scale	Median of Flood Durations (1985 − 2015)					
	Trend Analysis					
	Median of flood durations [days]	Maximum of flood durations per year	Kendall's Tau	Sen's slope	*p*-value (two tailed test)	Trend
Global	6	168	0.484	0.125	0.000103	✓
Mid-Latitudes (North)	5	131	0.2667	0.0909	0.0346	✓
Subtropics (North)	6	122	0.3097	0.125	0.0141	✓
Tropics	6	168	0.4473	0.15	0.00037	✓
Subtropics (South)	6	93	0.3312	0.1667	0.0088	✓
Mid-Latitudes (South)	5	21	0.3613	0.2105	0.0034	✓

	Change-Point Analysis			
	K_T	*p*-value (two tailed test)	Change-Point year	Change-Point
Global	170	0.0071	2004	✓
Mid-Latitudes (North)	115	0.1515	2004	×
Subtropics (North)	118	0.1322	2007	×
Tropics	194	0.0013	2004	✓
Subtropics (South)	124	0.0996	2006	×
Mid-Latitudes (South)	134	0.0602	2001	×

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Table 4. Summary of Trend (Mann-Kendall Test with significance level $\alpha = 0.05$) and Change-Point analysis (Pettitt Test with significance level $\alpha = 0.05$) based on median absolute deviation (MAD) of flood durations at global scale and over 5 latitudinal belts.

Spatial Scale	Median Absolute Deviation (MAD) of Flood Durations (1985 − 2015)					
	Trend Analysis					
	Median of MAD of entire flood durations	Maximum of flood durations per year	Kendall's Tau	Sen's slope	*p*-value (two tailed test)	Trend
Global	3	5.5	0.372	0.0588	0.0021	✓
Mid-Latitudes (North)	2	6	0.1892	0.0417	0.1323	×
Subtropics (North)	3	12.5	0.2817	0.0909	0.0251	✓
Tropics	3	6.5	0.3763	0.0833	0.0025	✓
Subtropics (South)	2.5	10.5	0.2409	0.0769	0.0570	×
Mid-Latitudes (South)	0	9	0.1914	0.00001	0.0924	×
	Change-Point Analysis					
	K_T		*p*-value (two tailed test)		Change-Point year	Change-Point
Global	161		0.0127		2002	✓
Mid-Latitudes (North)	102		0.2627		2004	×
Subtropics (North)	121		0.1149		2007	×
Tropics	182		0.0031		2003	✓
Subtropics (South)	102		0.2627		1999	×
Mid-Latitudes (South)	117		0.1384		2001	×

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Table 5. Summary of Trend (Mann-Kendall Test with significance level $\alpha = 0.05$) and Change-Point analysis (Pettitt Test with significance level $\alpha = 0.05$) based on resistant skewness of flood duration distributions at global scale and over 5 latitudinal belts.

Spatial Scale	Resistant Skewness of Flood Duration Distributions (1985 − 2015)					
	Trend Analysis					
	Median of skewness of flood distributions	Average of skewness of flood distributions	Kendall's Tau	Sen's slope	*p*-value (two tailed test)	Trend
Global	5.41	5.89	0.2731	0.1146	0.0321	✓
Mid-Latitudes (North)	3.5395	4.1903	0.0925	0.0386	0.4750	×
Subtropics (North)	6.5385	6.6653	0.0129	0.0084	0.9322	×
Tropics	6.5	6.7885	0.4839	0.2468	0.00014	✓
Subtropics (South)	4.0227	6.6652	0.2839	0.2017	0.0260	✓
Mid-Latitudes (South)	0	1.1096	0.2903	0	0.0092	✓
	Change-Point Analysis					
	K_T		*p*-value (two tailed test)		Change-Point year	Change-Point
Global	171		0.0067		2002	✓
Mid-Latitudes (North)	86		0.4724		2004	×
Subtropics (North)	60		0.9908		1993	×
Tropics	198		0.000952		2002	✓
Subtropics (South)	128		0.0818		2000	×
Mid-Latitudes (South)	136		0.0542		2002	×

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Table 6. Summary of Trend (Mann-Kendall Test with significance level $\alpha = 0.05$) and Change-Point analysis (Pettitt Test with significance level $\alpha = 0.05$) based on 90^{th} percentile of flood duration distributions at global scale and over 5 latitudinal belts.

Spatial Scale	90^{th} Percentile of Flood Durations (1985 − 2015)					
	Trend Analysis					
	Median of 90^{th} percentile flood duration per year [days]	Maximum of 90^{th} percentile flood duration per year	Kendall's Tau	Sen's slope	*p*-value (two tailed test)	Trend
Global	24	39.6	0.3699	0.4417	0.0037	✓
Mid-Latitudes (North)	17.2	38.2	0.3355	0.4875	0.0084	✓
Subtropics (North)	24.4	52.3	0.0452	0.0750	0.7338	×
Tropics	25	81.3	0.3054	0.6364	0.0165	✓
Subtropics (South)	22	75.2	0.2946	0.7385	0.0206	✓
Mid-Latitudes (South)	4.8	21	0.3570	0.3182	0.0038	✓
	Change-Point Analysis					
	K_T		*p*-value (two tailed test)		Change-Point year	Change-Point
Global	164		0.0105		2002	✓
Mid-Latitudes (North)	143		0.0370		2002	✓
Subtropics (North)	68		0.8114		2009	×
Tropics	145		0.0331		2002	✓
Subtropics (South)	113		0.1656		1999	×
Mid-Latitudes (South)	136		0.0542		2001	×

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Table 7. Summary of Trend analysis (Mann-Kendall Test with significance level $\alpha = 0.05$) on three flood classes; short, moderate and long durations of flood events over 5 latitudinal belts.

Climate Zone	Total flood events [1985 to 2015]	Maximum number of events per year	Test Result	Standard deviation	Kendall's Tau	Sen's slope	*p*-value (two tailed test)	Trend
Short Duration (1 to 7 days)								
Mid-Latitudes (North)	724	68	Cannot Reject	-	-	-	-	×
Subtropics (North)	496	34	Cannot Reject	-	-	-	-	×
Tropics	1125	88	Cannot Reject	-	-	-	-	×
Subtropics (South)	121	8	Cannot Reject	-	-	-	-	×
Mid-Latitudes (South)	42	7	Cannot Reject	-	-	-	-	×
Moderate Duration (8 to 20 days)								
Mid-Latitudes (North)	256	20	Cannot Reject	-	-	-	-	×
Subtropics (North)	235	15	Cannot Reject	-	-	-	-	×
Tropics	586	48	Reject	58.6231	0.4602	0.6667	0.00028	✓
Subtropics (South)	58	5	Reject	57.4	0.4022	0.0909	0.0012	✓
Mid-Latitudes (South)	16	4	Cannot Reject	-	-	-	-	×
Long Duration (21 days and above)								
Mid-Latitudes (North)	97	11	Reject	58.0345	0.357	0.1111	0.0045	✓
Subtropics (North)	125	8	Cannot Reject	-	-	-	-	×
Tropics	306	37	Reject	58.6174	0.5462	0.5417	0.0000158	✓
Subtropics (South)	31	4	Cannot Reject	-	-	-	-	×
Mid-Latitudes (South)	1	1	Cannot Reject	-	-	-	-	×

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Table 8. Summary of Change-Point analysis (Pettitt Test with significance level $\alpha = 0.05$) on observed trends in flood classes.

Observed Trend	K_T	*p*-value (two tailed test)	Change-Point year	Number of flood occurrences before Change-Point year	Number of flood occurrences after Change-Point year
Moderate Duration (8 to 20 days)					
Tropics	210	0.0004	2000	205	381
Subtropics (South)	192	0.0015	2000	17	39
Long Duration (21 days and above)					
Mid-Latitudes (North)	176	0.0047	2000	27	70
Tropics	224	0.0001	2000	60	249

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Table 9. Summary of Generalized Linear Model (GLM) results relating selected predictors to flood frequency (F_C), median and 90th percentile of flood durations (F_D) for the global scale and over 5 latitudinal belts from 1985 to 2015.

Trend (✓or –)	Model	Descriptive Formula		Global	Mid-Latitudes (North)	Subtropics (North)	Tropics	Subtropics (South)	Mid-Latitudes (South)
F_C	GLM (Poisson)		*Trend in flood data*	✓	–	–	✓	✓	✓
			$a+b_1PWC+b_2GPH+b_3ENSO+b_4PWC\times GPH$	a,b_1,b_2,b_3,b_4	–	–	a,b_1,b_2,b_3,b_4	–	–
		MK Test on Residuals	*p-value =*	0.71	–	–	0.28	0.18	0.09
			Explanation	✓	–	–	✓	–	–
		Potential Driver		PWC, GPH, ENSO, PWC×GPH	–	–	PWC, GPH, ENSO, PWC×GPH	No Factor	No Factor
$F_{D_{Median}}$	GLM (Log-Normal)		*Trend in flood data*	✓	✓	✓	✓	✓	✓
			$a+b_1PWC+b_2GPH+b_3ENSO+b_4PWC\times GPH$	–	–	a,b_1,b_2,b_4	b_3	a,b_1,b_2,b_3,b_4	b_3
		MK Test on Residuals	*p-value =*	0.083	0.22	0.012	0.048	0.292	0.62
			Explanation	–	–	✓	✓	✓	✓
		Potential Driver		No Factor	No Factor	PWC, GPH, PWC×GPH and Unexplained Factor	ENSO and Unexplained Factor	PWC, GPH, ENSO, PWC×GPH	ENSO
$F_{D_{90}}$	GLM (Poisson)		*Trend in flood data*	✓	✓	–	✓	✓	✓
			$a+b_1PWC+b_2GPH+b_3ENSO+b_4PWC\times GPH$	–	a,b_1,b_2,b_4	–	–	a,b_1,b_2,b_3,b_4	b_3
		MK Test on Residuals	*p-value =*	0.221	0.185	–	0.135	0.262	0.972
			Explanation	✓	✓	–	–	✓	✓
		Potential Driver		No Factor	PWC, GPH, PWC×GPH	–	No Factor	PWC, GPH, ENSO, PWC×GPH	ENSO

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Table 10. Summary of Trend and Change-Point analysis of flood frequency (F_C), different moments of flood durations (F_D) and classes of flood durations in different global/sub-global spatial scales from 1985 to 2015.

Trend (✓ or –) / Change-Point Year		Global	Mid-Latitudes (North)	Subtropics (North)	Tropics	Subtropics (South)	Mid-Latitudes (South)
F_C	*Total Number*	✓ 2000	– 1995	–	✓ 2000	✓ 1997	✓ 2001
F_D	*Median*	✓ 2004	✓ –	✓ –	✓ 2004	✓ –	✓ –
	MAD	✓ 2002	–	✓ –	✓ 2003	–	–
	Resistant Skewness	✓ 2002	–	–	✓ 2002	✓ –	✓ –
	90th Percentile	✓ 2002	✓ 2002	–	✓ 2002	✓ –	✓ –
F_C	*Short Duration*		–	–	–	–	–
	Moderate Duration		–	–	✓ 2000	✓ 2000	–
	Long Duration		✓ 2000	–	✓ 2000	–	–