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Published in:
Journal of Hydrology

DOI:
10.1016/j.jhydrol.2016.05.045

Published: 01/08/2016

Document Version
Early version, also known as pre-print

Please cite the original version:
Ward, P. J., Kummu, M., & Lall, U. (2016). Flood frequencies and durations and their response to El Niño Southern Oscillation: Global analysis. *Journal of Hydrology*, *539*, 358-378.
https://doi.org/10.1016/j.jhydrol.2016.05.045

Manuscript for submission to *Journal of Hydrology*

Title: Flood frequencies and durations and their response to El Niño Southern Oscillation: global analysis

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Keywords: ENSO; flood frequency; flood duration; global scale

Abstract

Floods are one of the most serious forms of natural hazards in terms of the damages they cause. In 2012 alone, flood damages exceeded $19 billion. A large proportion of the damages from several recent major flood disasters, such as those in South India and South Carolina (2015), England and Wales (2014), the Mississippi (2012), Thailand (2011), Queensland (Australia) (2010-2011), and Pakistan (2010), were related to the long duration of those flood events. However, most flood risk studies to date do not account for flood duration. In this paper, we provide the first global modelling exercise to assess the link between interannual climate variability and flood duration and frequency. Specifically, we examine relationships between simulated flood events and El Niño Southern Oscillation (ENSO). Our results show that the duration of flooding appears to be more sensitive to ENSO than is the case for flood frequency. At the globally aggregated scale, we found floods to be significantly longer during both El Niño and La Niña years, compared to neutral years. At the scale of individual river basins, we found strong correlations between ENSO and both flood frequency and duration for a large number of basins, with generally stronger correlations for flood duration than for flood frequency. Future research on flood impacts should attempt to incorporate more information on flood durations.

1. Introduction

Floods lead to large economic damage and losses, fatalities, injuries, and other social impacts all around the world. As a result, international stakeholders, such as International Financing Institutes, disaster relief organisations, reinsurance companies, and multinational businesses, increasingly require high quality information on flood risk at the global scale. How this risk is affected by current climate variability and future global change is a concern (e.g. UNISDR, 2013).

In response, a number of studies at the continental to global scale have used gauged discharge data to investigate how flood regimes are influenced by climate change and climate variability (e.g. Kundzewicz et al., 2005; Hannaford et al., 2013; Hall et al., 2014; and Mediero et al., 2015). At the same time, several models have been developed to simulate river flood hazard, exposure, and/or risk at the global scale (Dilley et al., 2005; UNISDR, 2009; Jongman et al., 2012; Pappenberger et al., 2012; Hirabayashi et al., 2013; Ward et al., 2013; Winsemius et al., 2013, 2015; Arnell and Gosling, 2014; Arnell and Lloyd-Hughes, 2014). To date, these models employ methods that use peak discharge time-series to assess flood hazard in terms of the flood extent and/or inundation depth. However, several recent flood disasters, such as those in South India and South Carolina (2015), England and Wales (2014), the Mississippi (2012), Thailand (2011), Queensland (Australia) (2010-2011), and Pakistan (2010), have shown that the duration of flooding is also an important parameter in determining the impacts of flooding (e.g. Hallegatte, 2008; Elmer et al., 2010; Dang et al., 2011; Koks et al., 2015). This is particularly the case for indirect losses and health-related issues and mortalities. Long duration floods cause business interruptions and disrupt local to global supply chains, as was the case during the floods in Thailand in 2011 (e.g. Haraguchi and Lall, 2015). Moreover, long periods of inundation can negatively influence clean water supply and sanitation, and can promote vector-borne diseases (e.g. Dang et al., 2011). Nevertheless, little is known of the influence of climate variability on flood duration and flood frequency at the large scale.

In this paper, we aim to provide a first global modelling study of the link between climate variability and flood durations and frequencies. For this study, we specifically examine relationships between simulated flood events and El Niño Southern Oscillation (ENSO). ENSO was chosen as it is the most dominant interannual signal of climate variability (McPhaden et al., 2006). Scores of studies at the local to basin scale have found relationships between ENSO and average river discharge (see Dettinger and Diaz, 2000, and Dettinger et al., 2000, and references therein), and others have examined global scale relationships between ENSO and average river discharge (Dettinger and Diaz, 2000; Dettinger et al., 2000; Chiew and McMahon, 2002; Labat, 2010). Fewer studies exist on relationships between ENSO and peak discharge, although such studies are available for the United States (e.g. Cayan and Webb, 1992; Cayan et al., 1999), Australia (Kiem et al., 2003; Kiem and Verdon-Kidd, 2013; Ishak et al., 2013), Peru (Waylen and Caviedes, 1986), southern Asia (Mirza, 2011), and the Mekong Basin (Räsänen and Kummu, 2013). Recently, global scale studies by Ward et al. (2010, 2014a, 2014b) have also shown that both peak annual discharge and flood risk (expressed as a combination of the probability of a flood and its impacts) are sensitive to ENSO in many parts of the world, thereby supporting the hypothesis emerging from previous work (e.g. Kiem et al, 2003; Kundzewicz et al., 2005; Kiem and Verdon-Kidd, 2013) that ENSO may influence flood risk. This is especially the case for southern Africa, parts of the Sahel and western Africa, East Africa, Australia, the western United States (especially during La Niña), and parts of South America and Central Eurasia. In the current paper we extend previous global modelling studies that have assessed the influence of ENSO on peak annual discharge, to also model, for the first time, ENSO's influence on flood frequency and duration at the global scale.

The analyses in this paper are based on modelled data, and this is done for several reasons. First and foremost, there are no observed datasets of flood durations. Observed discharge data give an estimate of specific discharge, but do not actually give information on whether a river is flooding or not. Using a global model that includes a dynamic river routing module, we are able to simulate within channel and floodplain discharge. Moreover, most observed discharge time-series contain the effects of human interventions, such as dams and diversions for flood control. To examine the hydrometeorological impacts of ENSO, naturalised flows are required, which can be derived from the model. Prior to carrying out the analyses based on the modelled data, validation of the model's ability to simulate differences in the number and duration of extreme discharge events between ENSO phases was carried out.

The paper is set up as follows. In Section 2 we describe the methods used. In Section 3 we describe the validation of the model results, followed by the results in Section 4. In Section 5 we discuss the main findings of our research, and concluding remarks are given in Section 6.

2. Methods

The methods used in this study can be broken down into three main steps: (1) simulating a time-series of daily overbank flood volumes; (2) constructing a database of flood events per basin; and (3) statistical analyses of the relationships between ENSO and flood duration and frequency. These steps are described in the following subsections. We also performed several statistical tests to validate the performance of the modelled data against observed data; these tests are also described in this section.

2.1. Simulating a time-series of daily overbank flood volumes

In this paper, overbank flood volumes are used to derive a database of flood events. Firstly, daily flood volumes at a horizontal resolution of 0.5° x 0.5° were taken from the simulations described in Ward et al. (2013). These simulations used the global hydrological model PCR-GLOBWB-dynRout (Van Beek and Bierkens, 2009; Van Beek et al., 2011). PCR-GLOBWB is a "leaky bucket" large scale raster-based hydrological model, used to simulate specific discharge. It is a distributed model that describes the hydrological cycle as a series of storage compartments and flows. For each grid cell and day, water storage is calculated in two vertical soil layers and an underlying groundwater reservoir. Changes in storage occur in the model due to exchanges of water between these layers (percolation, capillary rise), depletion (interflow and base flow), and the atmosphere (rainfall, snowmelt and evapotranspiration). The dynRout extension (Petrescu et al., 2010) of PCR-GLOBWB estimates the volume of water per day per cell that is stored outside the river channel. It is a dynamic river routing module, based on a kinematic wave approximation of the Saint-Venant Equation (Chow, 1988). DynRout converts the sum of specific discharge and the direct gains and losses from in-river discharge, with overland flow in floodplain areas. Maximum in-channel storage is parameterised using geomorphological laws that do not account for flood control measures (Allen et al., 1994). Both PCR-GLOBWB and dynRout are described in detail in Winsemius et al. (2013).

The simulations used in this paper were carried out by Ward et al. (2013). In brief, this simulation was carried out for the period 1958-2001, using climate forcing data (daily precipitation, temperature, and global radiation) from the WATCH project (Weedon et al., 2011). Following Ward et al. (2013), we assumed that no overbank flood volumes occur at return periods below 2 years. This assumption is based on empirical geomorphological studies, such as Dunne and Leopold (1978). Hence, we first estimated the magnitude of a 2-year flood volume per grid-cell from PCR-GLOBWB-dynRout, and then subtracted this volume from all daily values, to obtain the time-series of daily overbank flood volumes. To estimate the 2-year flood volume, we extracted an annual time-series of maximum overbank flood volumes per cell for hydrological years 1958-2001. Hydrological years were classed using the approach described in Ward et al. (2014a). For most basins, we used standard boreal hydrological years, i.e. October-September. For basins in which the maximum annual discharge at the most downstream cell occurs in September, October, or November, we defined the hydrological year as July to June. The hydrological years are referred to by the year in which they end, as per standard convention (i.e., hydrological year 1970 refers to the period October 1969 to September 1970, or July 1969 to June 1970). Then, for each cell, we estimated the parameters of the Gumbel distribution fit to the non-zero data of the flood volumes time-series. The 2-year return period flood volume was then estimated using the Gumbel parameters, conditional to the exceedance probability of zero flood volume. Hence, the 2-year flood volume is defined in a purely statistical sense based on an annual time-series of annual maximum flood volumes; it does not refer to the flood volume associated with a 2-year return period discharge. The latter would be extremely difficult to calculate, since a 2-year discharge can be associated with an infinite number of flood volumes (e.g. Gaál et al., 2015). For ephemeral and highly variable rivers in arid regions, several studies have found bankfull discharge to occur at longer return periods (Gregory and Walling, 1973; Soar and Thorne, 2001; García de Jalón, 2003), with García de Jalón (2003) suggesting 5-8 years. Hence, for rivers with ephemeral flows in arid regions we used the 5 year return period. To assess the sensitivity of the results to these assumptions, we also carried out the analyses whereby flood events were simply defined as all events above average annual maximum annual flood volume.

2.2. Constructing a database of flood events per basin

We then developed a database of simulated flood events per basin (for basin delineation, see Ward et al. 2014a). In this paper, we define a flood event as a period of *n* days, in which overbank flood volume in any cell within a basin exceeds zero, and the number of consecutive days between non-zero overbank flood volumes is smaller than a threshold of *n* days. For example, if the threshold is set to n = 7 days, then if flood volume exceeds zero for 5 consecutive days, the duration (d) is 5 days. If the flood volume exceeds zero for 5 consecutive days, followed by 6 days of zero flood volume, and then 2 more days exceeding zero flood volume, d = 13 days (5 days + 6 days + 2 days). However, if flood volume exceeds zero for 5 consecutive days, followed by 7 days of zero flood volume, and then 2 more days exceeding zero flood volume, this counts as two flood events of d = 5 and d = 2 days respectively. In this paper, we used a threshold of 7 days. We also test the sensitivity of the results to this assumption in Section 4.1, finding the results to be very insensitive. For each flood event, we recorded the following parameters: start date, end date, and duration (in days).

2.3. Statistical analyses of the relationships between ENSO and flood duration and frequency

Having derived a database of flood events per sub-basin, we conducted statistical analyses to examine possible relationships between ENSO and both flood frequency and flood duration. To do this, we required indicators of ENSO strength and phase.

2.3.1. Indicators of ENSO

For the analyses carried out in this paper, we used two indicators of ENSO. First, we used the Southern Oscillation Index (SOI; http://www.cru.uea.ac.uk/cru/data/soi.htm) to assess the correlation between ENSO and different indicators of flood duration and frequency. Specifically, we used mean values of the SOI index over the months December-January- February (SOI_{DJF}). This period was chosen since this is the season in which El Niño and La Niña events generally reach their fullest (tropical) expression.

Second, we also used a classification of each year as El Niño, La Niña, or neutral, in order to assess differences in flood frequency and duration between these ENSO phases. For this purpose, we used the classification of the Center for Ocean-Atmospheric Prediction Studies (COAPS) (http://coaps.fsu.edu/jma.shtml), as shown in Table 1. In the original COAPS classification, ENSO years refer to the period October-September, whereby ENSO year 1970 refers to the period October 1970 to September 1971. These were therefore adjusted by 1 year to be consistent with the hydrological year naming convention used (see Section 2.1).

Table 1: Hydrological years categorised as El Niño and La Niña, based on the ENSO classification of the Center for Ocean-Atmospheric Prediction Studies (COAPS) of Florida State University (http://coaps.fsu.edu/jma.shtml). Other years are classified as neutral. Note that in the original COAPS classification, ENSO years refer to the period October-September, whereby ENSO year 1970 refers to the period October 1970 to September 1971. These were therefore adjusted by 1 year to be consistent with the hydrological year naming convention used.

ENSO phase	Hydrological Year
El Niño	1964, 1966, 1970, 1973, 1977, 1983, 1987, 1988, 1992, 1998
La Niña	1965, 1968, 1971, 1972, 1974, 1975, 1976, 1989, 1999, 2000

2.3.2. Statistical analyses

Differences in flood frequency between ENSO phases at the global scale

We examined differences in the number of floods per year during each ENSO phase (El Niño, neutral, La Niña) at the global scale. This was done by summing the number of flood events per (hydrological) year for all basins. We then calculated the percentage anomaly in the number of floods between El Niño and neutral years, and between La Niña and neutral years. We then bootstrapped the Mann-Whitney U test, with 1000 realisations, to assess whether there is a statistically significant difference in the median flood duration between the ENSO phases.

Relationships between flood duration and ENSO phases at the global scale

We examined relationships between the duration of floods and ENSO phase at the globally aggregated scale. To do this, we extracted the duration (in days) of each flood event, and then split these into floods that occurred in the different ENSO phases. We then used 2-tailed Kolmogorov-Smirnov (KS) and Mann-Whitney U (MWU) tests to examine the statistical significance of difference (between El Niño and neutral years, and between La Niña years and neutral years) in the empirical cumulative frequency distributions (CDFs) of the probability of non-exceedance of different durations.

Differences in flood frequency and duration at the river basin scale

We also assessed relationships between ENSO and flood frequency and duration at the river basin scale. To do this, we computed the rank correlation (Spearman's rank) between annual (hydrological year) values of SOI_{DJF} and: (1) the number of floods per year per basin; and (2) the total flood duration per year per basin. Statistical significance per basin was assessed by bootstrapping and computing Spearman's rank correlations ($\alpha = 0.05$; 1000 repetitions) for each bootstrapped sample. The field significance of the correlation field was further assessed by testing the null hypothesis that the number of correlations identified as significant at the 0.05 level could result purely by chance. Recognising that there may be potential for spatial correlation across basins, bootstrap samples were drawn such that a full year preserving the spatial structure was drawn at a time, thus randomising time but not space, and then the correlations were computed for this bootstrap set. The number of sites where the correlation was significant at the 0.05 level based on the bootstrap samples was recorded. The probability distribution of the number that could be significant for this data set under chance was then assessed through the empirical probability distribution of such counts across the 1000 bootstrap samples. The observed number of significant correlations at the 0.05 level was then compared with this empirical distribution to assess whether or not the number found was in the tails of that distribution, such that one could reject the null hypothesis that the observed number of significant correlations occurred by chance.

The same experiment was repeated with a block size of 3 years and with a block size of 5 years to address the potential for serial correlation of the data. The conclusions were unchanged when this was done, and hence those results are not presented here.

2.4. Model validation

To validate the model's performance in terms of its ability to simulate the difference in flood frequency or duration between different ENSO phases, we compared our modelled discharge outputs with observed discharge. To do this, we selected all gauging stations in the GRDC dataset with an upstream area exceeding 10,000 km^2, for which daily discharge data are available for all days between 1958 and 2001. This yielded the 286 gauging stations shown in Figure 1, which are highly biased towards North America, northern Europe, and parts of Australia. We then extracted the daily discharge time-series from the modelled and observed datasets, and used them to create a dataset of modelled and observed flood events, whereby a flood event is defined as discharge in excess of 2 year return period (RP2), as estimated using the Gumbel distribution. The resulting time-series were reclassified to indicate for each day whether the river was flooding (1) or not (0). From this, we extracted the number of events per hydrological year, as well as the duration of each event in days.

Firstly, we validated whether the ratio of the number of flood events per year in El Niño years to the number of flood events per year in neutral years is similar in the observed and modelled datasets. To perform this validation, we developed a 2 x 2 contingency table for each station, showing the number of flood events per year (n) in El Niño years and neutral years, in both the modelled and observed datasets. We then performed 2-tailed Fisher's Exact Probability Tests (α = 0.10) to assess the statistical significance of the difference in the ratio found for the observed dataset compared to the ratio found for the modelled dataset. The same analysis was carried out for La Niña years versus neutral years.

Secondly, we validated the model's ability to simulate differences in flood duration between the different phases of ENSO. To validate model performance for median flood durations, we calculated for each station the percentage difference in median flood duration between El Niño years and neutral years (and between La Niña years and neutral years) in both the observed and modelled data. We then assessed the statistical significance of these differences using a 2-tailed MWU-test (α = 0.05), and examined whether the observed and modelled datasets agree (or disagree) on the sign of the difference in median duration between El Niño years and neutral years (and La Niña and neutral years). Similarly, we used the KS-test (α = 0.05) to assess the statistical similarity or difference of the frequency distributions of flood durations between El Niño years and neutral years, and between La Niña years and neutral years.

Finally, a quasi-validation was carried out against the Global Active Archive of Large Flood Events of the Dartmouth Flood Observatory (DFO)[1], hereinafter referred to as the DFO Archive. The DFO Archive is a database of reported flood events derived from news, governmental, instrumental, and remote sensing sources. One of the variables recorded in the DFO Archive is flood duration in days, and hence we compared our modelled flood durations with the flood durations in the DFO Archive. First, we removed all flood events from the DFO Archive for which the main cause was not related to riverine flooding and for processes which are not included in the model ('ice jam/break-up', 'dam/levee, break or release', 'tidal surge', 'avalanche related', and 'tsunami'), or where the main cause was listed as 'Unknown'. We then calculated the mean and median duration of floods exceeding day in the DFO Archive and in the modelled dataset. Since the definition of floods used in the DFO Archive is not exactly the same as that used here, this assessment is only intended for indicative proposes, and so no statistical conclusions can be drawn.

3. Validation

Various output of PCR-GLOBWB-dynRout have been validated against observed data in past studies, namely: mean annual discharge (Van Beek et al., 2011); terrestrial water storage (Wada et al., 2012); extreme discharge (Ward et al., 2013) ; interannual variability in peak discharge (Ward et al., 2014b); and relative differences in peak discharge between different phases of ENSO (Ward et al., 2014b). All these found good agreement with the simulated and observed parameters. Here, we further validate the model specifically in terms of its ability to simulate the difference in flood durations or the number of flood events between different ENSO phases, using the tests described in Section 2.4.

[1] G.R.Brakenridge, "Global Active Archive of Large Flood Events", Dartmouth Flood Observatory, University of Colorado, http://floodobservatory.colorado.edu/Archives/index.html.

Figure 1 shows whether the ratio of the number of flood events in El Niño years compared to neutral years, and in La Niña years compared to neutral years, is similar between the observed and modelled datasets (Fisher's Exact Probability Test, $\alpha = 0.10$); this is the case for the vast majority of stations. In fact, there are just six gauging stations with a different ratio (between observed and modelled) of the number of flood events in El Niño years compared to neutral years and a similar ratio for La Niña years compared to neutral years; and five stations with a similar ratio (between observed and modelled) in El Niño years compared to neutral years and a different ratio in La Niño years compared to neutral years. The analysis was repeated using only flood events with durations of at least 2, 5, 7, and 10 days. These results are shown in Figure A.1. The results show the same general results as those shown in Figure 1. Moreover, we assessed the number of observed gauging stations for which there is a significant difference in the number of floods per year between El Niño and neutral years ($n = 33$), and La Niña and neutral years ($n = 36$) (2-tailed Mann Whitney U-test (MWU-test), $\alpha = 0.10$). For these stations, we then assessed the differences per ENSO phase in the modelled data, and found the signal to agree for 97% (El Niño versus neutral) and 86% (La Niña versus neutral) of the stations.

Figure 1 approximately here

In Figure 2a, we show whether the modelled and observed datasets agree (or disagree) on the sign of the difference in median flood duration between El Niño years and neutral years (MWU-test, $\alpha = 0.05$). The same results are shown for La Niña years compared to neutral years in Figure 2b. The key finding is that there is either no statistically significant difference in median flood duration in both the observed and modelled datasets, or a statistically significant difference with the same sign in both the observed and modelled datasets, at 90% of the stations for El Niño versus neutral years, and at 87% of the stations for La Niña versus neutral years. There are no stations for which modelled and observed median flood duration show significant differences between El Niño and neutral (or La Niña and neutral years) years with the opposite sign. For the observed gauging stations for which there is a significant difference in the flood duration between El Niño and neutral years, or between La Niña and neutral years, we also assessed the differences per ENSO phase in the modelled data, and found the signal to agree for all but one basin for both El Niño years versus neutral (Grand River; Tributary of Lake Michigan, USA) and La Niña years versus neutral (Clark Fork, Montana, USA). Again, we also performed the analysis whilst only considering flood events with durations of at least 2, 5, 7, and 10 days. These results are shown in Figures A.2-A.5. The percentage of basins for which both modelled and observed data agree that there is either no statistical difference in the median flood duration between ENSO phase, or that there is a statistically significant difference with the same sign, is even higher than when considering floods of all durations.

Figure 2 approximately here

In Figure A.6, we show whether the modelled and observed datasets agree (or disagree) on the statistical similarity or difference in frequency distributions between El Niño years and neutral years (KS-test, $\alpha = 0.05$). In Figure 3b, the same results are shown for La Niña years compared to neutral years. Again, for the majority of basins, the observed and modelled datasets show agreement on the statistical similarity or difference in the frequency distribution between different ENSO phases.

Comparing our results for all stations with the DFO Archive, we find a median flood duration of 6 days in both datasets, whilst the mean durations are 12 and 16 days in the DFO Archive and modelled dataset respectively.

The validation procedures described above indicate that PCRGLOB-WB-dynRout appears to simulate well the relative difference in the number of flood events, and their duration, between ENSO phases.

4. Results

In this section we first present results for the influence of ENSO on simulated flood frequency and durations at the global scale, followed by the basin scale.

4.1. ENSO and flood frequency and durations at the global scale

First, we examined the difference in number of floods per year during each ENSO phase (El Niño, neutral, La Niña) at the global scale. During the neutral phase, we simulated a median of 6491 flood events per year. During the El Niño and La Niña phases, we simulated 3.2% and 2.8% fewer flood events per year, although neither of these differences is statistically significant (Mann-Whitney U test: $p = 0.167$ (El Niño vs. neutral); $p = 0.363$ (La Niña vs. neutral). Hence, at this globally aggregated scale, we found no statistically significant difference in the number of floods during El Niño and La Niña years, compared to neutral years.

Next, we examined relationships between the duration of floods and ENSO phase. Even at the globally aggregated scale, we found significant differences in the distribution of flood durations between ENSO phases. We found longer duration flooding during El Niño years compared to neutral years (KS-test, $p < 0.001$; MWU-test, $p < 0.001$), and in La Niña years compared to neutral years (KS-test, $p = 0.049$; MWU-test, $p = 0.076$).

The analyses above assume that overbank flood volumes occurring within 7 days of each other belong to the same flood event (see Section 2.2). We tested the sensitivity of the results to this assumption, by also using thresholds of 3 days and 10 days. The resulting p-values of the bootstrapped Mann-Whitney U test can be found in Table B.1. These are shown at the globally aggregated scale, and also aggregated to 12 regions (defined by Kummu et al. (2010) and based on United Nations macroregions (United Nations, 2000).

4.2. ENSO and flood frequency and durations at the basin scale

Here, we present relationships between ENSO and flood frequency and duration at the river basin scale. For both flood frequency and flood duration, the results are shown only for floods above different duration thresholds (parts a-j of Figure 3 and Figure 4).

For flood frequency, the results are shown in Figure 3. Field significance of the correlations at the global scale led to a rejection of the hypothesis that the number of basins with significant correlations could occur by chance ($p < 0.001$ up to the 28 day threshold inclusive; and $p = 0.004$ for the thresholds of 56 and 84 days). The lowest number of basins with significant correlation was found when considering all floods (i.e. duration ≥ 1 day). Considering floods of only longer duration, the number of basins with significant correlation increases, and the strength of the correlation also increases in many cases. For example, in South Asia only a few basins show significant correlation between ENSO and flood frequency when all floods are considered (Figure 3a). However, if we only consider floods of 2 days or longer in the analysis (Figure 3b), there is a negative correlation (more floods in El Niño years and/or fewer floods in La Niña years) in the majority of the basins in South Asia. Similarly, for the basins in Southern Africa we see few statistically significant correlations when all floods are included (Figure 3a) or all floods of 2 days or longer (Figure 3b), but strong significant correlations when floods of 5 days or longer are analysed.

Figure 3 approximately here

In Figure 4, we show similar results, but in this case for the rank correlation between SOI_{DJF} and the total flood duration per year (in days) per basin. Again, the results for all thresholds show very strong field significance ($p < 0.001$ up to the 28 day threshold inclusive; and $p = 0.003$ for the thresholds of 56 and 84 days). Compared to the results for flood frequency at the basin scale, we find much more and stronger correlations between ENSO and flood duration when floods of all durations (≥1 day) are included. In particular, large parts of southern Africa show significant positive correlation between flood duration and ENSO (longer floods during La Niña phase and/or shorter during El Niño), where no significant correlation was seen between ENSO and the number of floods. Also, basins around the Uruguay and Paraná rivers in South America show significant negative correlation (longer floods during El Niño phase and/or shorter during La Niña) (Figure 4), where no significant correlations were seen for flood frequency (Figure 3). Similarly, the number and strength of significant correlations is greater for durations than for flood frequencies, when we exclude floods shorter than 2 to 10 days in the analysis. However, for longer durations (≥14 days and longer), the overall patterns are similar (although there are of course differences between individual basins).

Figure 4 approximately here

The results in this section are based on the assumption described in Section 2.1, namely that flood events are defined as those with a flood volume exceeding the estimated 2-year return period flood volume. As described in the methods section, we also relaxed this assumption and carried out the analyses whereby flood events are defined as those with a flood volume exceeding annual maximum flood volume. These results can be found in Figure A.7 (flood frequencies) and Figure A.8 (flood durations), which show very similar patterns to the results in Figure 3 and Figure 4. Hence, the sensitivity of the analyses and results to this assumption is low.

5. Discussion

5.1. Influence of ENSO on flood frequency and duration

When aggregated globally, our findings suggest that ENSO does not have a significant influence on the number of flood events. This is in line with findings of Dilley and Heyman (1995) and Goddard and Dilley (2005), who examined differences in the frequency of reported flood disasters in two disaster reporting databases. However, our results do show significant anomalies in flood duration, even at the globally aggregated scale, between both El Niño versus neutral years, and La Niña versus neutral years.

At the basin scale, we show that there are strong relationships between ENSO and both flood frequency and duration across a large number of basins spread across the world. Similar findings have been found for flood magnitudes or frequencies for several basins at the regional scale, as described below. The strength of the correlations tends to become stronger when the shortest duration flood events are excluded from the analysis. In general, the strength of the correlations in many basins appears to be stronger between ENSO and flood duration, than between ENSO and flood frequency.

Generally, the basin scale relationships show similar spatial patterns to global scale studies of ENSO influence on mean annual discharge (e.g. Dettinger and Diaz, 2000; Dettinger et al., 2000; Chiew and McMahon, 2002; Labat, 2010), and peak annual discharge (Ward et al., 2010; 2014a). Only few studies at local or regional scale have specifically assessed ENSO's influence on floods. Most of those have examined relationships between observed annual peak discharge and indices of ENSO (e.g. Waylen & Caviedes, 1986; Cayan and Webb, 1992; Kiem et al., 2003; Kiem and Vernon-Kidd, 2013). Only a handful of studies have specifically addressed ENSO's influence on the number of floods per year and/or the duration of floods. The following section provides a comparison of the results of these past studies to our new simulated results for flood frequencies and durations. Since scores to hundreds of studies have examined relationships between ENSO and mean annual discharge for individual river basins or countries, and the focus of this paper is not on mean discharge, we do not include a comparison to all of these studies in this paper.

Using observed daily discharge data, Cayan and Webb (1992) showed that the magnitude of 100-year discharge at the Santa Cruz river at Tucson is significantly larger during El Niño years. Our study does not specifically examine discharge magnitudes. However, for flood durations, we found statistically significant negative correlations (α=0.10) between SOI_{DJF} and flood durations (Figure 4) (Spearman's rank correlation ranging from -0.36 to -0.33 depending on the duration thresholds). For flood frequency, a statistically significant correlation is only found between SOI_{DJF} and the number of floods per year when a flood duration threshold of 84 days is used.

Extending this analysis, Cayan et al. (1999) examined relationships between ENSO and the number of days with high daily discharge for 303 locations in the western USA. They found that the number of days with high discharge is higher than average during El Niño years in southwest USA, and lower than average in northwest USA. For La Niña years, they found an almost opposite pattern. Although the days with high discharge do not necessarily correspond to flood events in the sense of the current paper (i.e. events leading to overbank inundation), we do simulate negative correlations between ENSO and flood frequency and duration in the southwest USA (i.e. more and longer duration floods during El Niño and /or fewer and shorter during La Niña) (Figures 3 and 4).

For coastal California, Andrews et al. (2004) specifically examined anomalies in flood frequencies (expressed as changes in exceedance probabilities) between El Niño years and non-El Niño years. They found significantly higher flood frequencies during El Niño years, with larger anomalies in Southern California and lower anomalies in northern California. Similarly, we found significant positive correlations between SOI_{DJF} and the number of flood events per year, with the largest anomalies in the southern parts of the state (Figure 3). For flood durations, we also found significant positive correlations (Figure 4); the strength of the correlations is generally similar to those found for flood frequencies.

For Eastern Australia, Kiem et al. (2003) and Kiem and Vernon-Kidd (2013) have carried out studies to condition flood return periods for a regional flood index for New South Wales on El Niño and La Niña years only. These results show higher flood magnitudes during La Niña years compared to El Niño years, although the neutral phase is not shown. Our results agree with these findings, in that they show increased flood duration in Eastern Australia during La Niña years, especially when we consider only the longest duration floods.

Our results show increased flood durations in Eastern Australia, especially when we consider only the longest duration floods.

Mosley et al. (2000) assessed the influence of ENSO on flood frequency, based on an analysis of observed discharge time-series in New Zealand. Whilst significant negative anomalies in annual peak discharge were found during El Niño years, especially in rivers of the North Island, the effect of ENSO on flood frequency was weaker. In our study, we simulated few significant correlations between flood frequency and SOI_{DJF} in New Zealand (Figure 3), and in an existing study on flood magnitudes using the same model output (Ward et al., 2014b), they also found negative anomalies in flood magnitude during El Niño years in the North Island.

In north-eastern Peru, Waylen and Caviedes (1986) assessed anomalies in peak discharge during El Niño years, based on time-series of annual peak discharge for 13 rivers in the region. They found strong positive peak discharge anomalies during El Niño years. Similarly, we found strong positive correlations between SOI_{DJF} and both flood frequency and flood duration in this region (Figures 3 and 4). The strength of the correlations is greater for flood durations than for flood frequencies.

Even fewer studies have assessed the influence of ENSO on flood durations. Räsänen and Kummu (2013) assessed the impacts of ENSO on the hydrology of the Mekong, including flood duration. Compared to long-term average flood pulse duration (194 days), they found that flood pulse durations are on average 5 days shorter during El Niño years and 17 days longer during La Niña years. Another study in a flood pulse driven river, the Amazon (Schöngart and Junk, 2007), found prolonged flood durations during La Niña events. Both of these studies are in line with our findings (cf. Figure 4). Chowdhury (2010) examined the response of the flood pulse in the Brahmaputra basin to ENSO. The flood pulse duration was found to be 9 days shorter than the average of 123 days during strong El Niño events, and 6 days longer than average during strong La Niña events. Whilst we found no significant correlation between ENSO and flood durations in the Brahmaputra when flood events of all durations are considered, we did find significant positive correlation when examining longer duration floods (≥56 days) (Figure 4). The latter is therefore in agreement with the results of Chowdhury (2010), which are related to the long duration flood pulse.

5.2. Implications for flood assessments

Our findings show that strong relationships exist between ENSO and both flood frequency and flood duration in river basins covering large parts of the globe, indicating strong links between these flood characteristics and climate. This has several implications for assessing the societal impacts of flooding.

In terms of flood risk assessment, methods to date at the global scale (Arnell and Gosling, 2014; Arnell and Lloyd-Hughes, 2014; Hirabayashi et al., 2013; Ward et al., 2013, 2014b) do not incorporate flood duration, instead focusing on maximum flood extent and depth for theoretical events with different return periods. Also in more local scale flood risk assessments, flood extent and depth are the most often considered components (Merz et al., 2010; Meyer et al., 2013). Whilst some research does suggest that flood depth is the main determinant of flood damage in some areas (e.g. Penning-Rowsell and Chatterton, 1977; Penning-Rowsell et al., 1994; Wind et al., 1999), the duration of flooding is also a key determinant of overall risk (e.g. Parker et al., 1987; Lekuthai and Vongvisessomjai, 2001; FEMA, 2005; Hallegatte et al., 2008; Elmer et al., 2010; Dang et al., 2011; Koks et al., 2015). This is particularly the case for indirect losses and health-related issues and mortalities. Since our results indicate a linkage between climate and flood duration, this aspect deserves more attention in studies of flood risk.

On the other hand, the annual flood pulse is an essential hydrological component in many wetland and floodplain areas (Junk et al., 1989). The regular flood pulse of some floodplains is believed to be an important factor in their high biological productivity (e.g. Junk et al. 1989; Thorp and Delong 1994). By increasing the understanding of the linkages between ENSO and the important flood pulse parameters, flood peak (Ward et al 2014a), and flood duration (this study), the understanding of the drivers behind the variability in biological productivity in globally and locally important floodplains could be increased.

The results of this study could also be relevant to discussions on future risks due to changing climate. While the impacts of future climate change on ENSO dynamics is highly uncertain (Van Oldenborgh et al., 2005; Paeth et al., 2008; Guilyardi et al., 2009), there is evidence that El Niño sea surface temperature variability has responded to greenhouse warming since 1950 (Kim et al., 2015). Recent research also suggests that interannual variations of sea surface temperatures and precipitation related to ENSO, are likely to intensify in the future (IPCC, 2013; Power et al., 2013), and that extreme El Niño (Cai et al., 2014) and La Niña events (Cai et al., 2015) may increase in frequency. If this were to occur, it could lead to changes in flood frequencies and durations around the world. Whilst studies abound that attempt to project the influence of climate change on discharge, and on extreme discharge (for reviews, see Kundzewicz et al., 2007; IPCC, 2012; and Kundzewicz et al., 2014), only a few research studies have examined the potential impacts of climate change on flood duration, for example Arias et al. (2012, 2014) for the Tonle Sap lake in Cambodia; Västilä et al. (2010) for the Lower Mekong floodplains of Cambodia and Vietnam; and Panagoulia and Dimou (1997) for the Mesochora catchment in Central Greece.

5.3. Key limitations and future work

The research described in this paper is intended to give a first assessment of the influence of ENSO on flood frequency and flood duration. However, for a more detailed understanding of the influence of climate variability, and indeed climate change, on flood durations, more detailed studies are required using fully hydrodynamic models that are better capable of solving overbank flows, and hence flood duration. At the same time, it would also be useful to carry out more local to regional scale studies based on observed hydrological data, especially in those regions where the influence of ENSO on hydroclimatology is known to be strong. This would also allow us to gain an improved understanding of the sensitivity of the results to the assumptions required to carry out a global modelling exercise such as that described here; such as using different indices of ENSO and classifications of ENSO years, different classifications of hydrological years, and different threshold for defining individual flood events.

In this assessment we only used results from one hydrological model forced by one reanalysis dataset. A more thorough understanding of the relationships between climate and flood duration and frequency could be gained in future by carrying out analyses based on an ensemble of hydrological models and climate forcing datasets, including longer duration forcing datasets. Moreover, a global scale analysis of the potential influence of projected future climate change on flood durations would be very useful from a flood risk planning and development perspective.

Moreover, in future research it would be useful to examine whether, and if so how, the relationship between ENSO and flood durations and frequency has changed over time. Related to this, our research does not account for changes in river management practices over time, which could have a very strong influence on all aspects of hydrology, including flood hydrology. Hence, our results should be interpreted as an assessment of ENSO's influence on flood frequency and durations under naturalised conditions. It would be useful to examine how changes in river management practices may have altered these relationships over time, particular in more detailed studies at the basin or more local scale.

This study does not assess the influence of ENSO on flood volumes, which are also important for the design of retention basins, reservoir spillways, and other hydraulic structures (Gaál et al., 2015). In future studies it would be useful to extend the analyses to include this aspect. Since the dependence between flood peaks, durations, and volumes are very different between basins (e.g. Gaál et al., 2015), this would involve a different approach to the univariate statistical methods used here. For example, the use of copula theory has recently been used to assess the dependence between flood peaks and volumes (e.g.Grimaldi and Serinaldi, 2006; Chowdhary et al., 2011; Bačová-Mitková and Halmová, 2014). Given the challenges of identifying the correct copula function (e.g. Favre et al., 2004; Genest and Favre, 2007; Chowdhary et al., 2011), we believe that it would be most useful to first develop such an assessment at the local or regional scale, in one of the areas where hydrology is known to be influenced by ENSO.

Next to ENSO, many other large-scale climate oscillations can influence hydrological variables, and different climate oscillations may event interact and modulate or enhance each other's impacts. Examples of such interactions include those reported for the Pacific Decadal Oscillation (e.g. Gershunov and Barnett, 1998; Gershunov et al., 1999; McCabe Jr. and Dettinger, 1999; Gobena and Gan, 2006). Other large scale climate oscillations that can influence hydrological variables include the Atlantic Oscillation, North Atlantic Oscillation, and Indian Ocean Dipole. Further research is required to examine the interactions between these large scale climate oscillations and their resulting influence on floods and flood risk.

6. Concluding remarks

The main objective of this paper was to provide a preliminary understanding of the link between climate and flood durations and frequencies, at the global scale. The results show clear relationships between ENSO and flood durations. In general, the results suggest that ENSO has a greater impact on flood durations than on flood frequency across large parts of the world.

The link between climate variability and flood duration is of particular relevance for large scale flood risk assessment. To date, most flood risk assessment methods do not include flood duration in their representation of flood hazard. This is true for flood risk assessments at all spatial scales, but especially for global scale studies. Several studies have shown that flood durations are important in terms of flood impacts, especially for indirect damage and flood-related health issues. Given this importance, and the fact that we have found clear relationships between flood durations and climate variability, we suggest that future developments in (global scale) flood risk assessment should pay increased attention to flood duration. Our results further indicate that in many basins with globally important wetlands (e.g. Zambezi, Mekong, parts of Amazon), ENSO has significant impacts on flood duration.

Acknowledgements

This research was funded by a VENI grant (863.11.011) from the Netherlands Organisation for Scientific Research (NWO). M.K. received funding from the Academy of Finland project SCART (grant no. 267463). U.L. received funding through a project funded by AIG, and through an IPA with the US Army Corps of Engineers. We thank the anonymous reviewers and editor for their valuable comments on earlier versions of the manuscript.

Figure captions

Figure 1: Indicator of the statistical similarity / difference in the ratios of the number of flood events per year in El Niño compared to neutral years (and La Niña years compared to neutral years) in the modelled dataset compared to the ratio in the observed data. Statistical significance was assessed using a 2-tailed Fisher's Exact Probability Test for a 2 x 2 contingency matrix ($\alpha = 0.10$).

Figure 2: Indicator of the agreement / disagreement between modelled and observed median flood duration between: (a) El Niño years and neutral years; and (b) La Niña years and non-La Niña years. Statistical significance was assessed using a 2-tailed Mann Whitney U (MWU) test, $\alpha = 0.05$.

Figure 3: Spearman's rank correlation coefficient per sub-basin between SOI_{DJF} and the number of floods per hydrological year exceeding different durations. Statistical significance per basin was assessed by bootstrapping the Spearman's rank correlations with 1000 repetitions ($\alpha = 0.10$). Field significance was also assessed by bootstrapping, and found to be highly significant in all cases ($p < 0.001$ up to the 28 day threshold inclusive; and $p = 0.004$ for the thresholds of 56 and 84 days). Negative correlation generally represents more floods in El Niño years/fewer floods in La Niña years, while positive correlation generally represents the opposite.

Figure 4: Spearman's rank correlation coefficient per sub-basin between SOI_{DJF} and the total duration of all flood events (days) exceeding different durations per hydrological year. Statistical significance per basin was assessed by bootstrapping the Spearman's rank correlations with 1000 repetitions ($\alpha = 0.10$). Field significance was also assessed by bootstrapping, and found to be highly significant in all cases ($p < 0.001$ up to the 28 day threshold inclusive; and $p = 0.003$ for the thresholds of 56 and 84 days). Negative correlation generally represents longer durations in El Niño years/shorter durations in La Niña years, while positive correlation generally represents the opposite.

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Appendices

Figures

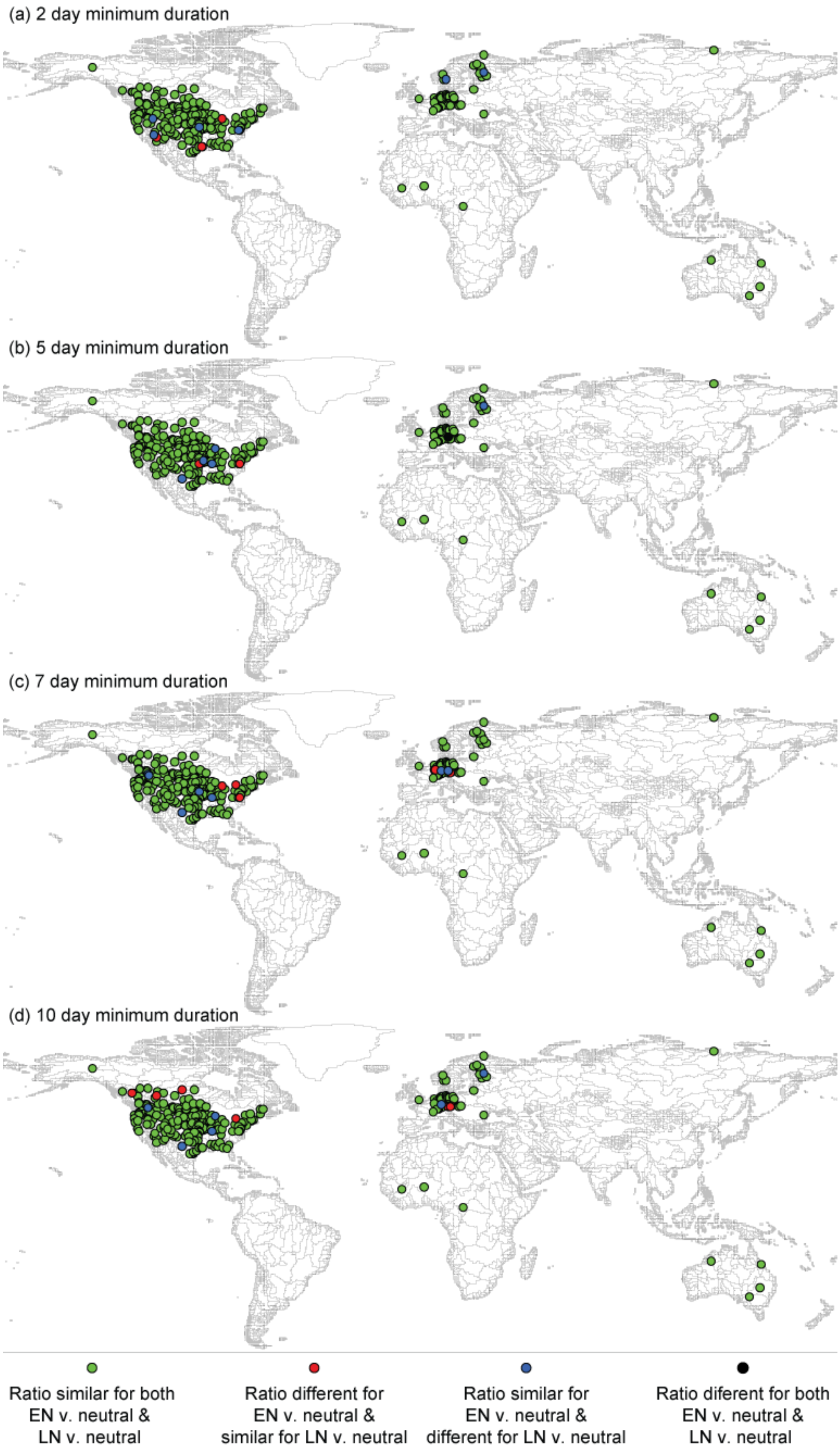
(a) 2 day minimum duration
(b) 5 day minimum duration
(c) 7 day minimum duration
(d) 10 day minimum duration
Ratio similar for both EN v. neutral & LN v. neutral
Ratio different for EN v. neutral & similar for LN v. neutral
Ratio similar for EN v. neutral & different for LN v. neutral
Ratio diferent for both EN v. neutral & LN v. neutral

Figure A.1: Indicator of the statistical similarity / difference in the ratios of the number of flood events per year in El Niño compared to neutral years (and La Niña years compared to neutral years) in the modelled dataset compared to the ratio in the observed data. Statistical significance was assessed using a 2-tailed Fisher's Exact Probability Test for a 2 x 2 contingency matrix (α = 0.10). The results are shown for floods with a duration of at least: (a) 2 days, (b) 5 days, (c) 7 days, or (d) 10 days).

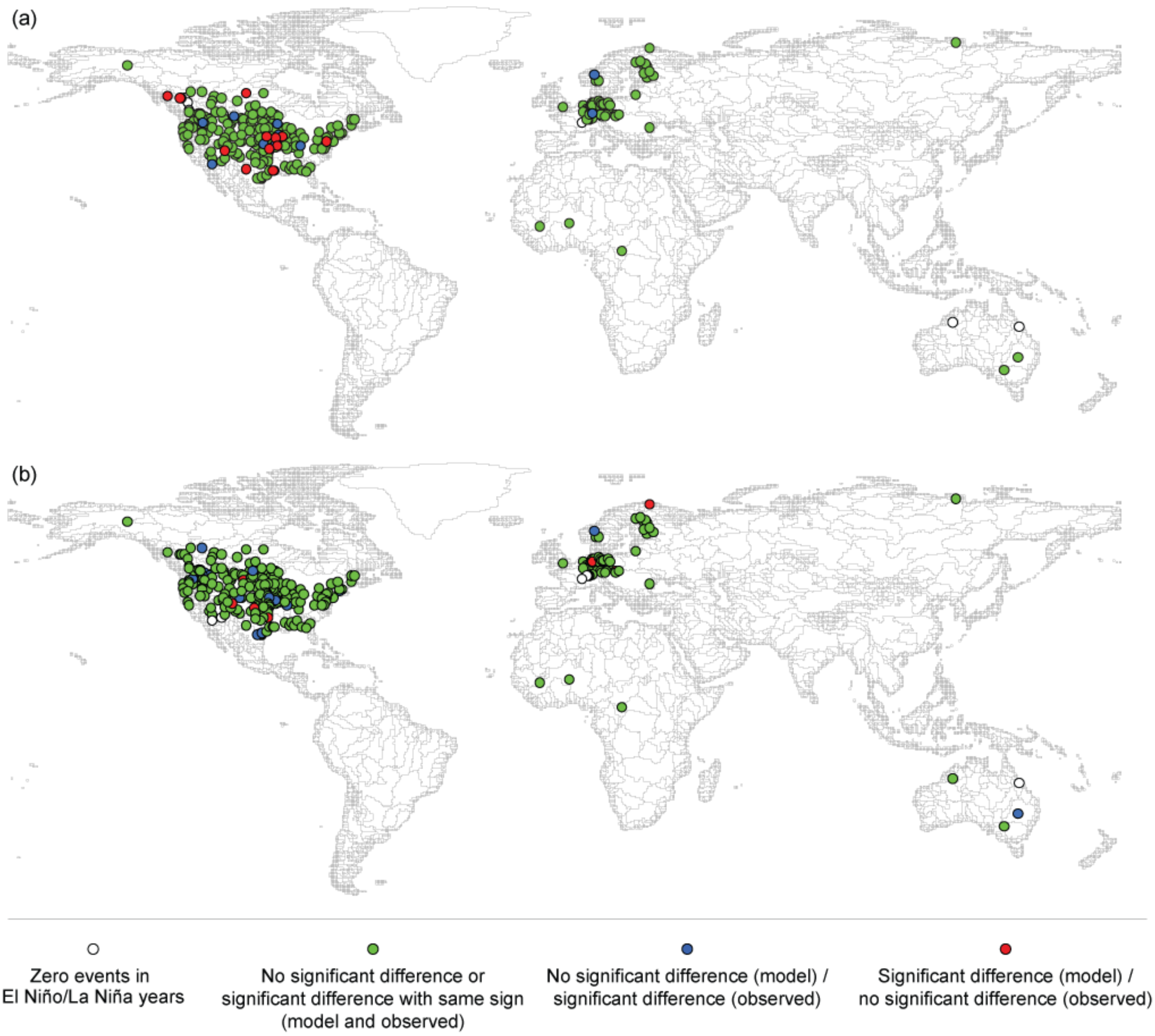

Figure A.2: Indicator of the agreement / disagreement between modelled and observed median flood duration, for floods of at least 2 day duration, between: (a) El Niño years and neutral years; and (b) La Niña years and non-La Niña years. Statistical significance was assessed using a 2-tailed Mann Whitney U (MWU) test, α = 0.05.

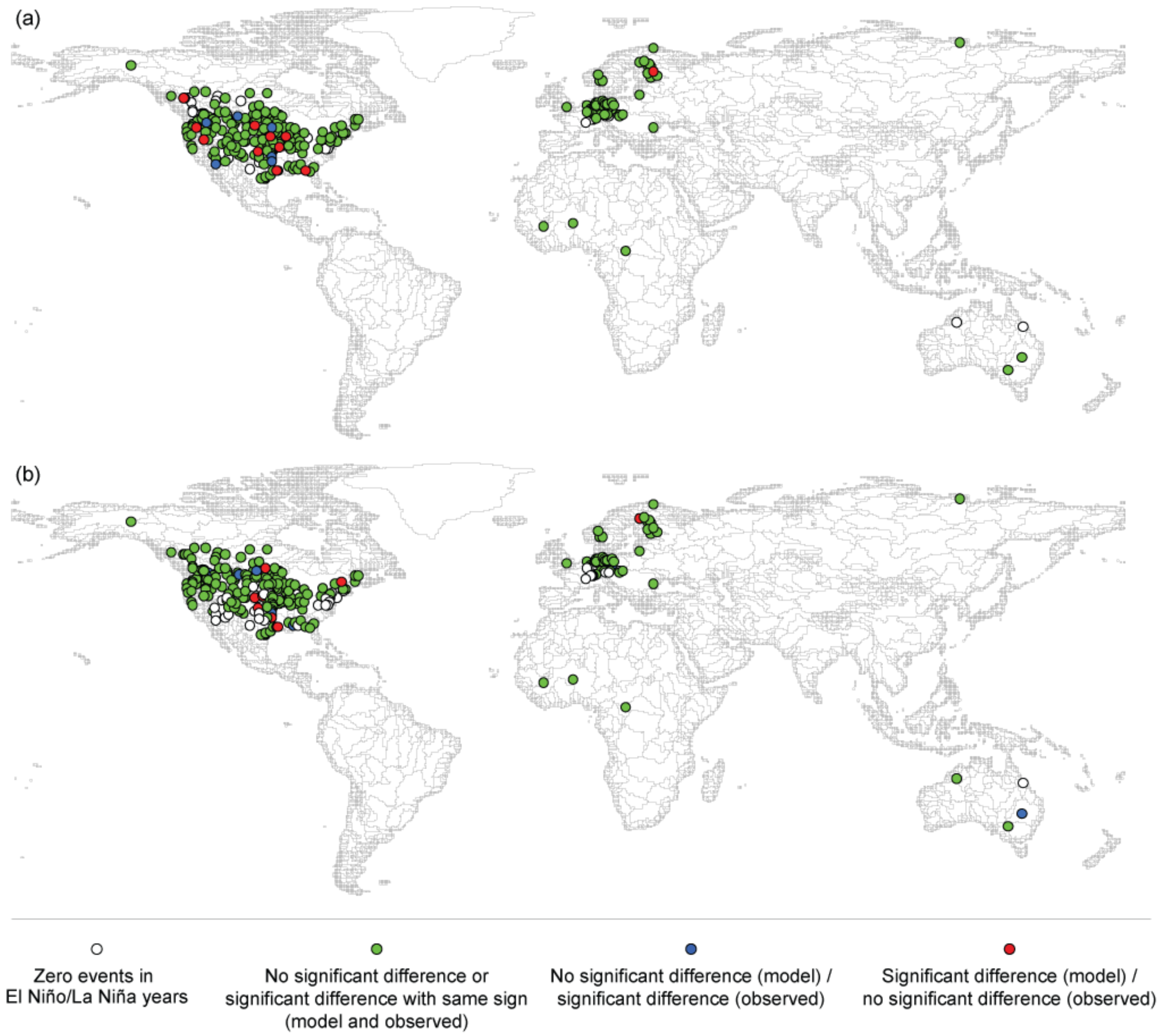

Figure A.3: Indicator of the agreement / disagreement between modelled and observed median flood duration, for floods of at least 5 day duration, between: (a) El Niño years and neutral years; and (b) La Niña years and non-La Niña years. Statistical significance was assessed using a 2-tailed Mann Whitney U (MWU) test, α = 0.05.

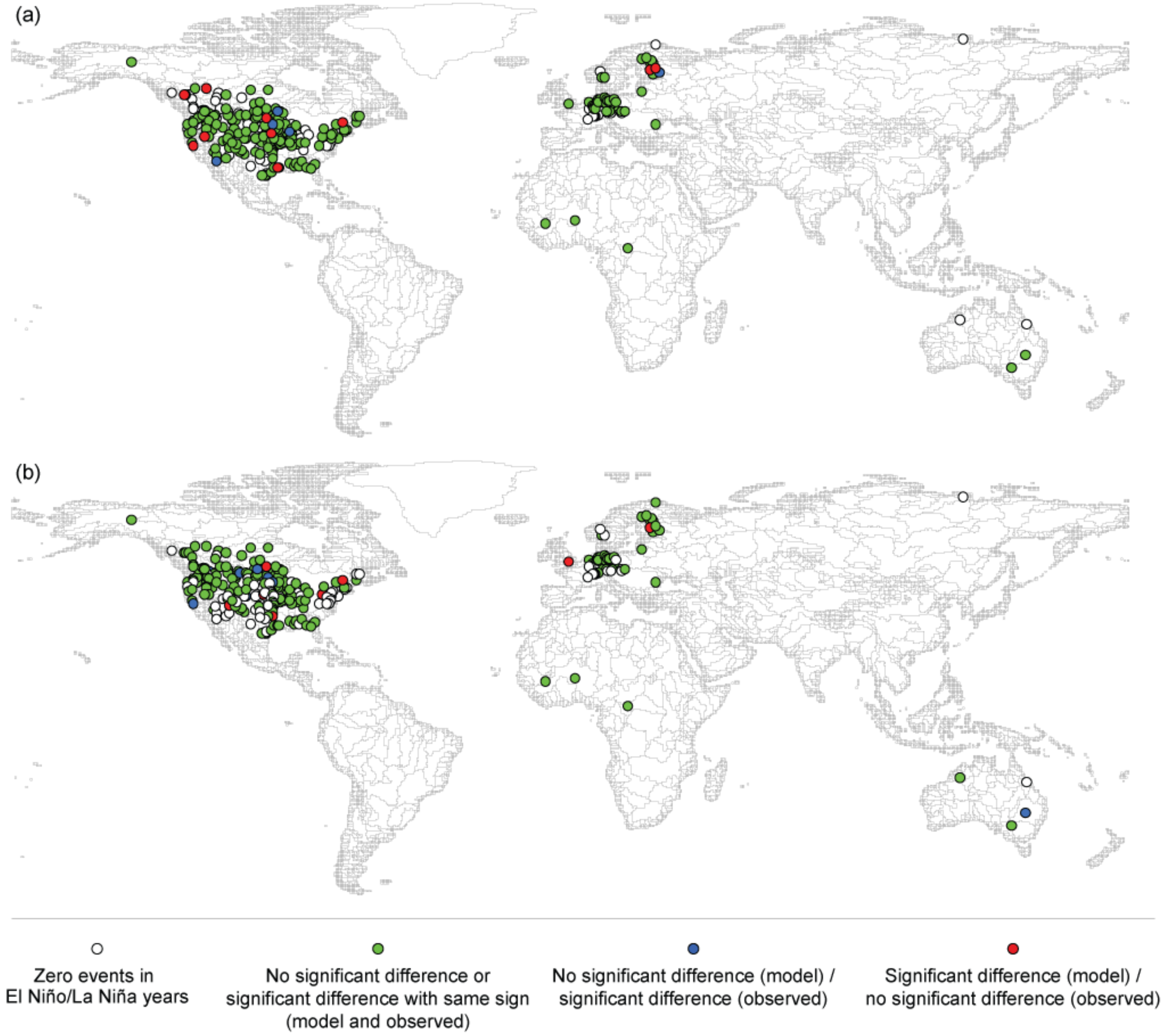

Figure A.4: Indicator of the agreement / disagreement between modelled and observed median flood duration, for floods of at least 7 day duration, between: (a) El Niño years and neutral years; and (b) La Niña years and non-La Niña years. Statistical significance was assessed using a 2-tailed Mann Whitney U (MWU) test, α = 0.05.

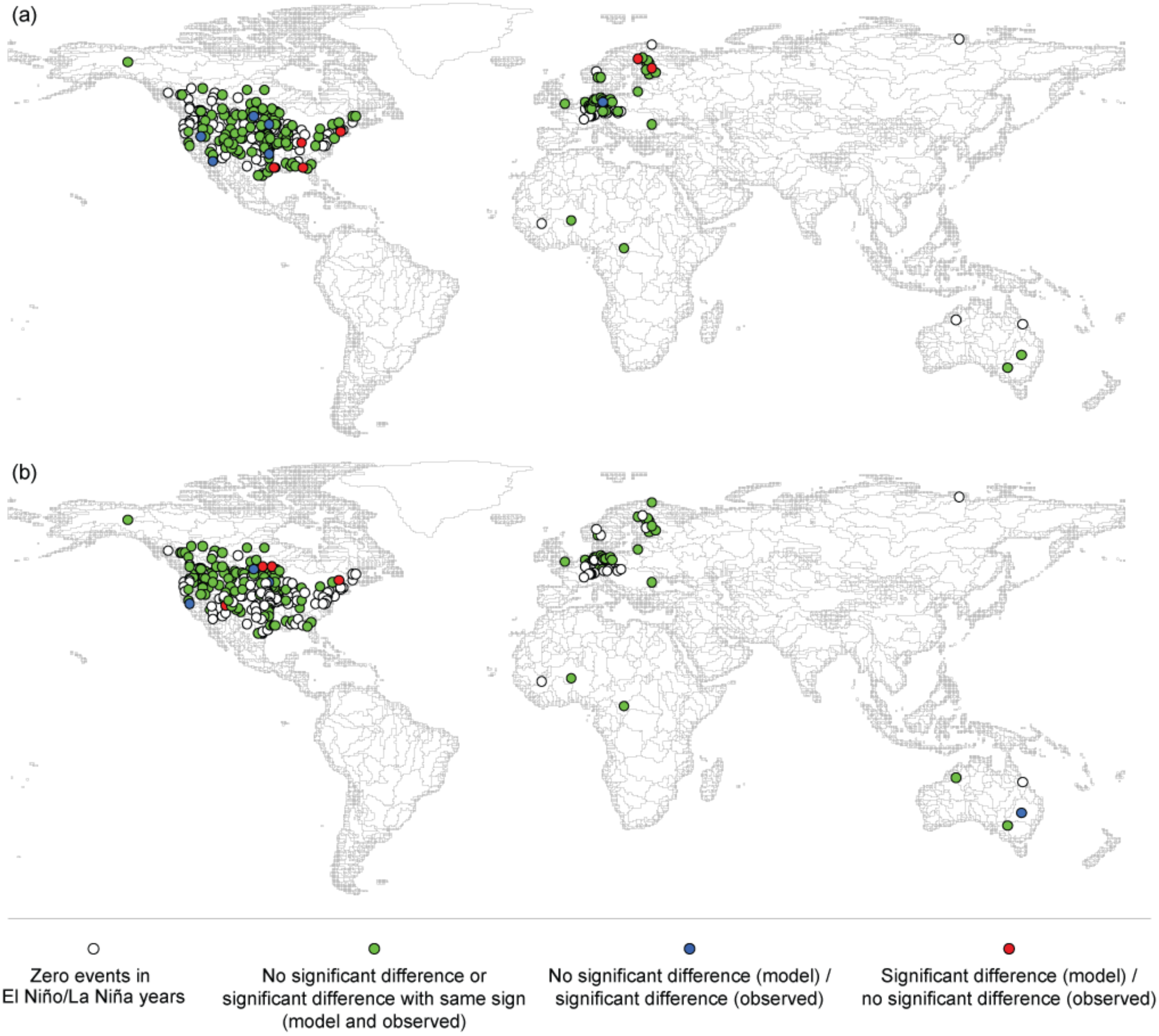

Figure A.5: Indicator of the agreement / disagreement between modelled and observed median flood duration, for floods of at least 10 day duration, between: (a) El Niño years and neutral years; and (b) La Niña years and non-La Niña years. Statistical significance was assessed using a 2-tailed Mann Whitney U (MWU) test, α = 0.05.

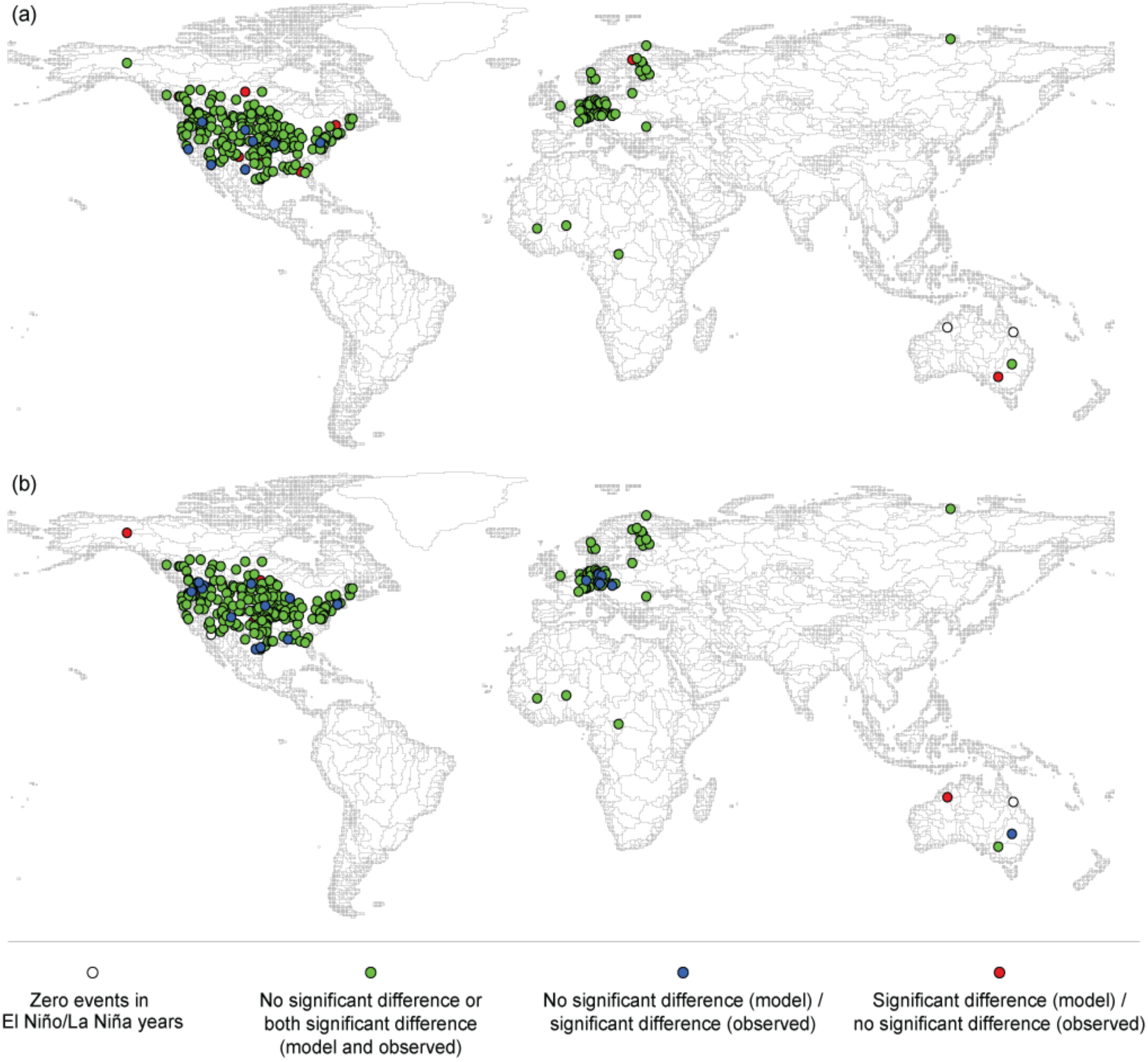

Figure A.6: Indicator of the agreement / disagreement between modelled and observed frequency distributions of flood duration between: (a) El Niño years and neutral years; and (b) La Niña years and non-La Niña years. Statistical significance was assessed using a 2-tailed Kolmogorov-Smirnov (KS) test, α = 0.05.

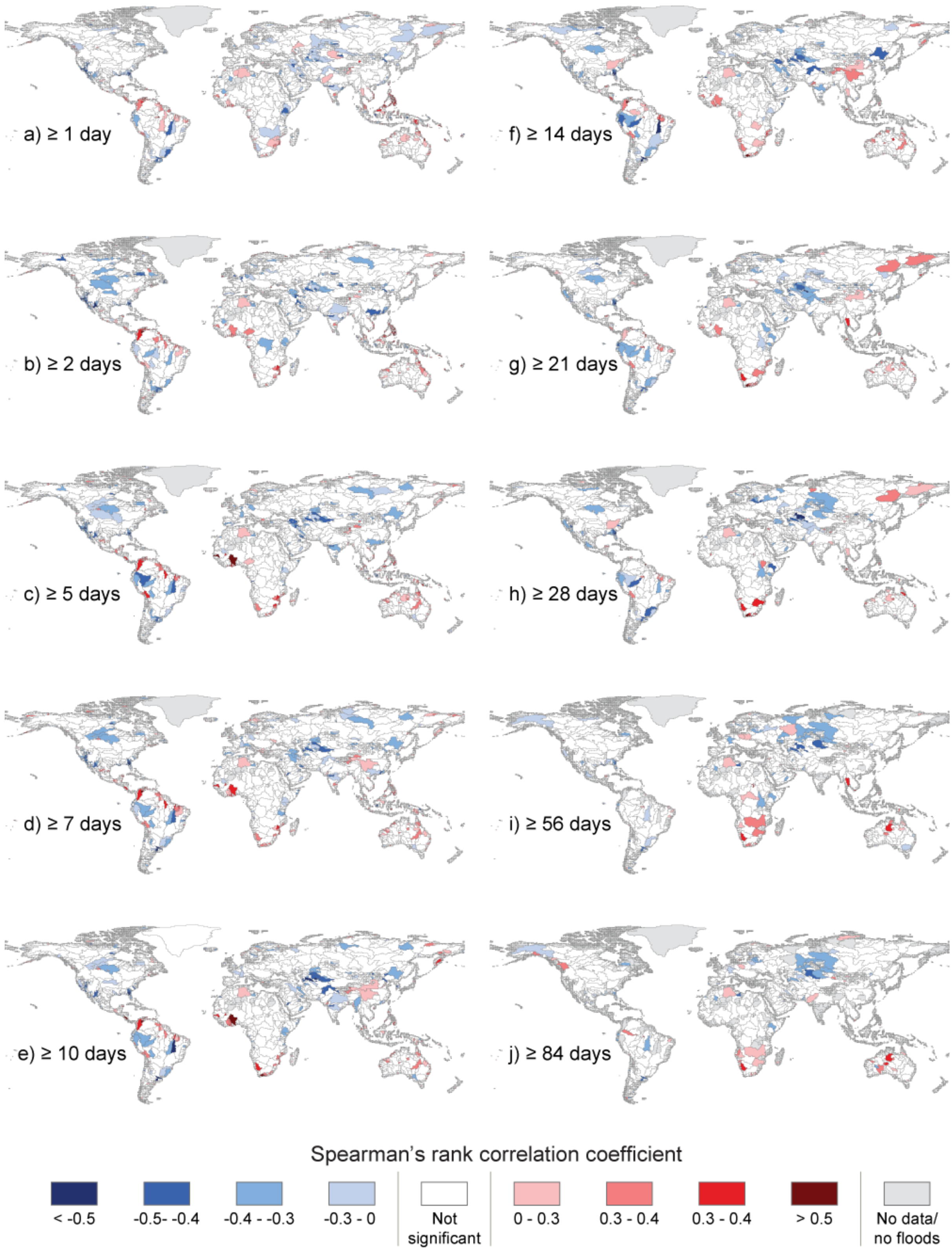

Figure A.7: Same as Figure 3, but flood events defined as events with flood volumes exceeding annual maximum flood volume. Spearman's rank correlation coefficient per sub-basin between SOI_{DJF} and the number of floods per hydrological year exceeding different durations. Statistical significance per basin was assessed by bootstrapping the Spearman's rank correlations with 1000 repetitions (α = 0.10). Negative correlation generally represents more floods in El Niño years/fewer floods in La Niña years, while positive correlation generally represents the opposite.

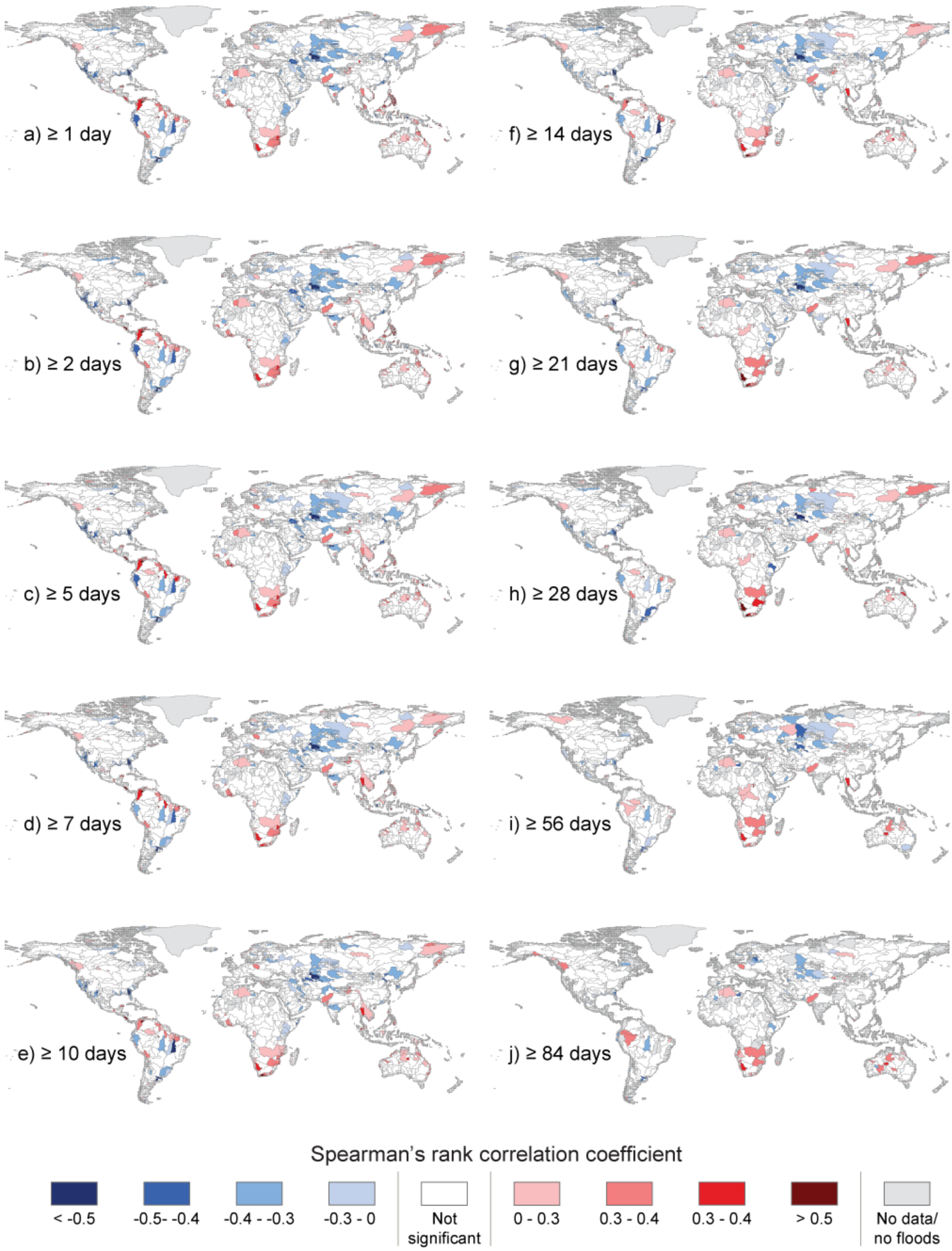

Figure A.8: Same as Figure 4, but flood events defined as events with flood volumes exceeding annual maximum flood volume. Spearman's rank correlation coefficient per sub-basin between SOI_{DJF} and the total duration of all flood events (days) exceeding different durations per hydrological year. Statistical significance per basin was assessed by bootstrapping the Spearman's rank correlations with 1000 repetitions (α = 0.10). Negative correlation generally represents longer durations in El Niño years/shorter durations in La Niña years, while positive correlation generally represents the opposite.

*Table B.1: p-values of bootstrapped Mann Whitney U test (1,000 realisations) to assess the statistical significance of differences in the median number of flood events per year in different phases of ENSO. The results are shown for three thresholds (n = 3, 7, 10 days) used to define a flood event. A flood event is defined as a period of n days, in which the flood volume exceeds zero and the number of consecutive days between non-zero overbank flood volumes is smaller than n days. Statistically significant differences are indicated by: *** for a 0.1% confidence interval; ** for a 1% confidence interval; * for a 5% confidence interval, and # for a 10% confidence interval*

	El Niño v. neutral			La Niña v. neutral		
Threshold (*n* days) →	3	7	10	3	7	10
Global	0.199	0.167	0.159	0.338	0.363	0.443
Regions						
Australia and Oceania	0.254	0.357	0.378	<0.001***	<0.001***	0.003***
Central America	0.934	0.976	0.884	0.407	0.543	0.516
East Asia	0.455	0.288	0.204	0.438	0.548	0.629
Eastern Europe & Central Asia	0.215	0.343	0.299	0.055#	0.040*	0.048*
South Asia	0.826	0.898	0.930	0.131	0.063#	0.058#
Latin America	0.400	0.428	0.651	0.978	0.976	0.976
Middle East	0.933	0.919	0.825	0.595	0.475	0.485
Middle and Southern Africa	0.751	0.853	0.853	0.615	0.568	0.673
North Africa	0.471	0.497	0.538	0.433	0.367	0.321
North America	0.597	0.652	0.649	0.390	0.317	0.463
Southeast Asia	0.205	0.205	0.227	0.526	0.454	0.548
Western Europe	0.543	0.377	0.410	0.039*	0.044*	0.035*