Hydrol. Earth Syst. Sci. Discuss., 10, 10231–10276, 2013
www.hydrol-earth-syst-sci-discuss.net/10/10231/2013/
doi:10.5194/hessd-10-10231-2013

Hydrology and Earth System Sciences Discussions
Open Access

Annual flood sensitivities to El Niño Southern Oscillation at the global scale

P. J. Ward[1,2], S. Eisner[3], M. Flörke[3], M. D. Dettinger[4,5], and M. Kummu[6]

[1]Institute for Environmental Studies (IVM), VU University Amsterdam, Amsterdam, the Netherlands
[2]Amsterdam Global Change Institute (AGCI), VU University Amsterdam, Amsterdam, the Netherlands
[3]Center for Environmental Systems Research, University of Kassel, Kassel, Germany
[4]United States Geological Survey (USGS), La Jolla, CA, USA
[5]Scripps Institution of Oceanography, La Jolla, CA, USA
[6]Water & Development Research Group, Aalto University, Espoo, Finland

Received: 17 July 2013 – Accepted: 25 July 2013 – Published: 9 August 2013

Correspondence to: P. J. Ward (philip.ward@ivm.vu.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Floods are amongst the most dangerous natural hazards in terms of economic damage. Whilst a growing number of studies have examined how river floods are influenced by climate change, the role of natural modes of interannual climate variability remains poorly understood. Here, we present the first global assessment of the influence of El Niño Southern Oscillation (ENSO) on river floods. The analysis was carried out by simulating daily gridded discharges using the WaterGAP model, and examining statistical relationships between these discharges and ENSO indices. We found that, over the period 1958–1999, ENSO exerted a significant influence on annual floods in river basins covering over a third of the world's land surface, and that its influence on floods has been much greater than its influence on average flows. We show that there are more areas in which annual floods intensify with La Niña and decline with El Niño than vice versa. However, we also found that in many regions the strength of the relationships between ENSO and annual floods have been non-stationary, with either strengthening or weakening trends during the study period. We discuss the implications of these findings for science and management. Given the strong relationships between ENSO and annual floods, we suggest that more research is needed to assess relationships between ENSO and flood impacts (e.g. loss of lives or economic damage). Moreover, we suggest that in those regions where useful relationships exist, this information could be combined with ongoing advances in ENSO prediction research, in order to provide year-to-year probabilistic flood risk forecasts.

1 Introduction

Floods are one of the most dangerous natural hazards in terms of economic damage, causing billions of dollars of damage each year (Munich Re, 2012), and global flood damages have risen steeply over the past half century (UNISDR, 2011). At the same time, floods are essential for many wetland ecosystems and agricultural practices

HESSD
10, 10231–10276, 2013

(Costanza et al., 1997). Hence, improvements in our understanding of global scale flood processes are generally beneficial.

In recent decades, a large number of studies have examined instrumental discharge records to identify possible changes in flood frequency and/or magnitude due to climate change (e.g. Allamano et al., 2009; Barros et al., 2004; Bhutiyani et al., 2008; Camilloni and Barros, 2003; Conway et al., 2009; Cunderlik and Ouarda, 2009; Delgado et al., 2009; Di Baldassarre et al., 2010; Douglas et al., 2000; Hannaford and Marsh, 2008; Hirsch and Ryberg, 2012; Jiang et al., 2008; Lindström and Bergström, 2004; Lins and Slack, 1999; Marengo et al., 2012; McCabe and Wolock, 2002; Mudelsee et al., 2003; Petrow and Merz, 2009; Renard et al., 2008; Robson et al., 1998; Shiklomanov et al., 2007; Tu et al., 2005; Villarini et al., 2009; Villarini and Smith, 2010; Yiou et al., 2006). There is also a growing literature on possible changes in flood frequency and/or magnitude based on future hydrological projections at different scales, including the local to basin-scale (Asokan and Dutta, 2008; Bell et al., 2007; Cameron, 2006; Charlton et al., 2006; Dairaku et al., 2008; Das et al., 2012; Fujihara et al., 2008; Graham et al., 2007; Kay et al., 2009; Kitoh et al., 2011; Lauri et al., 2012; Leander et al., 2008; Nakaegawa and Vergara, 2010; Poussin et al., 2012; Prudhomme and Davies, 2009; Raff et al., 2009; Shabalova et al., 2003; Taye et al., 2011; Te Linde et al., 2010; Thodsen, 2007; Van Pelt et al., 2009; Ward et al., 2011, 2013); continental scale (Dankers and Feyen, 2008, 2009; Feyen et al., 2012; Lehner et al., 2006); and global scale (Hirabayashi et al., 2008, 2013; Milly et al., 2002).

Despite this broad research attention to the possible influences of climate change on floods, there has been little attention to the role of present-day interannual climate variability at the global scale. As a result, the influence of this aspect on flooding is poorly understood, despite its importance for development and adaptation planning (IPCC, 2012). In this paper, we provide the first global assessment of the influences of ENSO-driven climate variations on historical flood discharges. We choose ENSO because it is the most dominant interannual climate signal on Earth (McPhaden et al., 2006) apart from the annual cycle.

HESSD
10, 10231–10276, 2013

Many past studies have assessed ENSO's impacts on average river flows at the local to basin scale (see, for example, Dettinger et al., 2000, and references therein), and a few have examined global scale relationships between ENSO and average river flows (Chiew and McMahon, 2002; Dettinger and Diaz, 2000; Dettinger et al., 2000; Labat, 2010). In contrast, only a few studies have examined relationships between ENSO and peak flows. Most of these studies have focused on the United States (e.g. Bell and Janowiak, 1995; Cayan and Webb, 1992; Cayan et al., 1999), although studies have also been carried out in northern Peru (Waylen and Caviedes, 1986), South Asia (Mirza, 2011), and the Mekong Basin (Räsänen and Kummu, 2013). To a large extent, the lack of observed daily discharge data in many regions has hampered the kinds of consistent global scale assessments that are needed. Ward et al. (2010) examined the relationship between ENSO and observed annual peak discharge for 622 gauging stations, but the geographical coverage of those stations was highly biased towards a few regions (particularly North America and Central Europe), and for many regions data were limited or lacking.

In this paper, we address this problem by simulating daily discharges, allowing for the first fully global assessment of ENSO-driven climate variability's influence on annual floods. Here, we define the annual flood as the peak daily discharge in a given year. We then discuss key implications of the results for water management and practice.

2 Methods

In brief, we modelled global daily discharges using a global hydrological model forced by daily meteorological re-analysis data. We then identified statistical relationships between annual floods and indices of ENSO. In the following paragraphs, our methods are described in detail.

2.1 Simulating daily discharge

We simulated global gridded daily discharge at a spatial resolution of $0.5^\circ \times 0.5^\circ$ using the WaterGAP model (Alcamo et al., 2003; Döll et al., 2003), forced by daily meteorological fields (precipitation, temperature, and global radiation) for 1958–2000 from the EU-WATCH project (Weedon et al., 2011).

WaterGAP consists of two main components: (1) a water-balance model to simulate characteristic macro-scale behaviours of the terrestrial water cycle in order to estimate water availability; and (2) a water-use model to estimate water withdrawals and consumptive water uses. In principle, WaterGAP can account for human influences on the terrestrial water cycle by its inclusion of flow regulation by large dams and reservoirs as well as water withdrawals. For model validation, we used simulations that included these human influences on river discharge. However, as the main focus of this study is climate induced variability of river floods, we based the present assessment of ENSO influences on naturalised-flow simulations, i.e. human interferences were excluded.

The climate data used to force WATERGAP in this study were obtained from the EU-WATCH project (Weedon et al., 2011). WATCH developed a global dataset of sub-daily meteorological forcing data for the period 1958–2000 at a horizontal resolution of $0.5^\circ \times 0.5^\circ$ (WATCH forcing data; WFD). The time-series were derived from the ERA-40 reanalysis product (Uppala et al., 2005) via sequential interpolation to a horizontal resolution of $0.5^\circ \times 0.5^\circ$, with elevation corrections and monthly-scale adjustments of daily values to reflect CRU (corrected-temperature, diurnal temperature range, cloud-cover) and GPCC (precipitation) monthly observations combined with new corrections for varying atmospheric aerosol-loading and separate precipitation gauge corrections for rainfall and snowfall derived from the ERA-40 reanalysis product. Full details of the forcing data can be found in Weedon et al. (2011). WATCH also developed time-series of the WFD for the period 1901–1957, but these were developed by reordering of the ERA-40 data for the later 1958–2000 period. Hence, the extremes in the pre-1958 dataset do not correspond to the extremes in actual years, which is essential for our research. Therefore, in this paper, we used data only from 1958 onwards.

While discharges were simulated on the grid scale, analyses were carried out at basin scales, i.e. correlations with ENSO (and other calculations) were based on values at the cells farthest downstream in each basin. Accounting for the fact that river basin areas vary significantly, the world's largest 34 river basins (in terms of surface area) were also divided into sub-basins.

2.2 Calculating mean and maximum annual discharges

For each grid cell and hydrological year, we calculated the maximum annual discharge, or annual flood discharge (Q_{max}), and the mean annual discharge (Q_{ann}) from the simulated daily discharge time series for 1958–1999. In most cases, we used the standard hydrological year (October–September), as also used in several other global assessments (Dettinger et al., 2000; Dettinger and Diaz, 2000; Ward et al., 2010). However, this is problematic for the allocation of the maximum annual discharge to a given hydrological year for those areas in which that maximum occurs around the boreal autumn (September–November). Therefore, for the most downstream cell of each drainage basin, we calculated the month in which the maximum annual discharge occurred (over the period 1958–2000 in the WaterGAP results). For those basins in which the maximum annual discharge in the most downstream cell occurred in September, October, or November, we defined the hydrological year as July to June. A map showing the hydrological year used for each basin can be found in Fig. A1.

2.3 Relationships between discharge and ENSO

The time-series of annual-flood discharges and mean-annual discharges were validated against observed discharge time-series (Sect. 3). We then examined the correlation between the natural logarithm of Q_{max} ($\ln Q_{max}$) (and $\ln Q_{ann}$) and the Southern Oscillation Index (SOI; http://www.cru.uea.ac.uk/cru/data/soi/), as well as their sensitivities (β_1) to variations in SOI, fitting (Bouwer et al., 2008):

$$\ln(Q_i) = \beta_0 + \beta_1 a_i + \varepsilon_i, \quad (1)$$

whereby Q_i is the simulated Q_{max} (or Q_{ann}) in hydrological year i, a_i is the 3-monthly mean value of the SOI (OND, NDJ, DJF, JFM), β_0 and β_1 are regression-derived coefficients, and ε_i is an error term. From this, it follows that a unit change in SOI (a_i) is associated with an average increase of $100 \cdot (\exp(\beta_1) - 1)$ in Q (Q_{max} or Q_{ann}); we refer to this as the "sensitivity". In the analyses, the correlations and sensitivity were estimated between $\ln Q_{max}$ (and $\ln Q_{ann}$) time-series and each of the three-month mean SOI values (OND, NDJ, DJF, JFM) separately. In some of the tables and figures, we show results for the three-month period with the highest correlation coefficient. To assess the robustness of the results when using other indices of ENSO, we also repeated the analyses with the negative of the Multivariate ENSO Index (http://www.esrl.noaa.gov/psd/enso/mei/), negative NINO3.4 index (http://www.cpc.ncep.noaa.gov/data/indices/), and negative Global Sea–Surface Temperature (SST) ENSO index (http://www.jisao.washington.edu/data_sets/globalsstenso/), where negatives were used to accommodate the difference in sign between SOI and SST-based ENSO indices.

The correlations between Q_{max} and SOI, and between Q_{ann} and SOI, were carried out using the natural logarithms (ln) of Q_{max} and Q_{ann}, because the log discharge data are normally distributed for basins covering around 90 % of land surfaces (normality was assessed using Lilliefors test; $\alpha = 0.05$). For the vast majority of the other basins, the data were not highly skewed. Given that the dataset is not small (n yr = 42), we primarily assessed the correlations using Pearson's r, given its greater power over non-parametric equivalents. For verification, we also examined correlations between the original Q_{max} and Q_{ann} data (not the natural logarithms) using the non-parametric Spearman's rank test, and found the results to be similar. The normality of SOI data was assessed using the Lilliefors test ($p = 0.24$).

We also examined the percentage anomalies in median Q_{max} between El Niño (and, separately, La Niña) years compared to the median Q_{max} of all years. We used the classification of ENSO years from the Center for Ocean–Atmospheric Prediction Studies (http://coaps.fsu.edu/jma.shtml), as shown in Table 1. The non-logarithmic Q_{max} time-series used in this composite analysis are only normally distributed in basins covering 50 % of land surfaces. Therefore, when assessing differences in Q_{max} between El Niño (La Niña) and all years, we used the non-parametric Mann–Whitney U test to assess the statistical difference in median values.

3 Validation

The general ability of global hydrological and land surface models, including WaterGAP, to reproduce various spatial and temporal characteristics of 20th century river discharge, using the WFD forcing data, has been evaluated extensively by the EU-WATCH project. Those analyses evaluated model performance for long-term mean runoff (Haddeland et al., 2011), as well as high and low flow indices (Gudmundsson et al., 2011; Prudhomme et al., 2011). WaterGAP was found to acceptably reproduce most regional characteristics of large-scale hydrological extremes.

However, these validations did not specifically assess the model's performance in simulating differences in peak discharges between different phases of ENSO. Thus, in this study we validated model findings against observed discharge time-series from the GRDC database, using only those stations with upstream areas greater than 10 000 km^2 for which daily data are available for every day of the hydrological year in at least 15 hydrological years between 1958 and 1999. This yielded a set of 721 observed discharge time-series. For model validation, we used WaterGAP simulations including human influence.

From Fig. 1, it is clear that there are large biases between modelled and observed Q_{max} for many stations. At 33 % of the stations, the percentage difference between modelled and observed median Q_{max} is less than 25 % (positive or negative), but large positive biases (> 50 %) were found for 15 % of stations, and large negative biases for 25 %.

For this study, though, we are most interested in the relative change in discharge magnitudes from year to year, and between different phases of ENSO, rather than absolute discharge values. In Fig. 2, we show that the correlation between modelled and observed $\ln Q_{max}$ is generally very good. For 80 % of stations, the correlation coefficient (r) is greater than 0.6, and greater than 0.4 for 92 % of stations. We also carried out correlation analyses using the non-parametric Spearman's rank correlation coefficient (not shown here), using the original Q_{max} data (instead of the natural logarithms), and found very similar values. Moreover, the majority of the stations with low correlation are located in upstream areas, whereas the analyses presented in this paper are based on values at the most downstream cell in each basin. This gives confidence that the model simulates interannual fluctuations in Q_{max} similar to those in the observed records.

Finally, we examined the agreement between the modelled and observed data in terms of the relative change in Q_{max} between El Niño and non-El Niño years (Fig. 3a) and between La Niña and non-La Niña years (Fig. 3b). For 90 % (92 %) of the stations, both modelled and observed median Q_{max} show either no significant difference between El Niño (La Niña) and non-El Niño (non-La Niña) years, or significant differences of the same sign (indicated by green symbols; "1"). For the other stations there was a statistically significant difference in modelled median Q_{max} between El Niño (La Niña) and non-El Niño (non-La Niña) years, but none for observed data (or vice versa). Finally, there are no stations at which modelled and observed median Q_{max} show significant changes between El Niño/non-El Niño years or La Niña/non-La Niña years with different signs.

4 Results and discussion

In this section, we first show and discuss the relationships between annual floods and ENSO at global and regional scales, and then examine how these relationships have changed over time. We also show and discuss the anomalies of annual flood discharge

HESSD
10, 10231–10276, 2013

associated with the two ENSO phases, and relate our findings to past research based on observed discharge times-series. Finally, we discuss the implications of our results, the main limitations of our study, and suggestions for future research. Although all of our analyses were carried out at the grid-cell level, we display results by hydrological basin, based on relationships to discharges at the most downstream cell.

4.1 Global sensitivity of flood discharge to ENSO

To the best of our knowledge, Fig. 4 is the first spatially explicit fully global representation of the sensitivity of annual flood discharge (Q_{max}) to ENSO. The figure shows the sensitivity of $\ln Q_{max}$ to 3-monthly averages of the SOI (OND, NDJ, DJF, JFM), where at each site the sensitivity shown is for the 3-monthly period of the SOI most highly correlated to the annual floods. In Fig. 4a, the sensitivity results are shown for all basins, whilst in Fig. 4b, they are only shown for basins in which the correlation reaches statistical significance. At locations for which observed daily discharge time-series were available in the study of Ward et al. (2010), the results in Fig. 4 are very similar to that study. This further supports the use of the modelled data for assessing the influence of ENSO on annual flood discharges. We also assessed how robust the correlations are to the selected ENSO index, by examining the correlations with three other indices of ENSO (negative of Multivariate ENSO Index, negative of NINO3.4 index, and negative of Global SST ENSO index). Those results are shown in Fig. A2, indicating broadly similar patterns among correlations to the four indices. In the rest of this paper, we focus on SOI, since this allows for direct comparison with past studies (Chiew and McMahon, 2002; Dettinger and Diaz, 2000; Dettinger et al., 2000; Ward et al., 2010) and may allow for somewhat greater predictability (Redmond and Koch, 1991).

We found significant correlations between SOI and $\ln Q_{max}$ ($\alpha < 0.1$) for basins covering over a third (37 %) of land surfaces (Fig. 4). These correlations are positive for basins covering 23 % of land surfaces, and negative for basins covering 14 % of land surfaces. In other words, there are more land areas where Q_{max} increases with La

HESSD
10, 10231–10276, 2013

Niña and decreases with El Niño conditions, than vice versa. This finding is important, since past studies examining relationships between the impacts of flood disasters and ENSO at the global scale have tended to only focus on El Niño episodes, and not La Niña. For example, a study of the relationship between ENSO and the frequency of global floods of sufficient magnitude to trigger international disasters (Dilley and Heyman, 1995) found no differences between El Niño and non-El Niño years, but La Niña years were not evaluated. Similarly, another study of the number of people affected by natural hazards also only examined differences between El Niño and non-El Niño years (finding strong relationships), but did not examine La Niña years (Bouma et al., 1997). Whilst the results here only show that annual floods (which come in all sizes) are correlated with ENSO, the relationships suggest that there may also be significant links between ENSO and floods large enough to lead to flood disasters. Indeed, fitting extreme value distributions (e.g. Gumbel, GEV, etc.) to the annual flood series leads to significantly different estimates of extreme floods when either El Niño or La Niña years are dropped from the time-series (not shown here).

We also found that Q_{max} is more sensitive to changes in SOI than is Q_{ann} in basins covering the majority (76 %) of the Earth's land surface (Fig. 5), with sensitivity results for Q_{ann} shown in Fig. A3. If we only consider basins in which the correlation between Q_{max} and SOI is statistically significant, the sensitivity of Q_{max} is greater than that of Q_{ann} for basins covering 32 % of land areas, whilst Q_{ann} is more sensitive for basins covering 4 % of land areas. If we only consider basins in which the correlation between Q_{ann} and SOI is statistically significant, the sensitivity of Q_{max} is greater than that of Q_{ann} for basins covering 31 % of land areas, whilst Q_{ann} is more sensitive for basins covering 16 % of land areas. In our earlier work (Ward et al., 2010) based on observed discharges at 622 gauging stations, we also found that, on average, ENSO has a greater impact on annual flood discharges than on mean discharges. Similarly, for observed discharges in the western USA, Cayan et al. (1999) found ENSO to have a greater impact on the number of days exceeding the 90 percentile values of streamflow as compared to the number of days exceeding the 50 percentile (i.e.

HESSD
10, 10231–10276, 2013

median) values. Our new results show that this pattern (annual floods generally more sensitive to ENSO than average flows) extends to the global scale. Similar results have been found for the sensitivity of discharge to the variability of atmospheric circulation over Europe (Bouwer et al., 2008).

4.2 Regional sensitivities of flood discharges to ENSO

There are several regions in which it is common knowledge that climate is affected by ENSO through teleconnections (Kiladis and Diaz, 1989), for example eastern Australia, Southeast Asia, parts of western South America, and western North America. However, little is known on the influence of ENSO teleconnections on annual floods at these large regional scales. In Table 2, we show the area-weighted percentage differences (unsigned) in Q_{max} per unit change in SOI, per by geographical region (Kummu et al., 2010) and Köppen climate zone (Kottek et al., 2006), for those basins where the correlations in Fig. 4 are significant, and the percentage of land in each region/zone combination for which the correlations are significant. Globally, in those basins with significant correlation (i.e. basins covering 37 % of global land surface), Q_{max} varies by 27 % for each unit change in SOI: this includes regions far removed from the classic ENSO-regions named above. In equatorial regions, Q_{max} is significantly correlated with SOI in basins covering half of the land areas.

The highest sensitivities are found in arid regions, followed by equatorial regions. The sensitivity of discharge to ENSO in tropical regions has been widely reported (e.g. Dettinger and Diaz, 2000; Dettinger et al., 2001; Ward et al., 2010), since ENSO affects climate in tropical regions through perturbations in the Walker circulation (Kiladis and Diaz, 1989). However, less research has assessed the influence of ENSO on the hydroclimatology in arid regions. Whilst the paucity of observed discharge data in many of these regions limits the validation of our model results there, the strength of the signal provides motivations for enhancing research activities in those regions. This is especially the case since many arid regions of the developing world are expected to show some of the world's largest increases in population and asset values in coming years (Jongman et al., 2012). One arid region in which there are good records of discharge, and an abundance of studies on ENSO and hydroclimatology, is the southwest USA. Here, several studies have indeed found strong relationships between ENSO and annual or seasonal discharge (e.g. Hidalgo and Dracup, 2003; Piechota et al., 1997) or between ENSO and drought conditions (Piechota and Dracup, 1996). Generally, these studies found wetter conditions in El Niño years and drier conditions in La Niña years. Cayan and Webb (1992) and Cayan et al. (1999) also found relationships between ENSO and extreme discharges at a large number of locations in the arid regions of the southwest USA, with high flows conditions being more likely in El Niño years (see Sect. 4.4 for details).

In terms of geographic regions, the highest sensitivities of annual floods to ENSO are found in Central America (54 %) and the lowest in Western Europe (13 %), with large differences between climatic zone in the geographical regions. For example, floods in the equatorial zone of Australia and Oceania are far more sensitive than in the equatorial zone of North Africa. Moreover, the sensitivity is particularly high in several less developed regions (e.g. Africa, Indian Subcontinent, Central America) compared to highly developed regions (Western Europe, North America), although this does not hold for all cases (for example, sensitivity is also high in Australia and Oceania). Brown and Lall (2006) found significant correlation between the coefficient of variation of rainfall variability and per capita GDP at the country scale, and it might be useful to evaluate similar relationships between ENSO-driven hydrological variability and GDP or other development indicators.

4.3 Changes in ENSO-flood relationships through time

Whilst we have shown significant correlations between SOI and annual floods for the overall 1958–1999 period, it is known that the strength of ENSO has changed over time on timescales from millennia to decades (e.g. Cane, 2005; Li et al., 2013; Mann et al., 2005; McPhaden et al., 2006; Tudhope et al., 2001; Wunsch, 1999) and that its teleconnected influences to at least some distant regions (e.g. western North America

HESSD
10, 10231–10276, 2013

and South America) have likewise varied (Gershunov and Barnett, 1998; Gershunov et al., 1999; McCabe and Dettinger, 1999; Dettinger et al., 2000). Hence, we examined whether we could find any indication of changes in the strength of the correlation between annual floods and ENSO through time. To do this, we assessed changes in the strength of the correlation between SOI_{DJF} (i.e. the mean SOI value for the months of December, January, and February) and $\ln Q_{max}$ using a 21 yr moving window, ranging from 1958–1978 to 1978–1998. DJF was chosen since the correlations are strongest for these months for the largest number of basins. In Fig. 6, we map the numbers of windows (out of 21) for which the flood-SOI correlations within the 21 yr windows are statistically significant (Pearson's r, $\alpha = 0.10$). This figure gives an indication of the temporal stationarity (and thus long-term reliability) of the correlation between SOI and annual floods by river basin. In those basins shown in the darkest shade of red, 21 yr correlations are statistically significant throughout the 1958–1999 era. Basins with the most persistent or reliable correlations are found in southern Africa, several parts of South America, eastern Australia, the southwest USA, the Nile basin, northern India, and several basins in central and northern Asia.

In Fig. 7, we show how the strength of this correlation has changed over the period 1968–1988 (again based on the 21 yr moving windows described above, whereby 1968–1988 are the central years of the moving windows) for selected basins. The blue lines indicate the time-varying correlations in 21 yr windows, and the red dashed lines indicate the critical value ($r = 0.369$, $\alpha = 0.10$). We also show whether there are significant linear trends in the strength of the correlations ("no trend"; correlations growing "stronger" over time; or growing "weaker" over time), based on the Mann–Kendall test ($\alpha = 0.10$). The analyses were carried out for the 50 largest basins for which correlation over the entire period 1958–1999 proved significant. In order to make the figure more clear, we then removed several upstream sub-basins (e.g. several Amazon tributaries), where the overall signal was similar to that at the most downstream sub-basin.

Several interesting regional patterns can be seen in Fig. 7. In South America, it appears that the strength of correlations between ENSO and flood discharges have strengthened over the period of analysis here in basins from Brazil southwards, except for the Tocantins. On the other hand, in northern South America, the strength of the correlation has weakened in the Essequibo, with no significant trend in the Magdalena. In North America, correlations for the Ohio and Lower Missouri (both tributaries of the Mississippi) have strengthened, albeit as an increasingly positive correlation in the former and a increasingly negative correlation in the latter. The results for the Colorado show no significant trend over the study period. The only basin shown here in North America for which the strength of the correlation weakened significantly is the Fraser River.

For basins in western and north central Eurasia, we found either weakening correlations, or no significant trends. For both the Yenisei and the Rhine, we found fairly strong negative correlations until the 21 yr period centred on ca. 1980, and much weaker correlation thereafter (reaching zero for 21 yr periods centred after 1996 in the case of the Rhine). In south Asia, the two basins shown both exhibit weakening correlations. On the other hand, the basins shown in eastern Asia (Chao Phraya, Yellow, Kolyma) all show trends of strengthening positive correlations over time. For the basins shown in Australia and Africa, a highly mixed picture in terms of trends emerges; however, it should be noted that the strength of the correlations remains rather strong in the majority of these basins throughout the study period.

On the whole, of the 35 basins highlighted in Fig. 7, correlations strengthened in 14 basins, weakened in 13, and exhibited no trend in 8. Thus, globally, there has been essentially no overall bias among the changing teleconnections in one direction or the other. This even global mix of strengthening vs. weakening teleconnections may suggest that the changes shown in Figs. 6 and 7 reflect changes in teleconnection strengths, rather than changes in the strength of the driving ENSO variations. The latter might more likely have yielded more universally consistent changes in flood correlations.

HESSD
10, 10231–10276, 2013

In some regions, these long-term variations in ENSO teleconnections have been recognised in annual precipitation and streamflow records. For example, in the Mekong Räsänen and Kummu (2013) found epochal behaviour in ENSO-discharge correlations, with strongly negative correlations in the pre-1940s and after the mid-1970s, but a rather weak relationship between these periods (Räsänen and Kummu, 2013). Similar results were found by Zubair and Chandimala (2006), who investigated ENSO-seasonal stream flow relationships in Sri Lanka, and found that the correlations changed from positive (pre-1950) to strongly negative (post-1970). These findings are supported by other studies, which found similar epochal behaviour in relationship between ENSO and Asian-Australian Monsoon (Wang et al., 2008), and ENSO and Indian Monsoon (Torrence and Webster, 1999). Outside Asia, Beebee and Manga (2004) found that ENSO correlations with snowmelt runoff in Oregon, USA, were weaker between 1920–1950 than in periods before and after those decades. Such long-term variations in ENSO teleconnections have been associated with interferences and enhancements from multi-decadal climate modes, for example ENSO interactions or reflections of the Pacific Decadal Oscillation (PDO) as reported by Gershunov and Barnett (1998), Gershunov et al. (1999), and McCabe and Dettinger (1999). There are many such "low frequency" modes in the climate system, including also modes in the Atlantic (e.g. Apipattanavis et al., 2009; McCabe et al., 2004) and Indian (e.g. Hoerling et al., 2009, 2010) Ocean basins, so that the particular interferences at work in any given river basin may be complex and likely requires more research to identify. Indeed, it is also possible that human-caused multi-decadal climate trends themselves may be modifying some of these teleconnection strengths, or may do so in the future.

4.4 Flood discharge differences between ENSO phases

We also examined the differences in anomalies of annual flood discharge between ENSO phases. Figure 8 shows anomalies of median Q_{max} in: (a) El Niño years compared to all years, and (b) La Niña years compared to all years. In a general sense, the patterns are similar to those shown in Fig. 4. However, this analysis allows

HESSD
10, 10231–10276, 2013

us to identify additional conditionalities and relationships that were obscured in the correlation and sensitivity analysis in Sect. 4.1. Here, we can see several regions in which there are asymmetric responses, i.e. there is an anomaly in either El Niño or La Niña years, but not in the opposite. For example, in the Darling basin in eastern Australia Q_{max} shows an anomaly in excess of +75 % in La Niña years, yet there is no (or little) average anomaly (−10 % to +10 %) during El Niño years; and the Mekong basin shows an anomaly of −25 % in La Niña years, yet no anomaly in El Niño years. On the other hand, there are also basins with anomalies in El Niño years, but no anomaly in La Niña years, for example the Limpopo River in southern Africa. Asymmetries between El Niño and La Niña influences may reflect some complications associated with interferences with multi-decadal climate modes, as discussed earlier, but are also reasonably well known to be direct outgrowths of the overall nonlinearities of the climate system (Hoerling et al., 1997). Further research into the driving mechanisms for such asymmetric patterns could advance our understanding of why basins respond differently to hydroclimatic variations.

This El Niño vs. La Niña comparative analysis allows us to compare our findings to the limited number of studies in the literature that have also examined such relationships based on observed annual flood discharge. Cayan and Webb (1992) analysed daily discharge data for the Santa Cruz river at Tucson, Arizona, for 1914–1986, and found that the presence of El Niño affects the probability of flooding in a given year. They estimated the magnitude of a 100 yr flood based on the time-series of maximum annual discharges with and without the data for El Niño years, and found the results to be a factor two higher when the El Niño data were included. In this region, we found large anomalies in simulated annual flood discharge of about +50 % in El Niño years. Cayan et al. (1999) then examined relationships between SOI and observed river discharge at 303 locations in the entire western USA. They analysed the number of days per year with discharge in excess of the 90th percentile in both El Niño and La Niña years. They found that in El Niño years, days with high daily discharge occur more frequently than average over the southwest USA and less frequently than average

HESSD
10, 10231–10276, 2013

over the northwest USA, and for La Niña years they found an almost opposite pattern. Although the metric used in our study is different, we find a corresponding pattern of higher (lower) flood discharges in the southwestern USA in El Niño (La Niña) years. In the northwestern USA, for example for the Columbia River, we find strongly higher flood discharge in La Niña years (+26 %) and somewhat lower flood discharge in El Niño years (−8 %).

Waylen and Caviedes (1986) analysed observed time-series of annual floods for 13 rivers in the northern coastal region of Peru. They found that the annual flood is generally higher in El Niño years than in La Niña years, with the greatest anomalies towards the more northern and coastal locations. For this area we found similar results, with significant negative correlations between SOI and $\ln Q_{max}$ ranging from −0.1 to −0.4 and the highest values in the northern coastal region ($r = -0.3$ to ca. −0.4 in this region).

Whilst the results of the above studies based on observed discharges generally corroborate our modelled findings, we did find some differences between our results and the analyses of Räsänen and Kummu (2013) for the Mekong. They examined the correlation between maximum annual discharge at Strung Teng (a downstream gauging station) and DJF values of the monthly ENSO index developed by Meyers et al. (2007) and later updated by Ummenhofer et al. (2009). Their analyses were carried out for the period 1981–2005, and yielded a correlation of $r = -0.49$. This is higher than the value of $r = -0.106$ that we found in our study for the period 1958–1999. However, it should be noted that our analyses of the change in correlation over time show that the strength of the simulated correlation changed significantly over the period 1968–1988, with values of r ranging from +0.13 to −0.27. The overall trend is towards stronger negative correlations in the later period, which corresponds most closely to the time-period used by Räsänen and Kummu (2013). Also, the two studies are based on a different index of ENSO. Thus the differences between that study and the present analysis may reflect analytical or temporal differences in the data and methodologies used.

HESSD
10, 10231–10276, 2013

Knowledge of these El Niño-La Niña asymmetries can be useful for more precisely targeting (on one ENSO phase or the other, or both) plans and accommodations for the ENSO influences on flood magnitudes and, ultimately, flood risks in individual basins around the world.

4.5 Implications and recommendations

Given our finding that ENSO correlates significantly with annual flood discharge in basins covering over a third of global land surfaces, there is a clear need for more research on the influence of interannual and longer term climate variability on flood hydrology. This would complement (and lend greater practical urgency to) ongoing efforts to better understand the roles of ocean–atmosphere interactions on climate more generally, such as that carried out under CLIVAR (Climate Variability and Predictability Programme of the World Climate Research Programme). Specifically, if significant correlations exist between ENSO and even more extreme flood discharges (i.e. larger than most annual-flood levels), then the socioeconomic impacts of flooding (e.g. loss of life, displacement of people, economic damage) in some regions may also be related to, and predictable from, ENSO. To examine this, future research may assess the impacts of ENSO directly on flood risk, where risk is a product of the probability of flooding and the consequences of flooding.

With regards to such an assessment of ENSO's impacts on flood risks, we have already mentioned that two past studies have explored possible relationships between ENSO and the frequency of floods of sufficient magnitude to trigger international disasters (Dilley and Heyman, 1995) and the number of people affected by natural hazards (Bouma et al., 1997). However, these studies only examined differences between El Niño years and non-El Niño years, and did not consider differences in the La Niña phase of ENSO. The latter analysis is essential, since our results show that there are more basins where annual floods increase with La Niña and decrease with El Niño than vice versa. Moreover, the analyses of Bouma et al. (1997) and Dilley and Heyman (1995) were based on statistics at national scales. Our results

HESSD
10, 10231–10276, 2013

show that analyses at such a scale will mask important relationships, since ENSO can have an opposite correlation with annual flood discharge within different regions of the same country (as in Brazil, China, and the USA). Finally, the studies named above were carried out almost twenty years ago, whilst reporting on flood impacts (especially deaths and economic losses) has since improved (Kron et al., 2012). An analysis of the relationships between ENSO and flood impacts could be considered using two approaches: (a) making use of reported impacts such as those documented in the EM-DAT database (The OFDA/CRED International Disaster Database – www.emdat.net – Université catholique de Louvain – Brussels – Belgium) or the NatCatService database (Munich Re, 2013); or (b) using recently developed flood risk models such as those of Hirabayashi et al. (2013), UNISDR (2011), or Winsemius et al. (2013).

Another promising research avenue would be to use the potential predictability of ENSO (Cheng et al., 2011) to provide probabilistic estimates of flood risk with lead times up to several seasons. The coupling of ENSO predictability with hydrometeorological variables such as precipitation and mean discharge has been on the research agenda for over a decade. However, also coupling such analyses with flood statistics and global risk models could provide probabilistic flood risk forecasts; enabling humanitarian and development agencies to prioritise short-term risk reduction efforts in the most at-risk regions; enabling (re-)insurance companies to accommodate anomalies in their risk portfolios in the coming seasons to years; and potentially enabling improved flood early warning and flood regulation by dam operators. However, in this study we have shown that the strength of the correlation between ENSO and annual floods is itself non-stationary through time. Hence, such analyses may be more suited to those regions where the temporal persistence of the ENSO-flood correlations is highest.

Technical flood-defences are designed to protect against floods with given return-periods, estimated from observed discharge records. However, should ENSO magnitude and frequency change over time, as has occurred in the recent and geological past (Mann et al., 1995), this would result in effective over- or underdesign of flood protection infrastructure, such as dikes, for decades at a time. The present study identifies some areas where this may be most likely, i.e. those locations where floods are particularly sensitive to changes in ENSO.

Along with these extensions of the current research to potentially facilitate flood risk analyses, a number of analytical steps could be improved in future research. For example, future research could examine the relationships between ENSO and floods using additional climate indices or several different global hydrological models. Also, given the possible interaction between ENSO and other large-scale climate oscillations (such as PDO) that may serve to modulate ENSO relationships with flood discharge, analyses should be carried out using a wide range of interannual ocean–atmosphere interactions, in addition to ENSO. Finally, we recommend that future studies carry out detailed analyses of relationships between Q_{max} and its climatological forcing to reveal regions in which climate dominates Q_{max} variability, vs. those where this effect may be decreased or amplified by other factors (e.g. terrain, soil, cropping, or human flow management).

5 Conclusions

In this paper, we provide the first fully global assessment of ENSO-driven climate variability's influence on annual floods. This was achieved by simulating daily discharges over the period 1958–1999 using the WaterGAP model forced by global climate reanalysis data from the WATCH project. We first validated the simulated annual flood discharges by comparisons to observed discharges. We found that whilst there are large biases between modelled and simulated annual floods, they simulate similar relative changes in annual floods from year to year, and that their agreement is good in terms of the signal of change between different phases of ENSO. Whilst studies on the linkages between ENSO and flood discharge based on observations are limited, for those studies that are available, their findings are generally in line with our model results, adding confidence to our use of modelled data in these analyses.

We found that ENSO has a significant influence on annual floods in river basins covering over a third of the world's land surface, and that its influence on annual floods is much greater than its influence on average flows. This includes relationships in the classic ENSO-regions, such as eastern Australia, Southeast Asia, western North America, and parts of western South America, but also areas far beyond. We also found that the strengths of the correlations between ENSO and flood discharge are non-stationary. In some regions, the strength of the relationships increased (e.g. South America, parts of the USA, and Eastern Eurasia) over the study period, whilst in others strengths have decreased (e.g. parts of western and north-central Eurasia). Thus, globally, there has been essentially no overall bias among the changing teleconnections in one direction or the other. Such changes may be related to the modulation of the general amplitudes of ENSO. However, given the global mix of strengthening vs. weakening teleconnections, this may suggest that the changes reflect changes in teleconnection strengths.

We also found that there are more basins in which annual floods increase with La Niña and decrease with El Niño than vice versa. This is an important finding, since past studies on relationships between ENSO and disaster impacts have only examined differences between the El Niño and neutral phases of ENSO. Moreover, these studies have only assessed relationships at the national scale, which may lead to the masking of ENSO relationships in (large) countries where ENSO and floods are oppositely correlated in different regions (e.g. Brazil, China, USA).

Finally, we discussed some important implications of these findings for future flood risk analyses and management. Additional research is needed to examine possible relationships between ENSO and flood impacts (e.g. loss of life and economic damage), to supplement the current analysis of ENSO and flood discharges alone. Where such relationships exist, and the relationships are persistent through time, it could potentially be useful to combine this information with ongoing advances in ENSO predictability research, in order to provide probabilistic flood risk forecasts. This information may enable humanitarian and development agencies to prioritise short-

HESSD
10, 10231–10276, 2013

term risk reduction efforts in the most at risk regions; (re-)insurance companies to assess anomalies in their risk portfolios in the coming seasons to years; and potentially enable improved flood early warning and flood regulation of dams.

Acknowledgements. This research was funded by a VENI grant from the Netherlands Organisation for Scientific Research (NWO). M. Kummu received funding from Aalto University Postdoc grants. We acknowledge the Global Runoff Data Centre, Koblenz, Germany, for providing river discharge time-series. The financial support from the EU's Research Framework Programme (FP6) under contract no. 036946 (WATCH – Water and Global Change) is gratefully acknowledged.

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S.: Development and testing of the WaterGAP2 global model of water use and availability, Hydrolog. Sci. J., 48, 317–337, doi:10.1623/hysj.48.3.317.45290, 2003.

Allamano, P., Claps, P., and Laio, F.: Global warming increases flood risk in mountainous areas, Geophys. Res. Lett., 36, L24404, doi:10.1029/2009GL041395, 2009.

Apipattanavis, S., McCabe, G. J., Rajagopalan, B., and Gangopadhyay, S.: Joint spatiotemporal variability of global sea surface temperatures and global Palmer Drought Severity Index values, J. Climate, 22, 6251–6267, doi:10.1175/2009JCLI2791.1, 2009.

Asokan, S. M. and Dutta, D.: Analysis of water resources in the Mahanadi River Basin, India under projected climate conditions, Hydrol. Process., 22, 3589–3603, doi:10.1002/hyp.6962, 2008.

Barros, V., Chamorro, L., Coronel, G., and Baez, J.: The major discharge events in the Paraguay River: magnitudes, source regions, and climate forcings, J. Hydrometeorol., 5, 1161–1170, doi:10.1175/JHM-378.1, 2004.

Beebee, R. A. and Manga, M.: Variation in the relationship between snowmelt runoff in Oregon and ENSO and PDO, J. Am. Water Resour. As., 40, 1011–1024, doi:10.1111/j.1752-1688.2004.tb01063.x, 2004.

Bell, G. D. and Janowiak, J. E.: Atmospheric circulation associated with the Mid-west Floods of 1993, B. Am. Meteorol. Soc., 76, 681–695, doi:10.1175/1520-0477(1995)076<0681:ACAWTM>2.0.CO;2, 1995.

Bell, V. A., Kay, A. L., Jones, R. G., and Moore, R. J.: use of a grid-based hydrological model and regional climate model outputs to assess changing flood risk, Int. J. Climatol., 27, 1657–1671, doi:10.1002/joc.1539, 2007.

Bhutiyani, M. R., Kale, V. S., and Pawar, N. J.: Changing streamflow patterns in the rivers of northwestern Himalaya: implications of global warming in the 20th century, Curr. Sci. India, 95, 618–626, 2008.

Bouma, M. J., Kovats, R. S., Goubet, S. A., Cox, J. St. H., and Haines, A.: Global assessment of El Niño's disaster burden, The Lancet, 350, 1435–1438, doi:10.1016/S0140-6736(97)04509-1, 1997.

Bouwer, L. M., Vermaat, J. E., and Aerts, J. C. J. H.: Regional sensitivities of mean and peak river discharge to climate variability in Europe, J. Geophys. Res., 113, D19103, doi:10.1029/2008JD010301, 2008.

Brown, C. and Lall, U.: Water and economic development: the role of variability and a framework for resilience, Nat. Resour. Forum, 30, 306–317, doi:10.1111/j.1477-8947.2006.00118.x, 2006.

Cameron, D.: An application of the UKCIP02 climate change scenarios to flood estimation by continuous simulation for a gauged catchment in the northeast of Scotland, UK (with uncertainty), J. Hydrol., 328, 212–226, doi:10.1016/j.jhydrol.2005.12.024, 2006.

Camilloni, I. A. and Barros, V. R.: Extreme discharge events in the Paraná River and their climate forcing, J. Hydrol., 278, 94–106, doi:10.1016/S0022-1694(03)00133-1, 2003.

Cane, M. A.: The evolution of El Niño, past and future, Earth Planet. Sc. Lett., 230, 227–240, doi:10.1016/j.epsl.2004.12.003, 2005.

Cayan, D. R. and Webb, R. H.: El Niño/Southern Oscillation and streamflow in the western United States, in: El Niño. Historical and Paleoclimatic Aspects of the Southern Oscillation, edited by: Diaz, H. F. and Markgraf, V., Cambridge University Press, Cambridge, 29–68, 1992.

Cayan, D. R., Redmond, K. T., and Riddle, L. G.: ENSO and hydrologic extremes in the western United States, J. Climate, 12, 2881–2893, doi:10.1175/1520-0442(1999)012<2881:EAHEIT>2.0.CO;2, 1999.

Charlton, R., Fealy, R., Moore, S., Sweeney, J., and Murphy, C.: Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques, Climate Change, 74, 475–491, 2006.

Cheng, Y., Tang, Y., and Chen, D.: Relationship between predictability and forecast skill of ENSO on various time scales, J. Geophys. Res., 116, C12006, doi:10.1029/2011JC007249, 2011.

Chiew, F. H. S. and McMahon, T. A.: Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability, Hydrolog. Sci. J., 47, 505–522, doi:10.1080/02626660209492950, 2002.

Conway, D., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C., and Mahe, G.: Rainfall and water resources variability in sub-Saharan Africa during the twentieth century, J. Hydrometeorol., 10, 41–59, doi:10.1175/2008JHM1004.1, 2009.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neil, R. V., Paruelo, J., Raskin, R. G., Sutton, P., and Van den Belt, M.: The value of the world's ecosystem services and natural capital, Nature, 387, 253–260, 1997.

Cunderlik, J. M. and Ouarda, T. B. M. J.: Trends in the timing and magnitude of floods in Canada, J. Hydrol., 375, 471–480, doi:10.1016/j.jhydrol.2009.06.050, 2009.

Dairaku, K., Emori, S., and Higashi, H.: Potential changes in extreme events under global climate change, J. Disaster Res., 3, 39–50, 2008.

Dankers, R. and Feyen, L.: Climate change impact on flood hazard in Europe: an assessment based on high-resolution climate simulations, J. Geophys. Res., 113, D19105, doi:10.1029/2007JD009719, 2008.

Dankers, R. and Feyen, L.: Flood hazard in Europe in an ensemble of regional climate scenarios, J. Geophys. Res., 114, D16108, doi:10.1029/2008JD011523, 2009.

Das, T., Dettinger, M. D., Cayan, D. R., and Hidalgo, H. R.: Potential increase in floods in California's Sierra Nevada under future climate projections, Climatic Change, 109, 71–94, doi:10.1007/s10584-011-0298-z, 2012.

Delgado, J. M., Apel, H., and Merz, B.: Flood trends and variability in the Mekong river, Hydrol. Earth Syst. Sci., 14, 407–418, doi:10.5194/hess-14-407-2010, 2010.

Dettinger, M. D. and Diaz, H. F.: Global characteristics of stream flow seasonality and variability, J. Hydrometeorol., 1, 289–310, doi:10.1175/1525-7541(2000)001<0289:GCOSFS>2.0.CO;2, 2000.

Dettinger, M. D., Cayan, D. R., and McCabe, G. J.: Multiscale streamflow variability associated with El Niño/Southern Oscillation, in: El Niño and the Southern Oscillation-Multiscale Variability and Global and Regional Impacts, edited by: Diaz, H. F. and Markgraf, V., Cambridge University Press, Cambridge, 113–147, 2000.

Dettinger, M. D., Battisti, D. S., Garreaud, R. D., McCabe, G. J., and Bitz, C. M.: Interhemispheric effects of interannual and decadal ENSO-like climate variations on the Americas, in: Interhemispheric Climate Linkages: Present and Past Climates in the Americas and their Societal Effects, edited by: Markgraf, V., Academic Press, San Diego, 1–16, 2001.

Di Baldassarre, G., Montanari, A., Lins, H., Koutsoyiannis, D., Brandimarte, L., and Blöschl, G.: Flood fatalities in Africa: from diagnosis to mitigation, Geophys. Res. Lett., 37, L22402, doi:10.1029/2010GL045467, 2010.

Dilley, M. and Heyman, B. N.: ENSO and disaster: droughts, floods and El Niño/Southern Oscillation warm events, Disasters, 19, 181–193, 1995.

Döll, P., Kaspar, F., and Lehner, B.: A global hydrological model for deriving water availability indicators: model tuning and validation, J. Hydrol., 270, 105–134, doi:10.1016/S0022-1694(02)00283-4, 2003.

Douglas, E. M., Vogel, R. M., and Kroll, C. N.: Trends in floods and low flows in the United States: impact of spatial correlation, J. Hydrol., 240, 90–105, doi:10.1016/S0022-1694(00)00336-X, 2000.

Feyen, L., Dankers, R., Bódis, K., Salamon, P., and Barredo, J. I.: Fluvial flood risk in Europe in present and future climates, Climatic Change, 112, 47–62, doi:10.1007/s10584-011-0339-7, 2012.

Fujihara, Y., Tanaka, K., Watanabe, T., Nagano, T., and Kojiri, T.: Assessing the impacts of climate change on the water resources of the Seyhan River Basin in Turkey: use of dynamically downscaled data for hydrologic simulations, J. Hydrol., 353, 33–48, doi:10.1016/j.jhydrol.2008.01.024, 2008.

Gershunov, A. and Barnett, T. P.: Interdecadal modulation of ENSO teleconnections, B. Am. Meteorol. Soc., 79, 2715–2725, doi:10.1175/1520-0477(1998)079<2715:IMOET>2.0.CO;2, 1998.

Gershunov, A., Barnett, T. P., and Cayan, D. R.: North Pacific interdecadal oscillation seen as factor in ENSO-related North American climate anomalies, EOS T. Am. Geophys. Un., 80, 25–30, doi:10.1029/99EO00019, 1999.

Graham, L. P., Andreasson, J., and Carlsson, B.: Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods – a case study on the Lule River basin, Climatic Change, 81, 293–307, doi:10.1007/s10584-006-9215-2, 2007.

Gudmundsson, L., Tallaksen, L. M., Stahl, K., Clark, D. B., Dumont, E., Hagemann, S., Bertrand, N., Gerten, D., Heinke, J., Hanasaki, N., Voss, F., and Koirala, S.: Comparing large-scale hydrological model simulations to observed runoff percentiles in Europe, J. Hydrometeorol., 13, 604–620, doi:10.1175/JHM-D-11-083.1, 2011.

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

Hannaford, J. and Marsh, T. J.: High-flow and flood trends in a network of undisturbed catchments in the UK, Int. J. Climatol., 28, 1325–1338, doi:10.1002/joc.1643, 2008.

Hidalgo, H. G. and Dracup, J. A.: ENSO and PDO effects on hydroclimatic variations of the Upper Colorado River Basin, J. Hydrometeorol., 4, 5–23, doi:10.1175/1525-7541(2003)004<0005:EAPEOH>2.0.CO;2, 2003

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

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., and Kanae, S.: Global flood risk under climate change, Nature Climate Change, online first, doi:10.1038/nclimate1911, 2013.

Hirsch, R. M. and Ryberg, K. R.: Has the magnitude of floods across the USA changed with global CO_2 levels?, Hydrolog. Sci. J., 57, 1–9, doi:10.1080/02626667.2011.621895, 2012.

Hoerling, M. P., Kumar, A., and Zhong, M.: El Niño, La Niña, and the non-linearity of their teleconnections, J. Climate, 10, 1769–1786, doi:10.1175/1520-0442(1997)010<1769:ENOLNA>2.0.CO;2, 1997.

Hoerling, M., Quan, X., and Eischeid, J.: Distinct causes for two principal US droughts of the 20th century, Geophys. Res. Lett., 36, L19708, doi:10.1029/2009GL039860, 2009.

Hoerling, M., Eischeid, J., and Perlwitz, J.: Regional precipitation trends: distinguishing natural variability from anthropogenic forcing, J. Climate, 23, 2131–2145, doi:10.1175/2009JCLI3420.1, 2010.

IPCC: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2012.

Jiang, T., Kundzewicz, Z. W., and Su, B.: Changes in monthly precipitation and flood hazard in the Yangtze River Basin, China, Int. J. Climatol., 28, 1471–1481, doi:10.1002/joc.1635, 2008.
Jongman, B., Ward, P. J., and Aerts, J. C. J. H.: Global exposure to river and coastal flooding – long term trends and changes, Global Environ. Chang., 22, 823–835, doi:10.1016/j.gloenvcha.2012.07.004, 2012.
Kay, A. L., Davies, H. N., Bell, V. A., and Jones, R. G.: Comparison of uncertainty sources for climate change impacts: flood frequency in England, Climatic Change, 92, 41–63, doi:10.1007/s10584-008-9471-4, 2009.
Kiladis, G. N. and Diaz, H. F.: Global climatic anomalies associated with extremes in the Southern Oscillation, J. Climatol., 2, 1069–1090, doi:10.1175/1520-0442(1989)002<1069:GCAAWE>2.0.CO;2, 1989.
Kitoh, A., Kusunoki, S., and Nakaegawa, T.: Climate change projections over South America in the late 21st century with the 20 and 60 km mesh Meteorological Research Institute atmospheric general circulation model (MRIAGCM), J. Geophys. Res., 116, D06105, doi:10.1029/2010JD014920, 2011.
Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F.: World map of the Köppen–Geiger climate classification updated, Meteorol. Z., 15, 259–263, doi:10.1127/0941-2948/2006/0130, 2006.
Kron, W., Steuer, M., Löw, P., and Wirtz, A.: How to deal properly with a natural catastrophe database – analysis of flood losses, Nat. Hazards Earth Syst. Sci., 12, 535–550, doi:10.5194/nhess-12-535-2012, 2012.
Kummu, M., Ward, P. J., De Moel, H., and Varis, O.: Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia, Environ. Res. Lett., 5, 034006, doi:10.1088/1748-9326/5/3/034006, 2010.
Labat, D.: Cross wavelet analyses of annual continental freshwater discharge and selected climate indices, J. Hydrol., 385, 269–278, doi:10.1016/j.jhydrol.2010.02.029, 2010.
Lauri, H., de Moel, H., Ward, P. J., Räsänen, T. A., Keskinen, M., and Kummu, M.: Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge, Hydrol. Earth Syst. Sci., 16, 4603–4619, doi:10.5194/hess-16-4603-2012, 2012.
Leander, R., Buishand, T. A., Van den Hurk, B. J. J. M., and De Wit, M. J. M.: Estimated changes in flood quantiles of the river Meuse from resampling of regional climate model output, J. Hydrol., 351, 331–343, doi:10.1016/j.jhydrol.2007.12.020, 2008.

HESSD
10, 10231–10276, 2013
Annual flood sensitivities to ENSO at the global scale
P. J. Ward et al.

Lehner, B., Doll, P., Alcamo, J., Henrichs, T., and Kaspar, F.: Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis, Climatic Change, 75, 273–299, doi:10.1007/s10584-006-6338-4, 2006.

Li, J., Xie, S.-P., Cook, E. R., Morales, M. S., Christie, D. A., Johnson, N. C., Chen, F., D'Arrigo, R., Fowler, A. M., Gou, X., and Fang, K.: El Niño modulations over the past seven centuries, Nature Climate Change, online first, doi:10.1038/NCLIMATE1936, 2013.

Lindström, G. and Bergström, S.: Runoff trends in Sweden, 1807–2002, Hydrolog. Sci. J., 49, 69–83, doi:10.1623/hysj.49.1.69.54000, 2004.

Lins, H. F. and Slack, J. R.: Streamflow trends in the United States, Geophys. Res. Lett., 26, 227–230, doi:10.1029/1998GL900291, 1999.

Mann, M., Cane, M., Clement, A., and Zebiak, S. E.: Volcanic and solar forcing of El Nino over the past 1000 years, J. Climate, 18, 447–456, doi:10.1175/JCLI-3276.1, 2005.

Mann, M. E., Park, J., and Bradley, R. S.: Global interdecadal and century-scale climate oscillations during the past five centuries, Nature, 378, 266–270, doi:10.1038/378266a0, 1995.

Marengo, J. A., Tomasella, J., Soares, W. R., Alves, L. M., and Nobre, C. A.: Extreme climatic events in the Amazon Basin, Theor. Appl. Climatol., 107, 73–85, doi:10.1007/s00704-011-0465-1, 2012..

McCabe, G. J. and Dettinger, M. D.: Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States, Int. J. Climatol., 19, 1399–1410, doi:10.1002/(SICI)1097-0088(19991115)19:13<1399::AID-JOC457>3.0.CO;2-A, 1999.

McCabe, G. J. and Wolock, D. M.: A step increase in streamflow in the conterminous United States, Geophys. Res. Lett., 29, 2185, doi:10.1029/2002GL015999, 2002.

McCabe, G. J., Palecki, M. A., and Betancourt, J. L.: Pacific and Atlantic influences on multidecadal drought frequency in the United States, P. Natl. Acad. Sci. USA, 101, 4136–4141, doi:10.1073/pnas.0306738101, 2004.

McPhaden, M. J., Zebiak, S. E., and Glantz, M. H.: ENSO as an integrating concept in Earth Science, Science, 314, 1740–1745, doi:10.1126/science.1132588, 2006.

Meyers, G., McIntosh, P., Pigot, L., and Pook, M.: The years of El Niño, La Niña, and interactions with the tropical Indian ocean, J. Climate, 20, 2872–2880, doi:10.1175/JCLI4152.1, 2007.

Milly, P. C. D., Wetherald, R. T., Dunne, K. A., and Delworth, T. L.: Increasing risk of great floods in a changing climate, Nature, 415, 514–517, doi:10.1038/415514a, 2002.

Mirza, M. M. Q.: Climate change, flooding in South Asia and implications, Reg. Environ. Change, 11, S95–S107, doi:10.1007/s10113-010-0184-7, 2011.
Mudelsee, M., Borngen, M., Tetzlaff, G., and Grunewald, U.: No upward trends in the occurrence of extreme floods in central Europe, Nature, 425, 166–169, doi:10.1038/nature01928, 2003.
Munich Re: Topics Geo 2012 Issue, Natural Catastrophes 2011, Analyses, Assessments, Positions, Münchener Rückversicherungs-Gesellschaft, Munich, 2012.
Munich Re: NatCatSERVICE Database, Münchener Rückversicherungs-Gesellschaft, Munich, 2013.
Nakaegawa, T. and Vergara, W.: First projection of climatological mean river discharges in the Magdalena River Basin, Colombia, in a changing climate during the 21st century, Hydrolog. Res. Lett., 4, 50–54, 2010.
Petrow, T. and Merz, B.: Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002, J. Hydrol., 371, 129–141, doi:10.1016/j.jhydrol.2009.03.024, 2009.
Piechota, T. C. and Dracup, J. A.: Drought and regional hydrologic variation in the United States: associations with the El Niño-Southern Oscillation, Water Resour. Res., 32, 1359–1373, doi:10.1029/96WR00353, 1996.
Piechota, T. C., Dracup, J. A., and Fovell, R. G.: Western US streamflow and atmospheric circulation patterns during El Niño Southern Oscillation, J. Hydrol., 201, 249–271, doi:10.1016/S0022-1694(97)00043-7, 1997.
Poussin, J. K., Bubeck, P., Aerts, J. C. J. H., and Ward, P. J.: Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse, Nat. Hazards Earth Syst. Sci., 12, 3455–3471, doi:10.5194/nhess-12-3455-2012, 2012.
Prudhomme, C. and Davies, H.: Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK, Part 2: Future climate, Climatic Change, 93, 197–222, doi:10.1007/s10584-008-9461-6, 2009.
Prudhomme, C., Parry, S., Hannaford, J., and Clark, D. B.: How well do large-scale models reproduce regional hydrological extremes in Europe?, J. Hydrometeorol., 12, 1181–1204, doi:10.1175/2011JHM1387.1, 2011
Raff, D. A., Pruitt, T., and Brekke, L. D.: A framework for assessing flood frequency based on climate projection information, Hydrol. Earth Syst. Sci., 13, 2119–2136, doi:10.5194/hess-13-2119-2009, 2009.

Räsänen, T. A. and Kummu, M.: Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong Basin, J. Hydrol., 476, 154–168, doi:10.1016/j.jhydrol.2012.10.028, 2013.

Redmond, K. T. and Koch, R. W.: Surface climate and streamflow variability in the Western United States and their relationship to large-scale circulation indices, Water Resour. Res., 27, 2381–2399, doi:10.1029/91WR00690, 1991.

Renard, B., Lang, M., Bois, P., Dupeyrat, A., Mestre, O., Niel, H., Sauquet, E., Prudhomme, C., Parey, S., Paquet, E., Neppel, L., and Gailhard, J.: Regional methods for trend detection: assessing field significance and regional consistency, Water Resour. Res., 44, W08419, doi:10.1029/2007WR006268, 2008.

Robson, A. J., Jones, T. K., Reed, D. W., and Bayliss, A. C.: A study of national trend and variation in UK floods, Int. J. Climatol., 18, 165–182, doi:10.1002/(SICI)1097-0088(199802)18:2<165::AID-JOC230>3.0.CO;2-#, 1998.

Shabalova, M., Van Deursen, W., and Buishand, A.: Assessing future discharge of the river Rhine using RCM integrations and a hydrological model, Clim. Res., 23, 233–246, 2003.

Shiklomanov, A. I., Lammers, R. B., Rawlins, M. A., Smith, L. C., and Pavelsky, T. M.: Temporal and spatial variations in maximum river discharge from a new Russian data set, J. Geophys. Res., 112, G04S53, doi:10.1029/2006JG000352, 2007.

Taye, M. T., Ntegeka, V., Ogiramoi, N. P., and Willems, P.: Assessment of climate change impact on hydrological extremes in two source regions of the Nile River Basin, Hydrol. Earth Syst. Sci., 15, 209–222, doi:10.5194/hess-15-209-2011, 2011.

Te Linde, A. H., Aerts, J. C. J. H., Bakker, A. M. R., and Kwadijk, J. C. J.: Simulating low probability peak discharges for the Rhine basin using resampled climate modeling data, Water Resour. Res., 46, WR03512, doi:10.1029/2009WR007707, 2010.

Thodsen, H.: The influence of climate change on stream flow in Danish rivers, J. Hydrol., 333, 226–238, doi:10.1016/j.jhydrol.2006.08.012, 2007.

Torrence, C. and Webster, P. J.: Interdecadal Changes in the ENSO-Monsoon System, J. Climate, 12, 2679–2690, doi:10.1175/1520-0442(1999)012<2679:ICITEM>2.0.CO;2, 1999.

Tu, M., Hall, M. J., De Laat, P. J. M., and De Wit, M. J. M.: Extreme floods in the Meuse river over the past century: aggravated by land-use changes?, Phys. Chem. Earth, 30, 267–276, doi:10.1016/j.pce.2004.10.001, 2005.

Tudhope, A. W., Chilcott, C. P., McCulloch, M. T., Cook, E. R., Chappell, J., Ellam, R. M., Lea, D. W., Lough, J. M., and Shimmield, G. B.: Variability in the El Niño-

Southern Oscillation through a glacial–interglacial cycle, Science, 291, 1511–1517, doi:10.1126/science.1057969, 2001.
Ummenhofer, C. C., England, M. H., McIntosh, P. C., Meyers, G. A., Pook, M. J., Risbey, J. S., Gupta, A. S., and Taschetto, A. S.: What causes southeast Australia's worst droughts?, Geophys. Res. Lett., 36, L04706, doi:10.1029/2008GL036801, 2009.
UNISDR: Global Assessment Report on Disaster Risk Reduction. Revealing Risk, Redefining Development, United Nations International Strategy for Disaster Reduction Secretariat, Geneva, 2011.
Uppala, S. M., Kallberg, P. W., Simmons, A. J., Andrae, U., Da Costa Bechtold, V., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B. J., Isaksen, L., Janssen, P., Jenne, R., McNally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Sanuders, R. W., Simon, P., Serl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woolen, J.: The ERA-40 re-analysis, Q. J. Roy. Meteor. Soc., 131, 2961–3012, doi:10.1256/qj.04.176, 2005.
van Pelt, S. C., Kabat, P., ter Maat, H. W., van den Hurk, B. J. J. M., and Weerts, A. H.: Discharge simulations performed with a hydrological model using bias corrected regional climate model input, Hydrol. Earth Syst. Sci., 13, 2387–2397, doi:10.5194/hess-13-2387-2009, 2009.
Villarini, G. and Smith, J. A.: Flood peak distributions for the Eastern United States, Water Resour. Res., 46, W06504, doi:10.1029/2009WR008395, 2010.
Villarini, G., Serinaldi, F., Smith, J. A., and Krajewski, W. F.: On the stationarity of annual flood peaks in the continental United States during the 20th century, Water Resour. Res., 45, W08417, doi:10.1029/2008WR007645, 2009.
Wang, B., Yang, J., Zhou, T., and Wang, B.: Inter-decadal changes in the major modes of Asian-Australian monsoon variability: strengthening relationship with ENSO since the late 1970s, J. Climate, 21, 1771–1789, doi:10.1175/2007JCLI1981.1, 2008.
Ward, P. J., Beets, W., Bouwer, L. M., Aerts, J. C. J. H., and Renssen, H.: Sensitivity of river discharge to ENSO, Geophys. Res. Lett., 37, L12402, doi:10.1029/2010GL043215, 2010.
Ward, P. J., Renssen, H., Aerts, J. C. J. H., and Verburg, P. H.: Sensitivity of discharge and flood frequency to 21st Century and late Holocene changes in climate and land use (River Meuse, northwest Europe), Climatic Change, 106, 179–202, doi:10.1007/s10584-010-9926-2, 2011.

Ward, P. J., Van Pelt, S. C., De Keizer, O., Aerts, J. C. J. H., Beersma, J. J., Van den Hurk, B. J. J. M., and Te Linde, A.: Including climate change projections in probabilistic flood risk assessment, J. Flood Risk Manage., online first, doi:10.1111/jfr3.12029, 2013.

Waylen, P. R. and Caviedes, C. N.: El Niño and annual floods on the north Peruvian littoral, J. Hydrol., 89, 141–156, doi:10.1016/0022-1694(86)90148-4, 1986.

Weedon, G. P., Gomes, S., Viterbo, P., Shuttleworth, W. J., Blyth, E., Österle, H., Adam, J. C., Bellouin, N., Boucher, O., and Best, M.: Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century, J. Hydrometeorol., 12, 823–848, doi:10.1175/2011JHM1369.1, 2011.

Winsemius, H. C., Van Beek, L. P. H., Jongman, B., Ward, P. J., and Bouwman, A.: A framework for global river flood risk assessments, Hydrol. Earth Syst. Sci., 17, 1871–1892, doi:10.5194/hess-17-1871-2013, 2013.

Wunsch, C.: The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations, B. Am. Meteorol. Soc., 80, 245–255, doi:10.1175/1520-0477(1999)080<0245:TIOSCR>2.0.CO;2, 1999.

Yiou, P., Ribereau, P., Naveau, P., Nogaj, M., and Brazdil, R.: Statistical analysis of floods in Bohemia (Czech Republic) since 1825, Hydrolog. Sci. J., 51, 930–945, doi:10.1623/hysj.51.5.930, 2006.

Zubair, L. and Chandimala, J.: Epochal changes in ENSO–Streamflow Relationships in Sri Lanka, J. Hydrometeorol., 7, 1237–1246, doi:10.1175/JHM546.1, 2006.

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). Hydrological years are identified according to the calendar year at their beginning.

ENSO mode	Hydrological year
El Niño	1963, 1965, 1969, 1972, 1976, 1982, 1986, 1987, 1991, 1997
La Niña	1964, 1967, 1970, 1971, 1973, 1974, 1975, 1988, 1998, 1999

HESSD
10, 10231–10276, 2013

Table 2. Sensitivity of annual flood discharge to SOI[a].

	Percentage change in Q_{max} per unit change SOI (land area, %)				
	Equatorial	Arid	Warm temperate	Cold[b]	All Köppen zones
Australia and Oceania	36 % (43 %)	63 % (45 %)	28 % (29 %)	16 % (23 %)	45 % (39 %)
Central America	29 % (41 %)	98 % (62 %)	26 % (21 %)	N/A	54 % (46 %)
Eastern Asia	N/A	31 % (18 %)	11 % (51 %)	21 % (10 %)	16 % (29 %)
Eastern Europe & Central Asia	N/A	24 % (33 %)	15 % (12 %)	11 % (22 %)	14 % (23 %)
Indian Subcontinent	15 % (45 %)	63 % (30 %)	N/A	N/A	35 % (26 %)
Latin America	14 % (53 %)	49 % (27 %)	16 % (82 %)	205 % (25 %)	17 % (54 %)
Middle East	N/A	42 % (40 %)	11 % (12 %)	13 % (72 %)	40 % (38 %)
Middle and South Africa	21 % (55 %)	52 % (49 %)	64 % (17 %)	N/A	35 % (51 %)
North Africa	5 % (73 %)	39 % (38 %)	25 % (34 %)	N/A	32 % (41 %)
North America	N/A	50 % (55 %)	17 % (32 %)	11 % (19 %)	19 % (25 %)
Southeastern Asia	20 % (37 %)	N/A	8 % (37 %)	N/A	18 % (37 %)
Western Europe	N/A	N/A	13 % (28 %)	11 % (27 %)	13 % (28 %)
All regions	19 % (50 %)	49 % (40 %)	16 % (37 %)	12 % (21 %)	27 % (37 %)

[a] Area-weighted percentage change in Q_{max} per unit change SOI for basins with significant correlations between $\ln Q_{max}$ and SOI, and percentage of land area (shown in brackets) with significant correlations. Results shown per geographical region and Köppen climate region. [b] Köppen regions "polar" and "snow" have been combined here into one "cold" region. Greenland and Antarctica are excluded from the analysis.

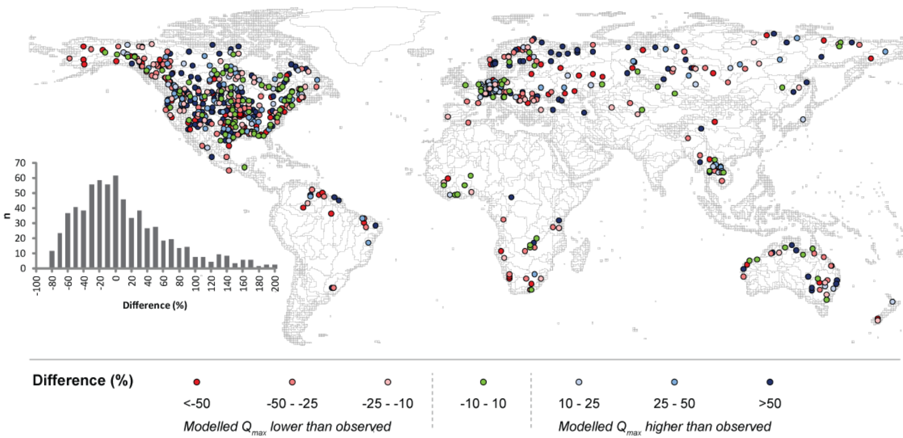

Fig. 1. Percentage difference between modelled and observed median Q_{max} over the period 1958–1999. Inset shows histogram of values for individual locations (difference > 200 % for 58 locations).

HESSD
10, 10231–10276, 2013

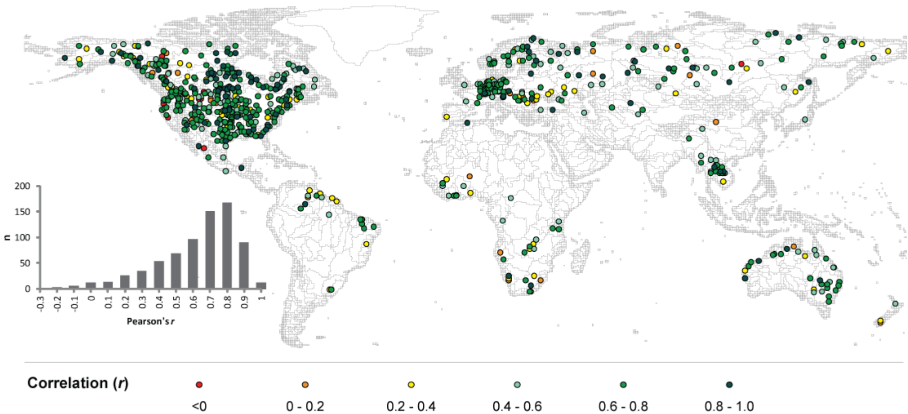

Fig. 2. Correlation (r) between modelled and observed $\ln Q_{max}$ time-series over the period 1958–1999. Inset shows histogram of values for individual locations.

HESSD
10, 10231–10276, 2013
Annual flood sensitivities to ENSO at the global scale
P. J. Ward et al.

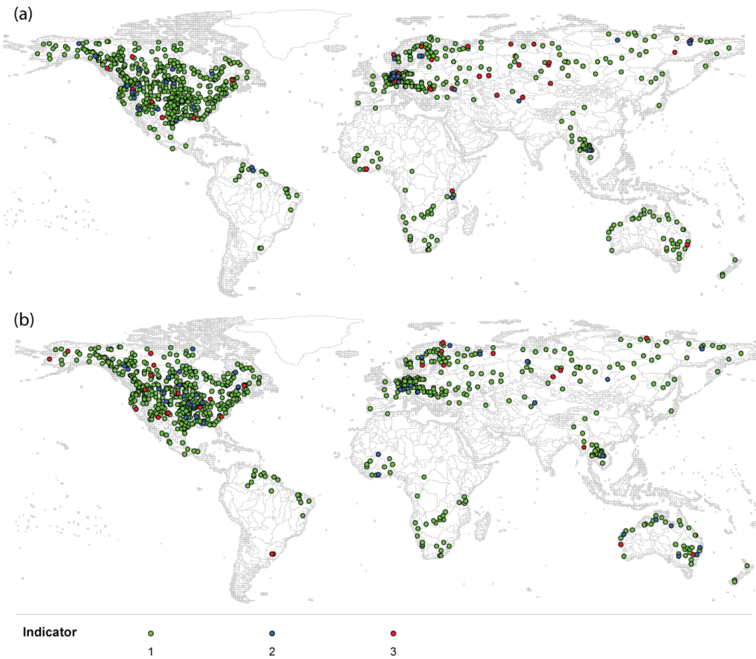

Fig. 3. Indicator of the (dis)-agreement between modelled and observed median Q_{max} between **(a)** El Niño years and non-El Niño years and **(b)** La Niña years and non-La Niña years, whereby: (1, green) indicates that both modelled and observed median Q_{max} show either no significant difference between **(a)** El Niño and non-El Niño years and **(b)** La Niñ a and non-La Niña years, or that both modelled and observed median Q_{max} show significant difference between **(a)** El Niño and non-El Niño years with same sign and **(b)** La Niña and non-La Niña years with same sign; (2, blue) indicates that modelled median Q_{max} shows no significant difference between **(a)** El Niño and non-El Niño years and **(b)** La Niña years and non-La Niñ a years, whilst observed shows a significant difference; and (3, red) indicates that observed median Q_{max} shows no significant difference between **(a)** El Niño and non-El Niño years and **(b)** La Niña years and non-La Niñ a years, whilst modelled shows a significant difference. There are no stations for which modelled and observed median Q_{max} show significant differences between El Niño and non-El Niño (or La Niña and non-La Niña years) years with the opposite sign. Statistical significance was assessed using a 2-tailed Mann–Whitney U (MWU) test, $\alpha = 0.05$.

HESSD
10, 10231–10276, 2013

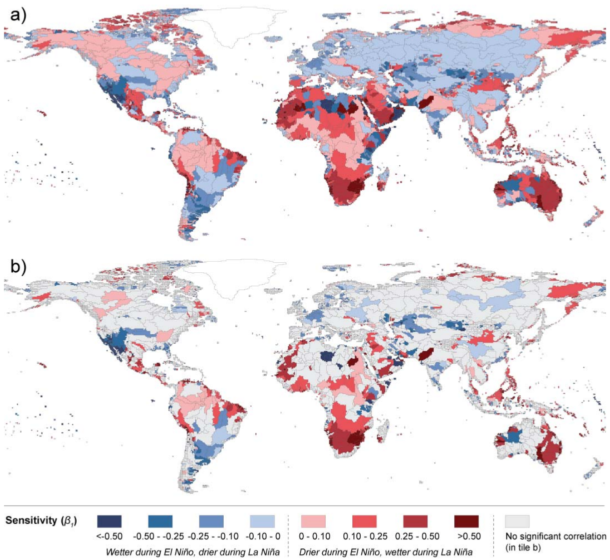

Fig. 4. Sensitivity (β_1) of ln Q_{max} to variations in SOI. In the upper plate **(a)**, the sensitivity is shown for all basins. In the lower plate **(b)**, the sensitivity is only shown for basins with significant correlation (Pearson's r, t statistic, $\alpha = 0.10$) (basins where the correlation is not significant are shown in grey). Blue indicates negative correlation (higher annual floods in El Niño years/lower annual floods in La Niña years); and red indicates positive correlation (lower annual floods in Niño years/higher annual floods in La Niña years).

HESSD
10, 10231–10276, 2013

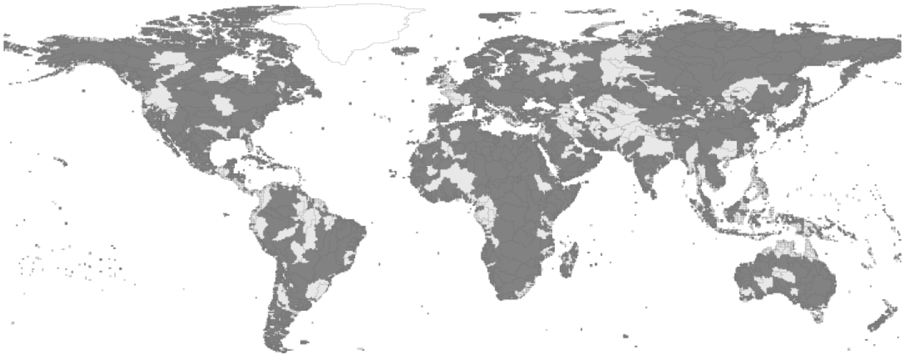

Fig. 5. Basins in which Q_{max} (Q_{ann}) is more sensitive than Q_{ann} (Q_{max}) to changes in SOI are shown in dark (light) grey.

HESSD
10, 10231–10276, 2013

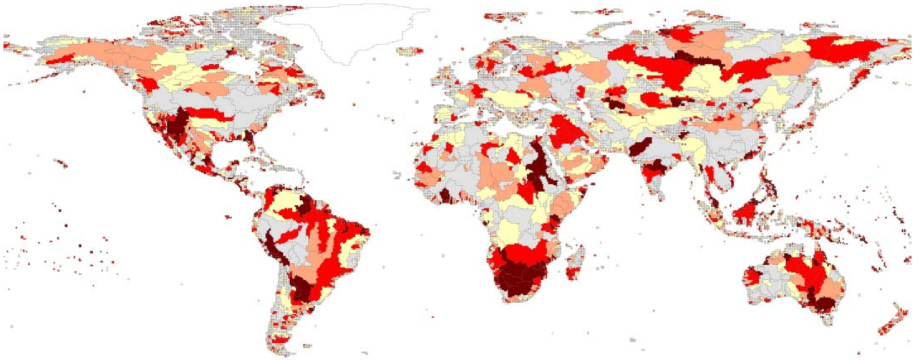

Fig. 6. Number of years (n) for which the correlation (Pearson's r) between $\ln Q_{max}$ and SOI_{DJF} is statistically significant ($\alpha = 0.10$), based on 21 yr moving-windows centred on 1968 to 1988.

HESSD
10, 10231–10276, 2013

Fig. 7. Correlation (Pearson's r) between ln Q_{max} and SOI_{DJF} for 21 yr moving windows centred on the years 1968–1988. On the line graphs, the axes are unlabelled due to space constraints: the x-axes show years (1968–1998) and the y-axes show the strength of Pearson's r (+1 to −1). The blue line indicates the strength of the correlation, and the red dashed lines indicate the critical values of the significance test (critical r = 0.369/−0.369, α = 0.10). The names of the basins are shown in text, as well as the trends in the strength of the correlation over time (Sect. 4.3).

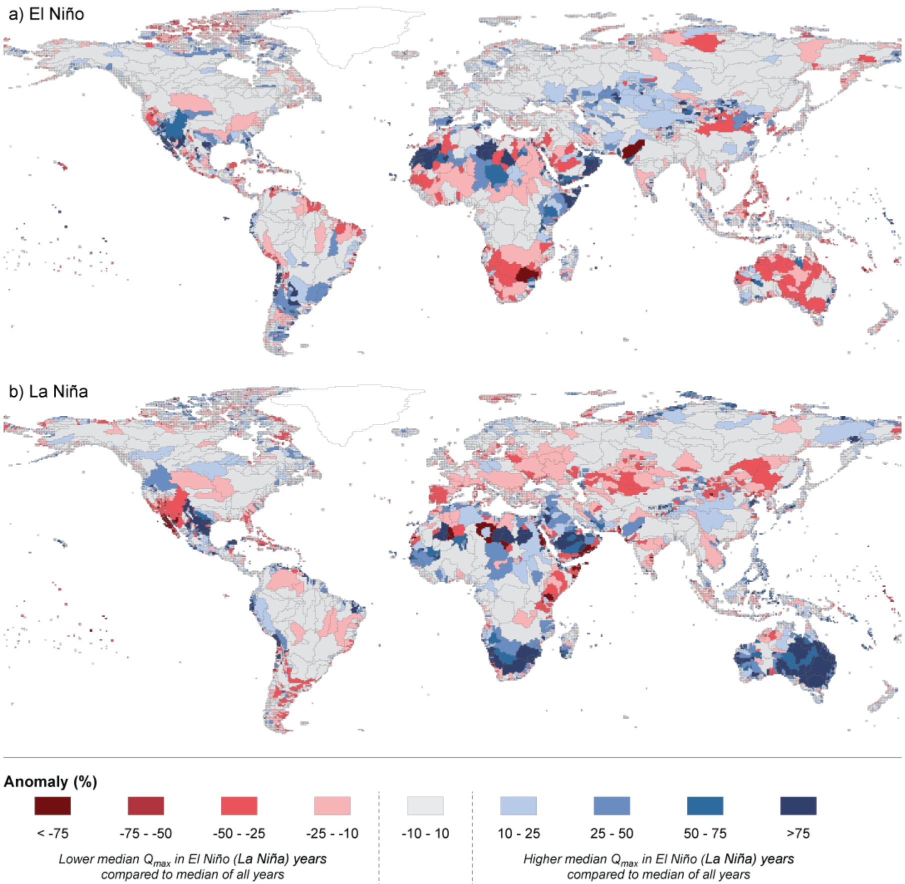

Fig. 8. Anomaly (percentage) in median Q_{max} between: **(a)** El Niño years and all years; and **(b)** La Niña years and all years. Blue indicates higher median Q_{max} (i.e. higher annual flood discharge) in El Niño (La Niña) years compared to the median of all years; and red the opposite.

HESSD
10, 10231–10276, 2013

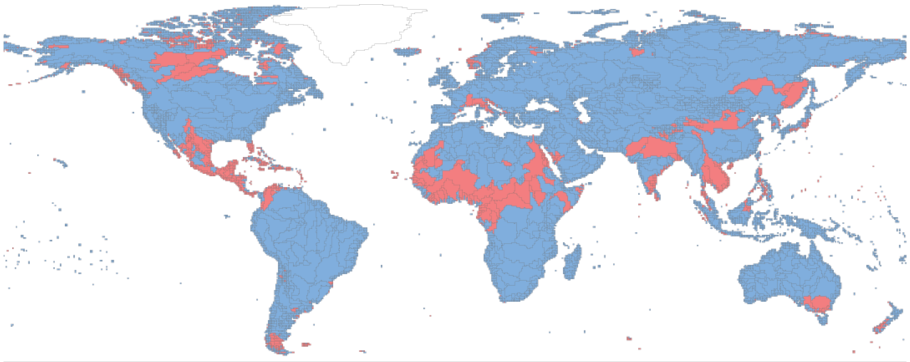

Fig. A1. Hydrological years used in this study for each basin. The standard hydrological year (October-September) was used as default, except for in those basins in which the mean Q_{max} of the most downstream cell occurs in the months of September, October, or November. In the latter case, the hydrological year was set to July–June.

HESSD
10, 10231–10276, 2013

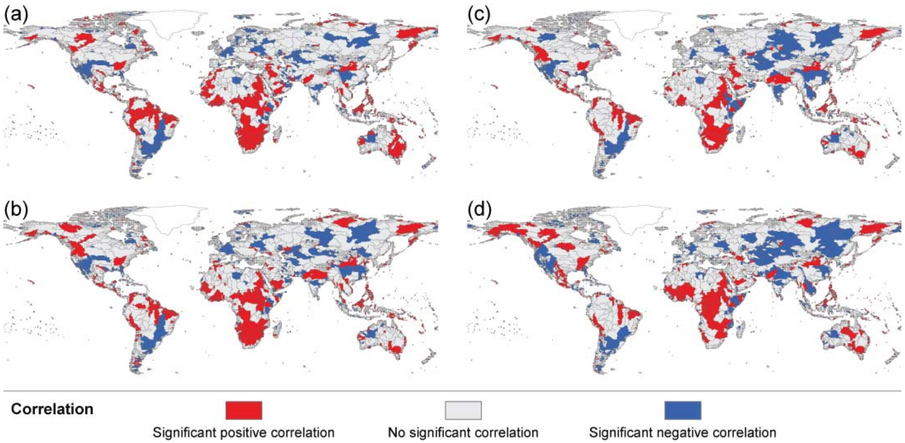

Fig. A2. Basins for which there is significant correlation (positive in red; negative in blue) between $\ln Q_{max}$ and various indices of ENSO: **(a)** SOI; **(b)** inverse Multivariate ENSO Index (MEI); **(c)** inverse NINO3.4 index; and **(d)** inverse Global SST ENSO index. Basins with no significant correlation are shown in grey. Statistical significance was tested using the *t*-statistic ($\alpha = 0.10$).

HESSD
10, 10231–10276, 2013

Annual flood sensitivities to ENSO at the global scale

P. J. Ward et al.

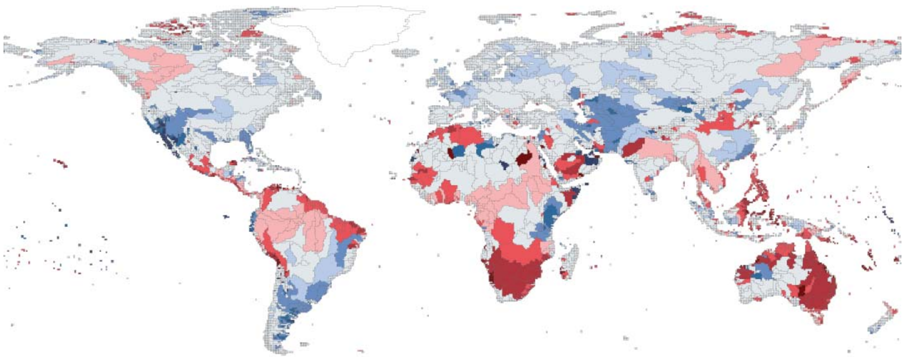

Fig. A3. Sensitivity ($\beta 1$) of $\ln Q_{\text{ann}}$ to variations in SOI. Basins with no significant correlation (Pearson's r, $\alpha = 0.10$) are shown in grey. Blue indicates negative correlation (wetter El Niño/drier La Niña); and red indicates positive correlation (drier El Niño/wetter La Niña).

HESSD
10, 10231–10276, 2013

Annual flood sensitivities to ENSO at the global scale

P. J. Ward et al.