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LETTER

Mapping the locations of asymmetric and symmetric discharge responses in global rivers to the two types of El Niño

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Abstract

River discharge variations play a pivotal role in global water and biogeochemical cycles and can impact the world's agro-economics. Here, variations associated with the Central Pacific and Eastern Pacific types of El Niño are contrasted for thirty of the world's largest rivers. Maps are constructed to identify the rivers that produce opposite-sign (i.e., asymmetric response (AR)) or same-sign (i.e., symmetric response (SR)) variations to these two types of El Niño. The mapping shows that the strongest AR occurs in North American rivers whereas the strongest SR occurs in the Murray River in Eastern Australia and the Danube River in Central Europe. Rivers in Asia and Africa vary in their response patterns depending on the phase (developing, mature or decaying) of El Niño. The response patterns are linked to precipitation variations within the river basins. The mapping presented offers an overview of which rivers may need new projection techniques and management strategies in response to the changes in El Niño type during recent decades.

1. Introduction

River discharge is an important part of global water and biogeochemical cycles. For the water cycle, the discharge serves as the main water outflux in the terrestrial water balance (Dai and Trenberth 2002) and contributes to the long-term water balance of the oceans (Oki and Kanae 2006). For the biogeochemical cycle, river discharge delivers great amounts of nutrients and dissolved minerals into the ocean that can have a large impact on biogeochemical processes in coastal and reef regions (Boyer *et al* 2006). Fluctuations in river discharge can have significant impacts on the global water and biogeochemical cycles, as well as on human economic and societal activities (Milly *et al* 2005, Iles and Hegerl 2015, Pal *et al* 2015). El Niño is one of the climate phenomena that are known to cause interannual fluctuations in the global river discharge. Previous studies have uncovered some El Niño-river discharge relationships (e.g., Dettinger and Diaz 2000, Chiew and McMahon 2002, Dai *et al* 2009, Ward *et al* 2010, 2014a, 2014b). Dai *et al* (2009), for example, correlated river discharge data globally with an El Niño index and concluded that El Niño events tend to decrease the discharge in the Amazon, Orinoco, and Niger River basins but to increase the discharge in the Mississippi, Paraná, and Uruguay River basins. The El Niño impacts on the discharge and potential flood risks have also been found to depend on the geographic locations of the river basins and to vary from continent to continent (Dettinger and Diaz 2000, Labat 2010, Ward *et al* 2014a, 2014b).

Most of these earlier studies did not explicitly consider the existence of different types or flavors of El Niño, a distinction that has been increasingly emphasized by the El Niño research community in recent years (Capotondi *et al* 2015). Two particular types of El Niño have been identified: the Eastern Pacific (EP) El Niño and the Central Pacific (CP) El Niño (Yu and Kao 2007, Kao and Yu 2009). The EP El Niño is the traditional type of El Niño that has its warm sea surface temperature (SST) anomalies centered in the equatorial EP, whereas the CP El Niño is a type of El Niño that has occurred more frequently in recent decades (e.g. Kao and Yu, 2009, Lee and McPhaden 2010, Yu *et al* 2012b) and has its SST anomalies centered around

the international dateline. It has been shown via observational analyses and numerical model experiments that these two types of El Niño produce distinct impacts on the US hydroclimate (Mo 2010, Yu *et al* 2012a, Yu and Zou 2013, Liang *et al* 2014, Ning and Bradley 2015), Amazon ecosystems (Li *et al* 2011), the Indian and Asian summer monsoons (Wang *et al* 2013), and drought events over southern China (Zhang *et al* 2014). Among them, Liang *et al* (2014) found that the springtime Mississippi River discharge increases during EP El Niños (consistent with the finding of Dai *et al* 2009) but decreases during CP El Niños. They referred to these opposite signs in discharge anomalies as an 'asymmetric response (AR)' to the two types of El Niño, in contrast to the 'symmetric response (SR)' that would produce the same signs of anomalies during the two types of El Niño. River basins that produce the AR pattern may have distinct year-to-year discharge variations in recent decades after El Niño changed from predominantly the EP to the CP type, whereas those that produce the SR pattern would be less affected by the change in El Niño type. Therefore, it is desirable to obtain an overview of which large river basins in the world produce the AR and SR patterns to the two types of El Niño. A method is developed in this study to identify these response patterns for global river basins during the developing, mature, and decaying phases of El Niño.

2. Data and methods

The major dataset used in this study is the Global River Flow and Continental Discharge Data Set (Dai *et al* 2009, http://www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/), which provides river discharge data for the world's 925 largest rivers primarily based on gauge observations. There are two versions of this discharge dataset available: one uses model simulations to fill data gaps (as described in Dai *et al.* 2009) and the other does not use the gap filling. The non-filling data set is used in this study and was downloaded from http://www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/coastal-stns-Vol-monthly.updated-oct2007.nc. We selected for this study thirty of the world's largest rivers according to the size of their drainage areas (based on the data from Oki and Sud 1998; http://hydro.iis.u-tokyo.ac.jp/~taikan/TRIPDATA/TRIPDATA.html). Large rivers in high-latitude regions were not considered because El Niño's impacts on their discharges tend to be interrupted by pulse-like seasonal irregularities (not shown) related to the spring snowmelt. Large rivers that show discontinuities or large gaps in their data were also excluded from the study. The thirty rivers we studied are listed in figure 1, together with the availability of their discharge data during the 1950–2006 analysis period. These selected rivers are numbered in figure 1 based on their rankings in terms of drainage area. The drainage areas, the locations, and the names of the corresponding gauge stations for each of the thirty rivers are listed in table S1 of the supplementary material (SM, available at stacks.iop.org/ERL/11/044012/mmedia). The total area of the investigated river basins is roughly 3.7445×10^7 km^2, about 25% of the total land area. Since human interventions (such as the construction of dam and reservoir) can change river discharge and interfere with the natural variations caused by El Niño, we examined the discharge time series of every river to determine if the data contains any significant changes in the amplitude, seasonality, and interannual variability of the discharge. Our analysis (see section 2 of SM and figure S1) indicates that discharges in Huanghe, Columbia, Colorado, Rio Grande, and Sao Francisco rivers may be affected by human interventions. These five rivers are marked with a '*' symbol in the figures to caution that the results may be altered by the interventions. Also used in this study is NOAA's PRECipitation REConstruction over Land (PREC/L, http://www.esrl.noaa.gov/psd/data/gridded/data.precl.html) dataset, which provides precipitation rates (in mm/day) from 1948 to 2015 with a 1×1 horizontal resolution (Chen *et al* 2002). Anomalies are defined as the deviations from the 1950 to 2006 climatology.

Yu *et al* (2012b) has identified the type of all major El Niño events since 1950. Our analysis period includes seven EP El Niño events (1951–1952, 1969–1970, 1972–1973, 1976–1977, 1982–1983, 1986–1987, and 1997–1998) and twelve CP El Niño events (1953–1954, 1957–1958, 1958–1959, 1963–1964, 1965–1966, 1968–1969, 1977–1978, 1987–1988, 1991–1992, 1994–1995, 2002–2003, and 2004–2005). These CP and EP El Niño events are indicated in figure 1 and are used to construct discharge and precipitation composites for analysis. We divide the lifecycle of El Niño into three phases: the developing phase (i.e. May(0)–September(0)), the mature phase (i.e. October(0)–February(1)), and the decaying phase (i.e. March(1)–July(1)). Here, (0) means the calendar year that an El Niño event begins to develop, and (1) denotes the year immediately following.

To test the statistical significance of the discharge anomalies composited for the two types of El Niño, a two-tailed Student's t test was performed. Due to the limited numbers of EP and CP Niño events available for the composites, the test is applied to the composite anomalies averaged in the developing, mature, and decaying phases of the El Niño. The null hypothesis of the test is that the phase-averaged discharge anomalies are zero at the 90% significance interval. If the composite anomalies for a particular phase pass the significance test for either the EP or CP El Niño, we consider the discharge anomalies during that phase for that river to be statistically significant.

The way we determine if a river basin produces an SR pattern or an AR pattern to the two types of El Niño is as follows. If the composite discharge anomalies are

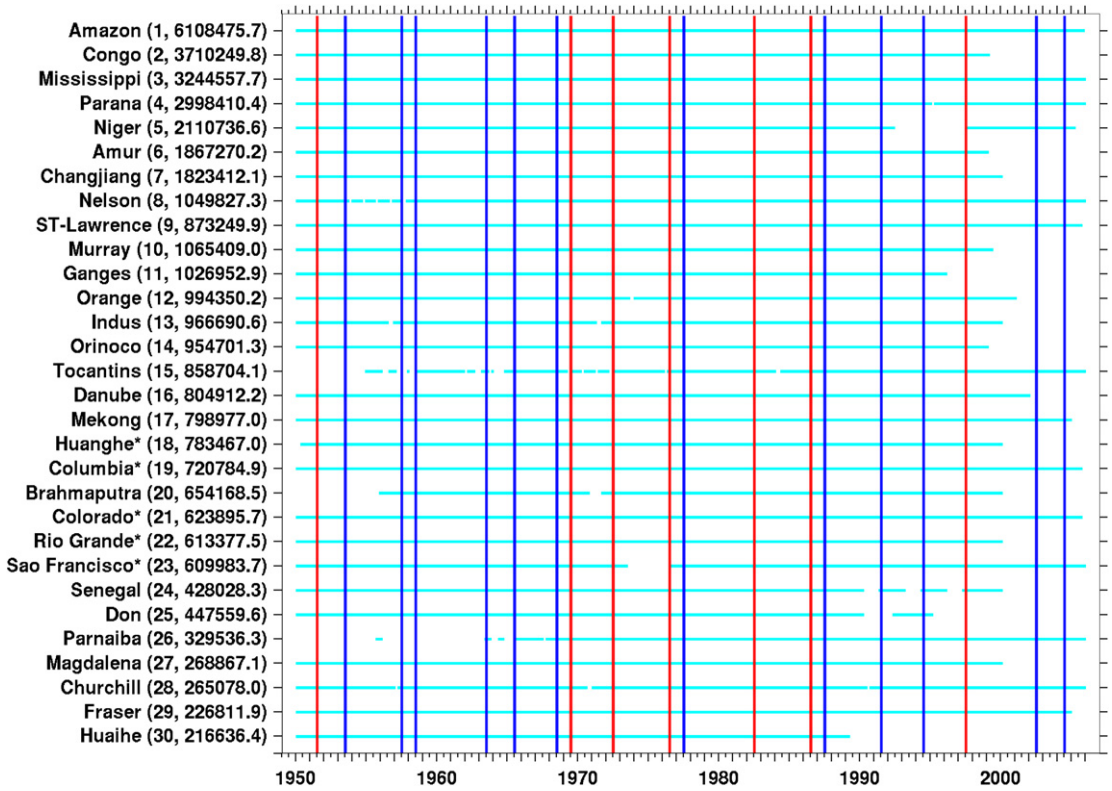

Figure 1. The availability of discharge data (horizontal light-blue bars) for the thirty rivers with the largest drainage areas. The drainage area ranking is based on Oki and Kanae (2006) and the discharge data originated from Dai *et al* (2009). The second number in the parenthesis indicates the river basin area (km^2). The vertical red and blue lines mark the years of the EP and CP El Niño events, respectively, according to Yu *et al* (2012b). The '*' symbol after the river name denotes that this river may be influenced by human interventions.

of the same sign for more than three months in one El Niño phase (i.e., for more than 50% of the phase), that river basin is regarded as producing an SR pattern to the two types of El Niño during that particular El Niño phase. If during three months or more in that phase, the EP composite anomalies are above-normal while the CP composite anomalies are below-normal, that river basin is considered to produce an AR+ pattern. Conversely, the reversed anomaly situation is referred to as the 'AR'−.

3. Response patterns of river discharge to the two types of El Niño

To stratify the global river responses to the two types of El Niño, we show in figure 2 the discharge anomalies composited for the EP and CP El Niño for each of the thirty selected rivers. Our significance tests (see section 2 and figures S2 and S3 of SM) indicate that, among the ninety total phases in the figure (i.e., thirty rivers times three El Niño phases per river), fifty-seven of them have discharge anomalies that pass the 90% two-tailed significance test. Based on this, we consider a large fraction (i.e., 57 out of 90; 63%) of the discharge anomalies in figure 2 to be statistically significant.

At first glance, four rivers (the Danube, Mekong, Murray, and Parnaiba) in figure 2 show an obvious and persistent SR pattern to the two types of El Niño throughout the El Niño lifecycle: their discharge anomalies in the EP and CP composites always (or almost always) have the same signs. Below-normal discharge is found in these rivers during El Niño years, regardless of the El Niño type. Another five rivers show an obvious and persistent AR pattern; these are the Mississippi, ST-Lawrence, Churchill, Niger, and Don rivers. For the first three, their discharge is mostly above normal during the EP El Niño but below normal during the CP El Niño (i.e. AR+). In contrast, the last two rivers (the Niger and Don) have above normal discharge during the CP El Niño but below normal discharge during the EP El Niño (i.e. AR−). For the remaining 21 rivers, their composite anomalies fluctuate among SR, AR+, and AR-during various phases of the El Niño lifecycle.

4. Global mapping of the response patterns

In order to examine whether there is a geographical dependence of the river discharge response to the two types of El Niño, we show in figure 3 the global distribution of the SR, AR+, and AR-patterns during the developing, mature, and decaying phases of the El Niño. The response pattern in each phase is determined using the method described in section 2. Based

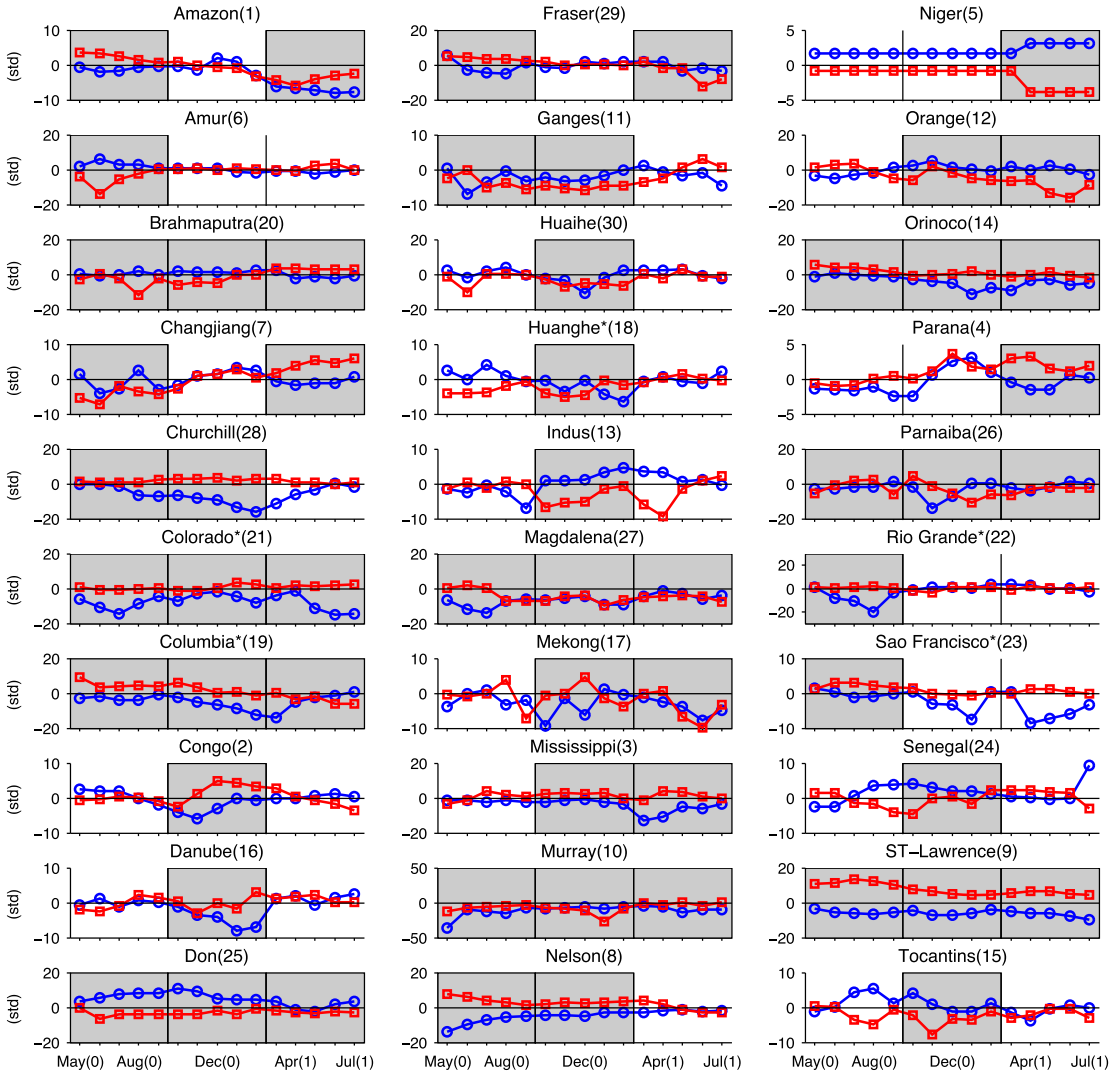

Figure 2. Composite monthly discharge anomalies for the EP El Niño (red) and CP El Niño (blue) for the thirty selected rivers. The discharge anomalies have been normalized by the standard deviation of the discharge calculated for that particular river basin for each particular calendar month. The normalization was performed to account for the fact that the magnitude of discharge variations varies from basin to basin. Rivers are listed in alphabetical order. The number in the parenthesis denotes the ranking of the drainage area size as shown in figure 1. The values shown are the discharge anomalies from zero in each river basin. Gray areas indicate the one or both of the CP and EP averaged discharge anomalies (to zero) in that phase pass the 90% significance level of a two-tailed Student's t test. Note that the *y*-axis scale is different for each river basin. The '*' symbol after the river name denotes that this river may be influenced by human interventions.

on figure 3, the response patterns are more uniform and persistent over North America, where the AR+ response pattern appears in most river basins and the response pattern does not change through the various phases of El Niño. Therefore, large rivers in North America tend to produce above-normal discharge during the EP type of El Niño but below-normal discharge during the CP type. This AR pattern indicates that El Niño type is important to the discharge variations for most large rivers in North America.

The global map in figure 3 also reveals systematic response patterns in other continents. In South America, the response pattern is relatively simple. A majority of the rivers exhibit the AR+ pattern in the developing phase and the SR pattern for the rest of the El Niño lifecycle. This result indicates that the El Niño type should be considered for the South American rivers only in the developing phase. For the Danube River in Central Europe and the Murray River in Eastern Australia, the SR pattern persists throughout all three El Niño phases. Apparently, the discharge anomalies in these two river basins are not sensitive to El Niño type. The Don River in Eastern Europe, however, shows a persistent AR-pattern throughout the El Niño lifecycle.

The response patterns are more complicated for rivers in Asia and Africa, where the patterns tend to vary not only during different phases of the El Niño lifecycle but also from river to river. Nevertheless, some general tendencies can be identified from figure 3. During the developing and mature phases (figures 3(a) and (b)), the SR pattern dominates the river basins in Asia, indicating that the El Niño type

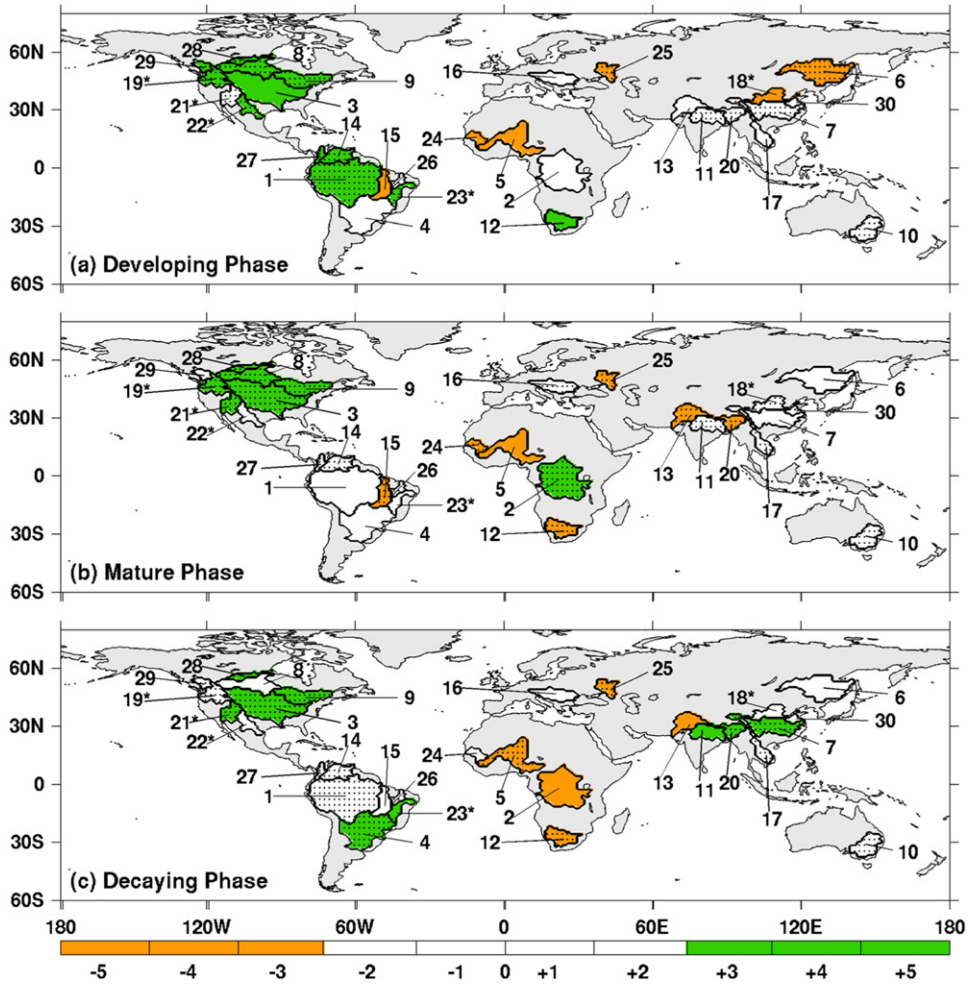

Figure 3. Discharge response patterns for global rivers during (a) the developing phase (May(0)–September(0)), (b) the mature phase (October(0)–February(1)), and (c) the decaying phase (March(1)–July(1)) of El Niño. The colors indicate the different response patterns for the thirty selected rivers: white for SR, green for AR+, and brown for AR-. The black numbers correspond to the river basins listed in figure 1. The '*' symbol after the number denotes that this river may be influenced by human interventions. The numbers under the colorbar represent the number of months in each phase showing an asymmetric response. The negative (positive) sign in front of the numbers indicates the AR- (AR+) response pattern. '0' implies a symmetric response. Discharge anomalies in each phase of EP and CP El Niño that pass 90% Student's t test following figure 2 are stippled.

probably matters little for the discharge variations during these two phases. During the decaying phase, the AR+ pattern dominates in Asia (figure 3(c)). As for Africa, the response is most consistent during the decaying phase of the El Niño, where the AR-pattern prevails for rivers in Africa as well as the Indus River.

To verify that the response patterns we identified in figure 3 are not due to possible measurement errors or human interventions, we conducted a forced model simulation with the Community Land Model, version 4 (CLM4, Oleson *et al* 2010) to produce a river discharge dataset free of human interventions (see section 4 of SM for the details of the simulation). This CLM4 simulation is driven by the observed precipitation and other atmospheric forcings from 1901 to 2014; we only use the 1950–2006 simulated river discharge for analysis. In this simulation, no anthropogenic influence is included. We repeated our mapping analysis using the simulated river discharge data. We find the response patterns identified (figure S4) are largely consistent with those identified from the observed discharge dataset (figure 3), particularly for large river basins in the North and South Americas, Northeastern Asia, and Northern India.

5. The linkage between river discharge and precipitation

Precipitation has been identified as the major freshwater input into a river basin (Gerten *et al* 2008, Milliman *et al* 2008, Dai *et al* 2009). To examine the possible relationship between precipitation and discharge anomalies during the three phases of El Niño, figure 4 displays the phase-averaged precipitation anomalies in each river basin separately for the two types of El Niño. When the signs of precipitation anomalies match the signs of discharge anomalies for both types of El Niño in one phase, we mark that phase with a '(v)' symbol. Taking the Amur River as an

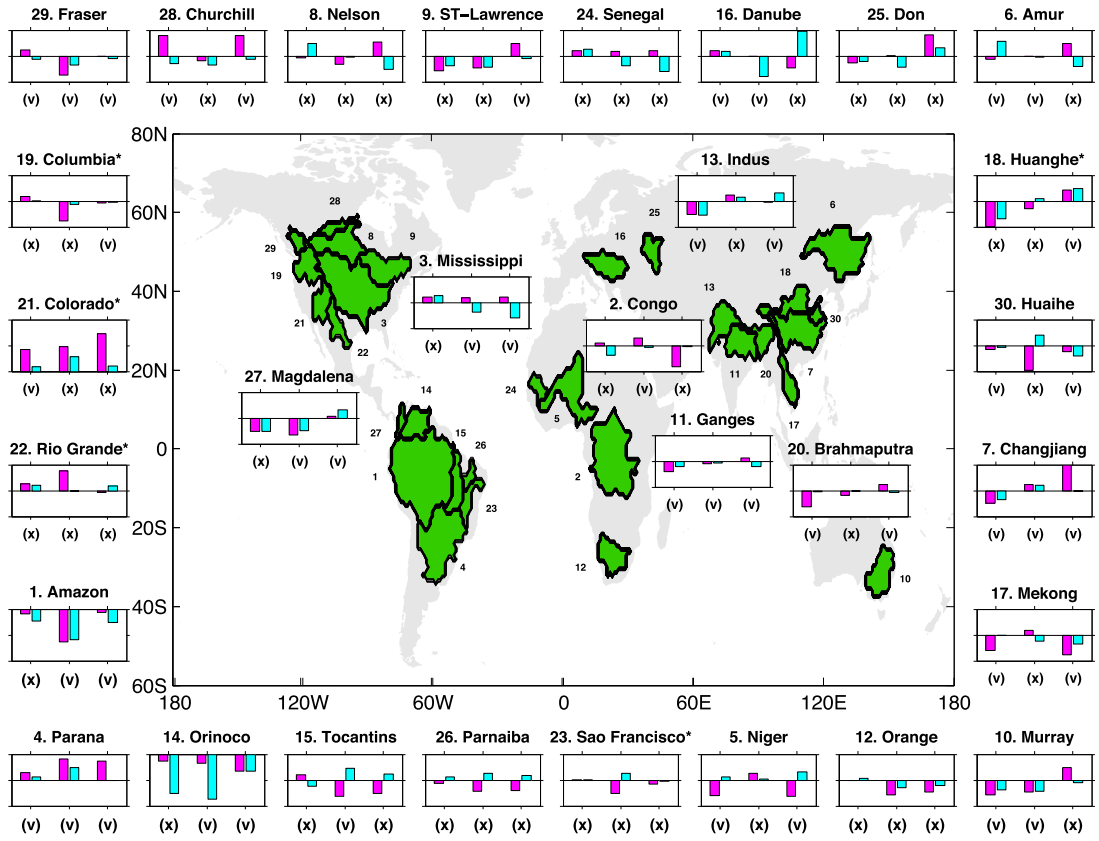

Figure 4. Composite precipitation anomalies for the EP (pink bars) and CP (light blue bars) El Niños during their developing (left-most pair of bars), mature (middle pair), and decaying phases (right-most pair). The bar shows precipitation anomalies, calculated by averaging precipitation anomalies in each phase. The check '(v)' indicates that the sign of precipitation anomalies matches the sign of the discharge anomalies, whereas the check '(x)' indicates that the signs do not match. The '*' symbol after the river name denotes that this river may be influenced by human interventions.

example, its discharge response pattern can be explained by the precipitation anomalies in all three phases. The Amur River basin experiences below-normal precipitation during the developing phase of the EP El Niño but above-normal precipitation during the CP El Niño. This is consistent with the AR-discharge anomaly pattern we identified in figure 3(a) for the developing phase. For the mature and decaying phases, the SR patterns shown in figures 3(b) and (c) can also be explained by the identically signed precipitation anomalies as seen in figure 4.

Examining the symbols in figure 4, we find seventeen rivers (57%) show consistent discharge and precipitation variations during at least two phases of El Niño. For these rivers, the discharge response patterns may be explained by the precipitation anomalies within the river basins during the two types of El Niño. These seventeen rivers are: the Amazon, Amur, Brahmaputra, Changjiang, Churchill, Danube, Fraser, Ganges, Huaihe, Indus, Magdalena, Mekong, Mississippi, Murray, Niger, Orinoco, and Paraná. It is worth noting that this group includes almost all the largest-drainage rivers on every continent, such as the Mississippi for North America, the Amazon for South America, and the Changjiang for East Asia. Due to their large drainage areas, it is reasonable that their discharge variations have strong linkages to variations in the precipitation within the river basins. The only exception is the Congo River, which is the largest river in Africa but whose discharge response patterns cannot be explained by local precipitation anomalies. For other rivers, the inconsistencies between the discharge and precipitation anomalies may be due to time lags between these two variables caused by land surface processes (e.g. Lo and Famiglietti 2010). Dettinger and Diaz (2000) found that the lags between peaks of precipitation and river discharge can vary from one geographic location to another. The results presented in figure 4 only provide a first-order linkage between El Niño-induced precipitation and river discharge, further studies considering lagged responses are required to fully elucidate the precipitation-discharge relationships.

6. Conclusion and discussion

In this study, the global distributions of asymmetric and SRs in river discharge to the EP and CP types of El Niño during their developing, mature and decaying phases are mapped for the first time. A few conclusions

can be drawn from this work. It is found that the discharge response patterns tend to be geographically dependent. Large rivers on the American continents show more persistent and simple response patterns throughout the various phases of the El Niño lifecycle, which are possibly caused by different atmospheric teleconnection patterns induced by different types of El Niño. For Mississippi River basin, for example, Liang *et al* (2014), have offered a mechanism to explain the AR+ pattern, which involves the excitation of the Pacific North American pattern or the Tropical Northern Hemisphere pattern (Yu *et al* 2012b, Zou *et al* 2014) by the two types of El Niño, and results in different impacts on precipitation and land-hydrology processes (Lo and Famiglietti 2010).

On the other hand, rivers in Asia and Africa show complex response patterns that vary from river to river and from phase to phase. It is well-known that El Niño events can induce Indian Ocean SST variations that can persist into the decaying phase of El Niño via Indian Ocean dynamics and local ocean–atmosphere coupling (e.g. Wang *et al* 2000, Xie *et al* 2009). Such an extended or delayed El Niño influence appears to be stronger during the EP El Niño than during the CP El Niño (see figure 4 of Yu *et al* 2015b). This difference may cause the rivers in Africa and parts of the India to respond differently to the two types of El Niño in their decaying phases. In addition, Kao and Yu (2009) have shown that, during the decaying phase, CP El Niño SST anomalies diminish locally in the CP while the EP El Niño SST anomalies retreat to the South American Coast. These very different locations of the SST anomalies can affect the Pacific Walker circulation and the regional Hadley circulation differently, leading to ARs in Asian rivers. The Danube River in Central Europe and the Don River in Eastern Europe, and the Murray River in Eastern Australia show persistent responses throughout different phases of El Niño. Further studies are required to understand why their response patterns are not sensitive to different flavors of the El Niño.

Local precipitation variations within the river basins are one important factor determining the discharge response pattern for rivers that have large drainage areas. For some other rivers, the discharge response patterns cannot be explained solely by local precipitation variations. Other factors, such as the lagged response of discharge to precipitation, volcanic eruptions (Iles and Hegerl 2015), and the dam effect (see SM for further discussion), need to be invoked. While we did not identify these factors explicitly, we are able to identify a group of rivers whose discharge variations are linked to precipitation variations and another group whose precipitation and discharge variations show less consistent patterns. This identification highlights the location of rivers whose discharge variation mechanisms require further study.

It has been reported that El Niño changed from the EP to the CP type in the early 1990s (Yu *et al* 2012b, Yu *et al* 2015a). The mapping produced in this study offers an overview of which global rivers may have experienced changes in their discharge variation patterns during the past two decades. By considering the El Niño type, the El Niño impacts on river discharge can be more accurately identified. For example, the El Niño impacts in the river basins that produce the AR patterns may be mistakenly considered insignificant if the impacts from the two types of El Niño are lumped together. New or different strategies may be needed to project and manage their discharge in the coming decades if the CP type of El Niño continues to dominate. Traditional ways of utilizing climate predictions (i.e., seasonal El Niño forecasts) for river flow management and agriculture planning may have to be revised.

It should be cautioned that the discharge data analyzed in this study may still be influenced by human interventions and measurement errors in unknown ways. Although we have made efforts to reduce the possible impacts via screening the data and repeating the analyses with a model simulation, the findings reported here should be taken with the data limitations and caveats in mind.

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References

Boyer E W, Howarth R W, Galloway J N, Dentener F J, Green P A and Vörösmarty C J 2006 Riverine nitrogen export from the continents to the coasts *Glob. Biogeochem. Cycles* **20** GB1S91

Capotondi A *et al* 2015 Understanding ENSO diversity *Bull. Am. Meteorol. Soc.* **96** 921–38

Chen M, Xie P, Janowiak J E and Arkin P A 2002 Global land precipitation: a 50-yr monthly analysis based on gauge observations *J. Hydrometeor.* **3** 249–66

Chiew F H S and McMahon T A 2002 Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability *Hydrol. Sci. J.* **47** 505–22

Dai A, Qian T and Trenberth K E 2009 Changes in continental freshwater discharge from 1948 to 2004 *J. Clim.* **22** 2773–92

Dai A and Trenberth K E 2002 Estimates of freshwater discharge from continents: latitudinal and seasonal variations *J. Hydrometeor.* **3** 660–87

Dettinger M D and Diaz H F 2000 Global characteristics of stream flow seasonality and variability *J. Hydrometeor.* **1** 289–310

Gerten D, Rost S, von Bloh W and Lucht W 2008 Causes of change in 20th century global river discharge *Geophys. Res. Lett.* **35** L20405

Iles C E and Hegerl G C 2015 Systematic change in global patterns of streamflow following volcanic eruptions *Nat. Geosci.* **8** 838–42

Kao H-Y and Yu J-Y 2009 Constrasting eastern-Pacific and central-Pacific types of ENSO *J. Clim.* **22** 615–32

Labat D 2010 Cross wavelet analyses of annual continental freshwater discharge and selected climate indices *J. Hydrol.* **385** 269–78

Lee T and McPhaden M J 2010 Increasing intensity of El Niño in the central-equatorial Pacific *Geophys. Res. Lett.* **37** L14603

Li W, Zhang P, Ye J, Li L and Baker P A 2011 Impact of two different types of El Niño events on the Amazon climate and ecosystem productivity *J. Plant Ecol.* **4** 91–9

Liang Y-C, Lo M-H and Yu J-Y 2014 Asymmetric responses of land hydroclimatology to two types of El Niño in the Mississippi River basin *Geophys. Res. Lett.* **41** 582–8

Lo M-H and Famiglietti J S 2010 Effect of water table dynamics on land surface hydrologic memory *J. Geophys. Res. Atmos.* **115** 1–12

Milliman J D, Farnsworth K L, Jones P D, Xu K H and Smith L C 2008 Climatic and anthropogenic factors affecting river discharge to the global ocean 1951–2000 *Glob. Planet. Change* **62** 187–94

Milly P C D, Dunne K A and Vecchia A V 2005 Global pattern of trends in sreamflow and water availability in a changing climate *Nature* **438** 347–50

Mo K C 2010 Interdecadal modulation of the impact of ENSO on precipitation and temperature over the United States *J. Clim.* **23** 3639–56

Ning L and Bradley R S 2015 Influence of eastern Pacific and central Pacific El Niño events on winter climate extremes over the eastern and central United States *Int. J. Climatol.* **35** 4756–70

Oki T and Kanae S 2006 Global hydrological cycles and world water resources *Science* **313** 1068–72

Oki T and Sud Y C 1998 Design of total runoff integrating pathways (TRIP)—a global river channel network *Earth Interact.* **2** 1–37

Oleson K W *et al* 2010 Technical description of version 4.0 of the community land model (CLM) *NCAR Technical Note* NCAR/TN-478+STR Natl. Cent. for Atmos. Res. Boulder Colo **257**

Pal I, Towler E and Livneh B 2015 How can we better understand low river flows as climate changes? *Eos* 96

Wang B, Wu R and Fu X 2000 Pacific–East Asian teleconnection: how does ENSO affect east Asian climate *J. Clim.* **13** 1517–36

Wang X, Jiang X, Yang S and Li Y 2013 Different impacts of the two types of El Niño on Asian summer monsoon onset *Environ. Res. Lett.* **8** 044053

Ward P J, Beets W, Bouwer L M, Aerts C J C H and Renssen H 2010 Sensitivity of river discharge to ENSO *Geophys. Res. Lett.* **37** L12402

Ward P J, Eisner S, Flörke M, Dettinger M D and Kummu M 2014a Annual flood sensitivities to El Niño–Southern Oscillation at the global scale *Hydrol. Earth Syst. Sci.* **18** 47–66

Ward P J, Jongman B, Kummu M, Dettinger M D, Weiland F C S and Winsemius H C 2014b Strong influence of El Niño Southern Oscillation on flood risk around the world *Proc. Natl Acad. Sci. USA* **111** 15659–64

Xie S-P, Hu K, Hafner J, Du Y, Huang G and Tokinaga H 2009 Indian ocean capacitor effect on Indo-western Pacific climate during the summer following El Niño *J. Clim.* **22** 730–47

Yu J-Y and Kao H-Y 2007 Decadal changes of ENSO persistence barrier in SST and Ocean heat content indices: 1958-2001 *J. Geophys. Res.* **112** D13106

Yu J-Y, Lu M-M and Kim S T 2012a A change in the relationship between tropical central Pacific SST variability and the extratropical atmosphere around 1990 *Environ. Res. Lett.* **7** 034025

Yu J-Y, Paek H, Saltzman E S and Lee T 2015a The early-1990s change in ENSO-PSA-SAM relationships and its impacts on Southern hemisphere climate *J. Clim.* **28** 9393–408

Yu J-Y, Wang X, Yang S and Paek H 2015b The changing El Niño–Southern Oscillation and associated climate extremes *Climate Extremes: Patterns and Mechanisms* (*AGU Monograph*) ed S-Y Wang *et al* (Washington, DC: American Geophysical Union) in press

Yu J-Y and Zou Y 2013 The enhanced drying effect of central-Pacific El Niño on US winter *Environ. Res. Lett.* **8** 014019

Yu J-Y, Zou Y, Kim S T and Lee T 2012b The changing impact of El Niño on US winter temperatures *Geophys. Res. Lett.* **39** L15702

Zhang W, Jin F-F and Turner A 2014 Increasing autumn drought over southern China associated with ENSO regime shift *Geophys. Res. Lett.* **41** 4020–6

Zou Y, Yu J-Y, Lee T, Lu M-M and Kim S T 2014 CMIP5 model simulations of the impacts of the two types of El Niño on US winter temperature *J. Geophys. Res.* **119** 3076–92