Linkages between ENSO/PDO signals and precipitation, streamflow in China during the last 100 years

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ABSTRACT

This paper investigates the single and combined impacts of the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) on precipitation and streamflow in China over the last century. Results indicate that the precipitation and streamflow overall decrease during the El Niño periods/PDO warm phase while increase during the La Niña periods/PDO cool phase in the majority of China, although there are still regional and seasonal differences. The precipitation/streamflow in the Yellow River basin, Yangtze River basin and Pearl River basin are more significantly influenced by El Niño and La Niña events compare to those in the Songhua River basin among different months, especially in October and November. Moreover, the significant influences of ENSO on streamflow in the Yangtze River mainly occur in summer and autumn while that in the Pearl River primary occur in the winter and spring. The precipitation/streamflow are relatively more in the warm PDO phase in the Songhua River basin and several parts of Yellow River basin while are relatively less in the Pear River basin and most parts of the northwest China compare to those in the cool PDO phase, though there are rarely significances clarified using the Wilcoxon signed ranks test. When considering the combined influences of ENSO and PDO, the responses of precipitation/streamflow are shown to be opposite from northern China to southern China, with the ENSO-related precipitation/streamflow enhance in the northern China and decrease in southern China during the warm PDO phases, and that enhance in the southern China and decrease in northern China during the cool PDO phases. This study conducted would beneficial for understanding how the precipitation/streamflow responses to the changing climate and would correspondingly provide valuable references for the water resources prediction and management over China.

1. Introduction

It is well known that El Niño-Southern Oscillation (ENSO) is an important factor influencing the interannual climate variability over East Asia (Zhou and Wu, 2010). The warm ENSO, which is also called El Niño, is usually accompanied by a weaker than normal East Asian winter monsoon (Zhang et al., 1996; Wang et al., 2008) and consequently induces a warmer and wetter climate over East Asia during El Niño winters (Li, 1990; Wen et al., 2000). As an exmaple, the ENSO influences can persist to the following summer, with significantly abundant precipitation and annual maximum streamflow over the Yangtze River valley during the decaying stage of El Niño event (Huang and Wu, 1989; Zhang et al., 2007). However, the aforementioned anomalies are generally reverse during the cool ENSO phase, namely La Niña events (Wang et al., 2008).

Some previous studies (Latif and Barnett, 1996; Mantua et al., 1997; Cayan et al., 1998; Nigam et al., 1999; Higgins and Shi, 2000; Minobe, 2000; Neal et al., 2002; Krishnan and Sugi, 2003; Wang et al., 2008) have indicated that the interannual relationship between ENSO and global climate is not stationary and the Pacific Decadal Oscillation (PDO), which is a largely interdecadal oscillation, could modulate the interannual ENSO-related teleconnections. For instance, the already enhanced precipitation and streamflow in eastern Australia are demonstrated to be even further magnified during La Niña events that occurred in the PDO/IPO (Interdecadal Pacific Oscillation) cool phase (Verdon et al., 2004). Additionally, the precipitation patterns showed different responses in the El Niño periods for Southeastern South America and Myanmar during the PDO warm/cool phase (Silva et al., 2011; Sen Roy and Sen Roy, 2011). These studies mentioned indicated that the in phase/out-of-phase of ENSO and PDO usually have distinct effects on precipitation and streamflow in different regions, and thus, the discussions considering the influences of ENSO in association with PDO are quite necessary in the related studies. There are various studies extensively documenting the linkages between ENSO/PDO and annual/ seasonal precipitation over China during the past several decades (Liu and Ding, 1995; Gong and Wang, 1999; Zhang et al., 1999; Wu et al., 2003; Zhu and Yang, 2003; Xu et al., 2004; Li et al., 2005; Chan and Zhou, 2005; Ma and Shao, 2006; Hao et al., 2008; Zhou and Wu, 2010). For example, Zhou and Wu (2010) revealed that the warm ENSO mainly led to lower-level southwesterly winds deflect from the southeast coast of China and consequently influenced the winter precipitation in southern China. In addition, Chan and Zhou (2005) found that there was less precipitation over South China Monsoon Region during the period of high PDO index and vice versa. However, majority of aforementioned studies did not consider the combined influences of both ENSO and PDO on regional precipitation. On the other hand, streamflow, as a comprehensive integrator of rainfall over basin areas, also related to the variations of ENSO and PDO signals. If a strong relationship between river discharge and ENSO/PDO can be quantified, the streamflow forecasting, which is vital for effective water resource management, would be highly improved. Although many studies have been conducted nowadays on the relations between river streamflow and ENSO/ PDO nowadays in China (Chen and Xu, 2005; Fu et al., 2007; Xu et al., 2007; Zhang et al., 2007; Lü et al., 2011), as far as the authors are aware, there has not been a related study documenting the combined influences of both ENSO and PDO signals on streamflow in the major large rivers over China. Considering all of the above, in this paper, the possible influences of ENSO and PDO, coupled and separately, on the annual/monthly precipitation and streamflow are conducted over China. Additionally, the precipitation and annual streamflow datasets adopted in this study were extended to the last 100 years (1901-2009) and full seasonal cycles were considered for presenting more reliable climate variability. The paper is organized as follows. Section 2 introduces the datasets and methodologies used. Section 3 examines the relationships among PDO, ENSO, precipitation and streamflow, and finally, the conclusions and proposed future research are presented in Section 4.

2. Data and method

2.1 Data

2.1.1 The precipitation data

The precipitation data (1901-2009) in China were extracted from the newest Climatic Research Unit (CRU) Time Series (TS) 3.10 high resolution gridded datasets (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276) at the University of East Anglia (Mitchell and Jones, 2005). The monthly CRU TS3.10 datasets , which were calculated on high-resolution (0.5×0.5 degree) grids based on more than 4000 weather stations distributed around the world (with more than 160 meteorological station from China), were validated well matched with the observations over China except for the western Tibetan Plateau (Ma and Shao, 2006).

2.1.2 The streamflow data

There are a few streamflow gauging stations have 100 years' continuous observational records in China. Therefore, four gauging stations, Harbin station in Songhua River basin, Shanxian Station (renamed Sanmenxia station in 1950) in Yellow River basin, Hankou Station in Yangtze River basin and Wuzhou Station in Pearl River basin, were chosen in this study considering the location, length of the observation period and the quality of the data observed. All of them are the control stations which locate on the main channel of four main rivers in China. The location of the gauging stations and the four river basins can be referred to Fig.1. Songhua River basin, Yellow River basin, Yangtze River basin and Pearl River basin, being the four major large river basins in China, cover approximately from the north to south of China and almost all climate types of China. Songhua River basin locates in the north of northern China belongs to the zone of temperate monsoon climate. Yellow River basin can be divided three sub-regions (i.e. the eastern monsoon sub-region, the arid and semi-arid sub-region, and the high-elevation sub-region), which is accordance with the three natural zones in China (Liang et al. 2014).The southern part of Yangtze River basin is close to the tropical zone and the northern part is close to the temperate region. Pearl River basin covers a region of subtropical to tropical monsoon climate straddling the Tropic of Cancer. The selected basins are expected to be able to present the streamflow variability over China under climate change. In this study, one hundred years (1901-2009) of continuous quality-controlled annual streamflow data and fifty to a hundred years of monthly streamflow data were collected from National Hydrology Almanac.

2.1.3 ENSO and PDO

The ENSO index is represented by the Niño 3.4 SST defined as the January to March SST anomaly averages over the region (5^oS-5^oN, 90-150^oW), which is downloaded from the National Oceanic and Atmospheric Administration (NOAA, http://www.cgd.ucar.edu/cas/catalog/climind/Nino_3_3.4_indices.html)(Trenberth, 1997). The PDO index "is the leading empirical orthogonal function (EOF) of SST anomalies (January to March) in the North Pacific Ocean, poleward of 20^oN" (Mantua et al., 1997; Chan and Zhou, 2005) and is available at the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) website: http://jisao.washington.edu/pdo/.

(Barnett et al.,1999).

<Fig.1 here, thanks>

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2.2 Method

2.2.1 Precipitation and streamflow stratification according to El Niño and La Niña

ENSO is a quasi-periodic climate pattern that occurs across the tropical Pacific Ocean every several years (three to seven years' recurrence) which always couples two variations: the warm oceanic phase (El Niño) accompanies high air surface pressure in the western Pacific and the cold phase (La Niña) accompanies low air surface pressure in the western Pacific (Trenberth et al., 2007). Generally, it has been very difficult to define an El Niño / La Niña event and there is no universal single definition (Trenberth and Hoar, 1997; Anthony and Stewart, 2001; Fu et al., 2007). In this study, the definition of Trenberth (1997) is adopted that is "... an El Niño can be said to occur if 5-month running means of sea temperature (SST) anomalies in the Niño 3.4 region (5°N–5°S, 120°–170°W) exceed 0.4°C for 6 months or more.". Similarly, La Niña, the opposite event of El Niño, can simply be said to occur if 5-month running mean of SST anomalies below the threshold -0.4°C (See the upper panel in Fig. 2).

In this paper, the periods of El Niño events and La Niña events were used to stratify the precipitation and streamflow time series for analyzing the influences of El Niño and La Niña on hydro-climatic variables in China. The precipitation/streamflow time series were firstly extracted for each calendar month conditioned by El Niño/La Niña events, for instance, the multiyear mean value of January precipitation occurs during El Niño periods was treated as "January precipitation in El Niño". Finally, the sum of monthly precipitation from January to December in El Niño/La Niña months was treated as "annual" precipitation in El Niño/La Niña year (Fu et al., 2007).

2.2.2 Precipitation/streamflow stratification according to the PDO cool/warm phase

The PDO is a pattern of Pacific climate variability that shifts phases usually on at least 20-30 years' inter-decadal time scale (Mantua et al., 1997). It is detected as warm/cool surface water in the Pacific Ocean (north of 20° N), during a "warm" or "positive" phase, the west Pacific becomes cool and part of the eastern ocean warms while during a "cool" or "negative" phase, the opposite pattern occurs. The cool and warm PDO phases (Fig. 2) are identified from the PDO index series in accordance with the approach used in Mantua and Hare (2000) and Sen Roy (2011). Over the past century, the PDO was in a cool phase approximately during the periods 1901-1924, 1947-1976 and 1998-2009, and warm phase PDO regimes existed during the periods 1925-1946 and 1977-1997 (See lower panel in Fig.2). It should be noted that these multi-decade epochs sometimes contain intervals of up to a few years in length in which the polarity of the PDO is reversed (e.g. the cool phase in 1998-2009 showed a warm phase in 2002-2005).

The precipitation/streamflow spanning the period 1901-2009 are stratified into two segments conditioned on the PDO warm/cool phase. Further, the series in warm PDO-El Niño, warm PDO-La Niña, Cool PDO- El Niño, and Cool PDO- La Niña are stratified used the method similar to the Section 2.2.1 from the precipitation/streamflow series extracted for PDO warm/cool phase, separately. Additionally, Wilcoxon signed ranks test were adopted to determine if average precipitation/streamflow received during PDO warm phases/ La Niña periods was statistically different from that received during PDO cool phase/ El Niño periods at the 0.05 significant level. It is a nonparametric test equivalent to the dependent t-test, which does not assume normality in the data and could be used for the case that there are only small number of samples available for analysis (Kolivras and Comrie, 2007).

<Fig.2 here, thanks>

3. Results and discussion

3.1Perspective impacts of ENSO on precipitation and streamflow over China

3.1.1 Precipitation impacts of El Niño and La Niña events

Compare to the long-term average (1901-2009), the “annual” precipitation changes in El Niño and La Niña periods are spatially opposite (Fig.3). For example, the overall “annual” precipitation increase in the North China Plain, southwest China as well as the Tibetan Plateau while decline in the northeast China, southeast China and northwest China during the La Niña periods(Fig.3). However, the trends in the El Niño periods over these regions are obviously reversed. The Yangtze River can be spatially treated as a dividing line of ENSO influences on precipitation for eastern China, with the “annual” average precipitation obviously less (differences < -5%) in the southern regions of Yangtze River while more (differences > 5%) in the northern regions (including the Yellow River, Hai River and Huai River) in La Niña periods rather than that in El Niño years. It should also be noted that the results obtained in the Yellow River basin (similar to North China Plain) are consistent with many previous studies (Gong and Wang, 1999; Fu et al., 2007; Hao et al., 2008).

<Fig.3 here, thanks>

The influences of El Niño and La Niña on precipitation are found have obviously seasonal-cycle and monthly characteristics (Fig. 4). For instance, the ENSO impacts on precipitation in summer and autumn are more significant than winter and spring, especially for September, October and November. Moreover, the precipitation in southeast China (including the lower parts of Pearl River and Yangtze River) are relatively larger during El Niño winter and spring while lower during El Niño summer and autumn compare to those during the correspondingly La Niña periods. The possible reason is that southern coast of the South China are always influenced by different anomalous circulation systems between wet season and dry seasons (Wu et al., 2003). In addition, the percentage changes for the wet season precipitation (June to September) between El Niño and La Niña periods are similar to that for "annual" precipitation, because that more than 40% of the total annual precipitation falls in summer (Zhang et al., 2009).

The influences of El Niño and La Niña events on precipitation are also spatial distributed unevenly and are different from month to month over the entire China (Fig.4). Although monthly precipitation changes between two ENSO phases over majority of regions do not statistically significant at the 0.05 level, some consistent and interesting results are still drawn. The overall influences of El Niño and La Niña on precipitation are more significant in the eastern and southern China rather than in the western and northern China. Correspondingly, the ENSO influences become increasingly weaker from Pearl River, Yangtze River and Yellow River to Songhua River. The possible reason is that the eastern and southern portions of China received more total precipitation because they near to the ocean and are significantly influences by the East Asian Monsoon and South Asian Monsoon (Zhang et al., 1996). More specifically, the precipitation from November to March received from La Niña events are less than that received from El Niño events over almost the entire China and the tendencies reverse in the remaining seven months, especially in the wet seasons (June, July, August and September). While in October, the trends found above are reversed in most parts of Yellow river and Yangtze River.

In addition, precipitation patterns responses to El Niño/ La Niña events are also discrepancies among different parts of basin. For example, the ENSO influences in the lower basin of Songhua River are opposite to the head and middle basin. The difference responses for the four river basins (or even for the different parts of basin) to ENSO properly attribute to the spatially diverse influences of the different monsoon circulations and mid-latitudinal circulations. For example, the Pearl River basin is impacted by the retreating monsoon, East Asian Winter monsoon as well as the Taifoon-season, the precipitation-streamflow regime in sub-basin is consequently considerable complex when response to the ENSO influences (Jiang et al., 2007; Zhang et al., 2011). Moreover, Li et al. (2010) indicated that the East Asia Summer Monsoon exhibited a southward shift in its major components due to the meridional asymmetric warming, which would weaken the influences of East Asian Summer Monsoon on Songhua River basin and result in difference ENSO responses on Songhua River basin and other three basins.

<Fig.4 here, thanks>

3.1.2 Streamflow impacts of *El Niño and La Niña events*

The “annual” streamflow changes overall more in the La Niña periods relatively to that in the El Niño periods for all four basins, especially for the Yellow River basin (Fig.5). Moreover, the ENSO influences on streamflow are spatial-temporally consistent with that on precipitation for the major river basins over China with obviously differences among months and basins. On the whole, the streamflow in the Yellow River basin, Yangtze River basin and Pearl River basin are more significantly influenced by El Niño and La Niña events compare to those in the Songhua River basin among different months, especially in the October and November. The streamflows in Songhua River basin for all twelve months in La Niña periods consistently increase while those in majority months (eight in twelve) in El Niño periods decrease compare to the multiyear average monthly streamflow during the past 100 years, only the La Niña impacts on August are found statistically significant. The monthly streamflow trends influenced by El Niño/La Niña events in the Yellow River basin are basically coincident with precipitation with relatively lower than normal in El Niño periods and higher amount in La Niña periods almost for all months, but the statistical significance tests do not exhibit obviously seasonal characteristics (Fig. 5). The overall percentage difference between El Niño-related and La Niña-related streamflow is 32.1%, and varies monthly from 10.1% (March) to 59.7% (November) (Fig. 5). The streamflow in January, February, April, July, October and November change significantly between El Niño and La Niña events. Moreover, the percentage changes of monthly streamflow are relatively smaller in spring (March to May) during the La Niña periods while larger in other seasons (especially in autumn), which are consistent with Fu et al. (2007) and Lü et al. (2011).

<Fig.5 here, thanks>

The significant influences of ENSO on streamflow in the Yangtze River mainly occur in summer and autumn while primary occur in winter and spring in the Pearl River. The spatial variability of streamflow is responsible for both the influences of El Niño mature phase on precipitation in summer when the intensified western Pacific subtropical high covers the southeastern periphery of China and the weakening of the Indian monsoon which provides less moisture inflow to the northern part of China (Zhang et al., 1999). The streamflow responses to ENSO for Yangtze River basin (Hankou station) exhibit obvious seasonal variations (Fig. 5). For example, the streamflow are relatively higher in El Niño periods relatively to that in La Niña periods in winter (December to February) and spring while reverse in summer and autumn (September to November). Especially, compare to correspondingly average monthly streamflow, the differences of La Niña-related streamflow and El Niño-related streamflow change significantly in June, July, August and September. In the Pearl River basin (Wuzhou Station), the ENSO impacts seem to be more complicated. The absolute percentage difference of streamflow between La Niña and El Niño periods are all more than 10% from October to March, as well as July. In September, the streamflow in La Niña month exceeds that in El Niño month and their percentage difference exceed 63.0%. Different to Yangtze River basin, the ENSO influences in the Pearl River are only statistically significant (0.05 level) on autumn and winter streamflow, which possibly because that the regions Pearl River locates at is in tandem with the strengthening and weakening of sea surface temperature (SST) in western Pacific (Juneng and Tangang, 2005).

3.2 Perspective impacts of PDO on precipitation and streamflow

3.2.1 Variability of precipitation due to PDO impacts

The percentage changes of “annual” precipitation also show spatially opposite responses to the PDO warm phase and cool phase, although only changes over a few regions are testified statistically significant at 0.05 levels (Fig. 6). Specifically, the “annual” precipitation in most parts of northeast China and northwest China tend to be higher during the PDO warm phase relatively to that in the cool phase, especially in the Songhua River basin and in the inland watersheds of Yellow River (blue regions in Fig 6b). The results obtained are consistent with Zhu and Yang (2003),which indicate that the summer precipitation (account for more than 50% of total annual precipitation) in the northeast and northwest China increase during a warm PDO phase due to the weakening of East Asian Summer monsoon and the southward shift of Western Pacific Subtropical High. In contrast, the "annual" streamflow responses are found opposite over the North China Plain, southwest China and Central China with the precipitation to be less during the warm PDO phase and to be more during the cool phase (Yang et al., 2005; Fu et al., 2009). The results in the northern China areas maybe because that they always dominated by high pressure and experiencing precipitation decrease when the Pacific is in warm phase, with the sea temperature over topical mideastern Pacific rises and that over the central part of northern Pacific is lower than normal (Yang et al., 2005). Additionally, the precipitation over the Yellow River basin (Fu et al., 2004), Yangtze River basin and Pearl River basin decrease from the mid and late 1970s to 1990s when the PDO is in a persistent warming phase, while increase after 2000 when PDO entered into an unstable cool phase.

<Fig.6 here, thanks>

3.2.2 Variability of streamflow due to PDO impacts

The "annual" streamflow changes against the long-term average shown in Fig.7 are basically consistent with those for precipitation during warm and cool PDO phases, although there are no significant trends tested. The PDO influences in Songhua River basin are opposite to that in other three basins with the streamflow obviously higher than the long-term average (6.1%) in the PDO warm phase while lower in the PDO cool phase (-4.0%). The streamflow changes related to the PDO warm/cool phase correspond to the variability of streamflow dry/wet stages: 1900-1907, 1915-1928, 1975-1980 and 1999-2005 are four dry stages, 1970-1974 is a medium water stage and 1908-1914, 1929-1969 and 1981-1998 are three wet stages (Song et al., 2010). Instead, in the Yellow River, Yangtze River and Pearl River, the streamflow are relatively lower in the PDO warm phase and are higher in the PDO cool phase and their percentage differences become increasing small from north to south. The results are consistent with Gordon and Giulivi (2004), which indicated that the high (low) runoff in the Yangtze River and Yellow River correspond to the PDO negative (positve) phase. Additionally, similar results are found when replace the 100 years streamflow observations by 50 years for analyzing the connections between streamflow and PDO in Songhua River and Yangtze River (not shown). It should be indicated that the gradually decreased streamflow tendency in the downstream of Yellow River in the PDO cool phase after 2000 maybe due to the influences of the human activities (Ren et al., 2002), for example, water withdrawal attributed to more than 60% of the streamflow decrease in the downstream of Yellow River after 2000 (Zhang et al., 2011).

<Fig.7 here, thanks>

3.3 Combined influences of ENSO and PDO on both streamflow and precipitation

Many evidences (Chan and Zhou, 2005; Andreoli and Kayano, 2005) indicated that the PDO, which always effects the precipitation coupled with ENSO acting constructively (strong and well-defined anomalies) when they are in phase and destructively (weak and noisy anomalies) when they are out-of-phases. In this study, the precipitation/streamflow in El Niño periods are compared to that in La Niña periods during the PDO warm/cool phase, respectively (Fig. 8 and Fig. 9). Results show that the “annual” precipitation changes in El Niño/ La Niña period compare to multi-year average in cool PDO phase are quite similar to Fig. 3, which indicates that the cool PDO phase do not significantly modulate the ENSO influences on precipitation. However, in the warm PDO phase, the percentage changes are obviously for the precipitation related to the El Niño/La Niña. For instance, in the northeast China and northwest China, the precipitation received from La Niña periods is obviously higher than that received from El Niño periods during the PDO warm phase while reverse during the PDO cool phase. However, the precipitation responses to the two PDO phases are almost opposite in the south China and central China, including the most parts of Yangtza River basin and the upper stream of the Pearl River basin.

<Fig.8 here, thanks>

The El Niño/ La Niña-related streamflow in the four basins show different responses during different PDO phases (Fig. 9). During the PDO cool phase, the streamflow in all basins tend to be higher in La Niña periods and to be lower in El Niño periods. The results obtained are quite similar to the single impacts of El Niño/ La Niña shown in Fig.5, which indicate that the cool PDO also do not obviously change the El Niño/La Niña influences on streamflow anomalies. However, the cool PDO phase still acts both more negative anomalies in El Niño-related streamflow and more positive anomalies in La Niña-related streamflow in south China (including most parts of the Yangtze River basin and the Pearl River basin) and induces both less negative anomalies in El Niño-related streamflow and less positive anomalies in La Niña-related streamflow in the Northern China (including the Songhua River basin and the Yellow River basin). Moreover, it should also be noted that the streamflow and precipitation responses to El Niño/La Niña are opposite during the PDO cool phase in the Songhua River basin, which maybe because that the Harbin station, locates at the middle stream cannot fully represent the entire basin.

<Fig.9 here, thanks>

During the PDO warm phase, the streamflow received from La Niña periods is relatively higher than that received from El Niño periods in Songhua River basin and Yellow River basin with the change percentages 9.7% and 44.1%, respectively. Obviously, the warm PDO enhances the anomalies in both two basins during the La Niña periods and the El Niño periods. However, the situations are different in the southern China. For example, fewer differences between the El Niño-related and La Niña-related streamlfow in Yangtze River basin are found with the overall percentage changes only 0.7%, which indicates that compare to the cool PDO phase, the warm PDO phase weakens the ENSO influences in the Yangtze River basin. In the Pearl River basin, the La Niña-related streamflow tends to be lower than El Niño-related streamflow with the percentage difference of -21.8%. In addition, compares to the percentage changes in the PDO cool phase (10%) and in the long-term average without considering the impacts of PDO (0.6%), the warm PDO is proved increase the El Niño-related steamflow and decrease the La Niña-related streamflow. In other words, similar to Andreoli and Kayano (2005), the warm PDO acts constructively influences in the north China and destructively influences in the south China. Overall, the El Niño/ La Niña-related precipitation/streamflow experience similar variability during the warm/cool PDO phase except for the Songhua River basin in the cool PDO phase. Moreover, the streamflow, which is also influenced by many other factors such as global SST, longwave radiation, snow and human activities (Xu et al., 2007), seems to be more sensitive than the precipitation during the El Niño/ La Niña periods in both warm and cool PDO phases (Fig. 9). However, the general influence patterns of the combined effects are basically consistent. Compare to the ENSO impacts, although the PDO indicator do not show significantly prediction capacity for annual streamflow which probably because of its multi-decadal cycles, its modulation effects on ENSO still deserve to be included in the researches when consider the long-term influences of ENSO on annual/seasonal/monthly water resources.

4. Summary and Conclusions

This study investigated the single and combined impacts of ENSO and PDO on the precipitation/streamflow over China during the last century, which would enrich our knowledge for understanding their complex spatial-temporal teleconnections and provide a scientific basis for water resources prediction using ENSO/PDO as a potential predictor. The following conclusions can be drawn:

Overall, the El Niño events mainly decrease while La Niña events increase the precipitation/streamflow over China. However, there are considerable differences exist among months and basins, for example, the precipitation/streamflow changes in the Yellow River basin, Yangtze River basin and Pearl River basin are more significantly influenced by El Niño and La Niña events compare to those in the Songhua River basin among different months, which properly because that the precipitation/streamflow in the regions/basins close to the ocean seem to be more significantly influenced due to the mixed impacts of ENSO and other factors such as the East Asian Monsoon, South Asian Monsoon, and the Typhoon systems. Additionally, due to the influences of different circulation systems (Wu et al., 2003), the significant influences of ENSO on streamflow in the Yangtze River mainly occur in summer and autumn while that in the Pearl River primary occur in winter and spring.

Although rarely significantly changes are detected, the influences of the PDO warm/cool phases on precipitation/streamflow are basically similar as but less than that of El Niño/La Niña. Spatially, the precipitation/ streamflow in the Songhua River basin and most parts of the Yellow River basin are relatively larger during the warm PDO phase than those during the cool PDO phase, while in the Pear River basin and the most parts of the northwest China these responses are reversed. When considering both the influences of the PDO and ENSO, the responses for precipitation/treamflow are shown to be opposite between northern China and southern China. The El Niño-related precipitation/streamflow decrease while the La Niña-related precipitation/streamflow increases during the PDO warm phase in the northern China (including Songhua River basin and Yellow River basin) , and the cool PDO phase do not obviously change the El Niño/La Niña influences on positive-negative streamflow anomalies.

The variability of streamflow corresponding to ENSO/PDO is roughly consistent with that of precipitation on the annual scale. On the seasonal/monthly scale, its response seems more complex than precipitation. It is obviously that the streamflow is also affected by more other factors such as human activities and land use changes. However, ENSO and PDO still showed a significant influence on the observed streamflow among all four major basins in China. The results obtained indicate that the monthly/seasonal ENSO could be a potential predictor for streamflow prediction in the Yangtze River, Pearl River or even for the Yellow River; however, further researches on the physical mechanism driving these relations are still necessary. Firstly, the influences should be further quantitatively conducted to enhance the forecast abilities of the ENSO/PDO indicator for streamflow and water resource modeling and forecasting. Additionally, there are also other factors influencing the streamflow changes which should be comprehensively considered in the future studies such as the East Asia Summer Monsoon (Wu and Wang, 2002) global SST, outgoing longwave radiation, sea level pressure, snow as well as human activities (Xu et al., 2007). Finally, ENSO/PDO events can be predicted one to two years in advance using the physical based coupled ocean-atmosphere models (Lü et al., 2011), their potential future states and influences of ENSO/PDO could be further conducted considering as much as possible aforementioned factors by coupling atmospheric/oceanic/land surface models with a proper distributed physical-based hydrological model.

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References

Andreoli, R.V. and Kayano, M.T.: ENSO-related rainfall anomalies in South America and associated circulation features during warm and cold Pacific decadal oscillation regimes, Int. J. Climatol., 25, 2017-2030,2005.

Anthony, S. and Stewart, W.F.: On the identification of ENSO-induced rainfall and runoff variability: a comparison of methods and indices, Hydrolog. Sci. J., 46, 715-727, 2001.

Barnett, T.P., Pierce, D.W., Latif, M., Dommenget, D., and Saravanan, R.: Interdecadal interactions between the tropics and midlatitudes in the Pacific basin, Geophys. Res. Lett., 26, 615-618, 1999.

Cayan, D.R., Dettinger, M.D., Diaz, H.F., and Graham, N.E.: Decadal variability of precipitation over western North America,. J. Climate, 11, 3148-3166, 1998.

Chan, J.C.L. and Zhou, W.: PDO, ENSO and early summer monsoon rainfall over south China, Geophys.Res.Lett., 32, L08810, doi:10.1029/2004GL022015, 2005. Chen, Y.N.and Xu, Z.X.: Plausible impact of global climate change on water resources in the Tarim River Basin, Sci. China Ser. D, 48, 65-73, 2005.

Fu, G.B., Chen, S.L., Liu, C.M., and Shepard, D.: Hydro-climatic trends of the Yellow River basin for the last 50 years, Climatic Change, 65: 149-178, 2004.

Fu, G.B., Charles, S.P., Viney, N.R., Chen, S.L., and Wu, J.Q.: Impacts of climate variability on stream-flow in the Yellow River, Hydrol. Process., 21, 3431-3439, 2007.

Fu, G.B., Charles, S.P., Yu, J.J., and Liu, C.M.: Decadal climatic variability, trends, and future scenarios for the North China Plain, J. Climate, 22, 2111-2123, 2009.

Gong, D.Y. and Wang, S.W.: Impacts of ENSO on rainfall of global land and China, Chinese Sci.Bull., 44, 852-857, 1999.

Gordon, A.L. and Giulivi, C.F.: Pacific decadal oscillation and sea level in the Japan/East sea, Deep-Sea Res. Pt. I, 51, 653-663, 2004.

Hao, Z.X., Zheng, J.Y., and Ge, Q.S.: Precipitation cycles in the middle and lower reaches of the Yellow River (1736-2000), J. Geogr. Sci., 18, 17-25, 2008.

Higins, R.W. and Shi, W.: Dominant factors responsible for interannual variability of the summer monsoon in the south-western United States, J. Climate, 13: 759-775, 2000.

Huang, R.H. and Wu, Y.F.: The influence of ENSO on the summer climate change in China and its mechanism, Adv. Atmos. Sci., 6, 21-32, 1989.

Jiang, T., Su, B.D., and Hartmann, H.: Temporal and spatial trends of precipitation and river flow in the Yangtze River Basin, 1961-2000, Geomorphology, 85, 143-154, 2007.

Juneng, L. and Tangang, F.T.: Evolution of ENSO-related rainfall anomalies in Southeast Asia region and its relationship with atmosphere-ocean variations in Indo-Pacific sector, Clim. Dynam., 25, 337-350, 2005.

Kolivras, K.N. and Comrie, A.C.: Regionalization and variability of precipitation in Hawaii, Phys.

Geogr., 28, 76-96, 2007.

Krishnan, R. and Sugi, M.: Pacific decadal oscillation and variability of the Indian summer monsoon rainfall, Clim. Dynam., 21, 233-242, 2003.

Latif, M. and Barnett, T.P.: Decadal climate variability over the North Pacific and North America: Dynamics and predictability, J. Climate, 9, 2407-2423, 1996.

Liang, K., Bai, P., Li, J.J., and Liu, C.M.: Variability of temperature extreme in the Yellow River basin during 1961-2011, Quanter. Int., 336, 52-64, 2014.

Li, C.Y.: Interaction between anomalous winter monsoon in East Asia and El Nino events, Adv. Atmos. Sci., 7: 36-46, 1990.

Li, J.P., Wu, Z.W., Jiang, Z.H., and He, J.H.: Can global warming strengthen the East Asian Summer Monsoon?, J. Climate, 23, 6696-6705, 2010.

Li, Q., Yang, S., Kousky, V.E., Higgins, R.W., Lau, K.-M., and Xie, P.: Features of Cross-Pacific climate shown in the variability of China and US precipitation, Int. J. Climatol., 25, 1675-1696, 2005.

Liu, Y.Q. and Ding, Y.H.: Reappraisal of the influence of ENSO events on seasonal precipitation and temperature in China, Sci. Atmos. Sin., 19, 200-208, 1995 (in Chinese).

Lü, A., Jia, S., Zhu, W., Yan, H., Duan, S. and Yao, Z.: El Niño-Southern Oscillation and water resources in the headwaters regions of the Yellow River: links and potential for forecasting, Hydrol. Earth Syst. Sci., 15, 1273-1281, doi: 10.5194/hess-15-1275-2011, 2011.

Ma, Z.G. and Shao, L.J.: Relationship between dry/wet variation and the Pacific Decade Oscillation (PDO) in northern China during the last 100 years, Chin. J. Atmos. Sci., 30, 464-474,2006 (in Chinese).

Mantua, N.J. and Hare, S.R.: The Pacific decadal oscillation, J. Oceargr. 58, 35-44, 2002.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C.:A Pacific interdecadal climate oscillation with impacts on salmon production, B. Am. Meteorol. Soc., 78, 1069-1080, 1997.

Minobe, S.:Spatio-temporal structure of the pentadecadal variability over the North Pacific, Prog. Ocearnogr., 47, 381-408, 2000.

Mitchell, T.D. and Jones, P.D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693-712, 2005.

Neal, E., Todd Walter, M., and Coffeen, C.:Linking the pacific decadal oscillation to seasonal stream discharge patterns in Southeast Alaska, J. Hydrol., 263, 188-197, 2002.

Nigam, S., Barlow, M., and Berbery, E.H.: Analysis links Pacific decadal variability to drought and streamflow in the United States, EOS T. Am. Geophys. Un., 80, 621-625, 1999.

Ren, L.L., Wang, M.R., Li, C.H., and Zhang, W.:Impacts of human activitiy on river runoff in the northern area of China, J. Hydrol., 261, 204-217, 2002.

Sen Roy, S.: Identification of periodicity in the relationship between PDO, El Niño and peak monsoon rainfall in India using S-transform analysis, Int. J. Climatol., 31, 1507-1517, 2011.

Sen Roy, S., and Sen Roy, N.:Influence of Pacific decadal oscillation and El Niño Southern oscillation on the summer monsoon precipitation in Myanmar, Int. J. Climatol., 31, 14-21, 2011.

Silva, G.A.M., Drumond, A., and Ambrizzi, T.:The impact of El Niño on South American summer climate during different phases of the Pacific Decadal Oscillation, Theor. Appl. Climatol., 106, 307-319, 2011.

Song, X., Mu, X., Gao, P., Wang, F., and Wang, S.:Analysis on historical evolution and driving force of rainfall and runoff of Harbin Station in Songhua River. Science of Soil and Water Conservation, 8, 46-51, 2010 (in Chinese).

Trenberth, K.E.: The Definition of El Niño, Bull. Amer. Meteor. Soc., 78, 2771-2777, 1997.

Trenberth, K.E. and Hoar, T.J.: El Niño and climate change, Geophys. Res. Lett., 24, 3057-3060, 1997.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Tank Klein, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B., and Zhai, P.M. :Observations: Surface and Atmospheric Climate Change. In: Solomon, S., D. Qin, M. Manning, Z. Chedvn, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Ed.), Climate Change 2007:The Physical Science Basis.Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chedvn, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H.L., Cambridge University Press, Cambridge,UK, 235-336, 2007.

Verdon, D.C., Wyatt, A.M., Kiem, A.S., and Franks, S.W.: Multidecadal variability of rainfall and streamflow: Eastern Australia, Water Resour. Res., 40, W10201, doi: 10.1029/2004WR003003234, 2004.

Wang, L., Chen, W., and Huang, R.H.: Interdecadal modulation of PDO on the impact of ENSO on the east Asian winter monsoon, Geophys. Res. Lett., 35, L20702, doi:10.1029/2008GL035287, 2008.

Wen, C., Graf, H.F., and Huang, R.H.: The interannual variability of East Asian winter monsoon and its relation to the summer monsoon, Adv. Atmos. Sci., 17, 48-60, 2000.

Wu, R., Hu, Z.Z., and Kirtman, B.P.: Evolution of ENSO-related rainfall anomalies in East Asia, J. Climat, 16, 3742-3758, 2003.

Xu, K.Q., Brown, C., Kwon, H., Lall, U., Zhang, J.Q., Hayashi, S., and Chen, Z.Y.: Climate teleconnections to Yangtze river seasonal streamflow at the Three Gorges Dam, China, Int. J. Climatol., 27, 771-780, 2007.

Xu, Z.X., Takeuchi, K., and Ishidaira, H.: Correlation between El Nino Southern Oscillation (ENSO) and precipitation in Southeast Asia and the Pacific region, Hydrol. Process., 18, 107-123, 2004.

Yang, X.Q., Xie, Q., Zhu, Y.M., Sun, X.Q., and Guo, Y.J.: Decadal-to-interdecadal variability of precipitation in North China and associated atmospheric and oceanic anomaly patterns, Chin. J. Geophys., 48, 789-797, 2005.

Zhang, Q. , Singh, V.P., Sun, P., Chen, X., Zhang, Z.X., and Li, J.F.: Precipitation and streamflow changes in China: Changing patterns, causes and implications, J. Hydrol., 401, 204-216, 2011.

Zhang, Q., Xu, C.Y., Jiang, T., and Wu, Y.J.: Possible influence of ENSO on annual maximum streamflow of the Yangtze River, China, J. Hydrol. 333, 265-274, 2007.

Zhang, Q., Xu, C.Y., Zhang, Z., Chen, Y.D., and Liu, C.L.:Spatial and temporal variability of precipitation over China, 1951-2005, Theor. Appl. Climatol., 95, 53-68, 2009.

Zhang, R., Sumi, A., and Kimoto, M.: Impact of El Niño on the East Asian monsoon: A diagnostic study of the '86/87 and '91/92 events J. Meteorol. Soc. Jpn., 74, 49-62, 1996.

Zhang, R., Sumi, A., and Kimoto, M.: A diagnostic study of the impact of El Nino on the precipitation in China, Adv. Atmos. Sci., 16, 229-241, 1999.

Zhou, L.T. and Wu, R.G.: Respective impacts of the East Asian winter monsoon and ENSO on winter rainfall in China, J. Geophys. Res., 115, D02107, doi: 10.1029/2009JD012502, 2010.

Zhu, Y.M.and Yang, X.Q.: Relationships between Pacific Decadal Oscillation (PDO) and climate variabilities in China, Acta Meteorol. Sin., 61,641-654, 2003 (in Chinese).

Table Captions:

Table 1 Background information of the four selected river basin in this study

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River basin	Station (Location)	Drainage area (km^2)	Annual streamflow record period	Monthly streamflow record period	Annual mean precipitation (mm per year)	Annual mean streamflow (10^8 m^3/a)
Songhua River (I)	Harbin (126°46′E, 45°45′N)	390,526	1901-2009	1901-1948,1953-2004	491 (1901-2009)	386 (1901-2009)
Yellow River (II)	Sanmenxia (111°22′E, 34°49′N)	688,421	1901-2009	-	385 (1901-2009)	489 (1901-2009)
Yellow River (II)	Huayuankou (113°40′E, 34°54′N)	730,036	-	1950-2004	449 (1901-2009)	555 (1950-2004)
Yangtze River (III)	Hankou (114°18′E, 30°37′N)	1,488,036	1901-2009	1901-2004	887 (1901-2009)	7256 (1901-2009)
Pearl River (IV)	Wuzhou (111°30′E, 23°48′N)	329,705	1901-2009	1950-2004	1307 (1901-2009)	2175 (1901-2009)

Figure Captions:

Fig.1 Map of China showing four major river basins (I: Songhua River basin; II: Yellow River basin; III: Yangtze River basin and IV: Pearl River basin) and streamflow gauging stations used in this study

Fig.2 The definition of ENSO events (El Niño and La Niña) from 5-month running mean series of Niño 3.4 SST index (upper panel) and the partition of warm/cool phase PDO from monthly PDO index (lower panel)

Fig.3 Percentage changes of annual precipitation in El Niño months and La Niña months over the long-term average (1901-2009): (a) annual precipitation occurred in La Niña events; (b) annual precipitation occurred in El Niño events; and (c) annual precipitation occurred in La Niña events minus that occurred in El Niño events

Fig.4 Monthly precipitation changes in La Niña months over China compared to El Niño months. Regions change significantly at the 0.05 level based on the Wilcoxon signed ranks test are shown with shadow.

Fig.5 Monthly and annual streamflow changes over four major river basins in China in El Niño months and La Niña month over the monthly/annual long-term average (1901-2004). The asterisks indicate the statistical significance based on Wilcoxon signed ranks test (lower than 0.05 is **, lower than 0.10 is * and otherwise is nothing). It should also be noted that the monthly streamflow changes in Yellow River basin and Pearl River basin were only calculated during the period 1950-2004 due to their limited availability of monthly streamflow data

Fig.6 Percentage changes of annual precipitation in PDO warm phase and cool phase over the long-term average (1901-2009): (a) annual precipitation in POD cool phase; (b) annual precipitation in POD warm phase; (c) annual precipitation in POD cool phase minus that in POD warm phase. Regions change significantly at the 0.05 level based on the Wilcoxon signed ranks test are shown with shadow

Fig. 7. Percentage changes of annual streamflow over four major river basins in China in PDO warm phase and cool phase over the long-term average (1901-2009). P values based on Wilcoxon signed ranks test are showed on the top/bottom of each bar

Fig.8. Percentage changes of precipitation between El Niño periods and La Niña periods during the PDO warm phase (left panel) and the PDO cool phase (right panel)

Fig.9. Percentage changes of streamflow between El Niño period and La Niña periods during the PDO warm phase (upper panel) and the PDO cool phase (lower panel)

Fig. 1. Map of China showing four major river basins (I: Songhua River basin; II: Yellow River basin; III: Yangtze River basin and IV: Pearl River basin) and streamflow gauging stations used in this study

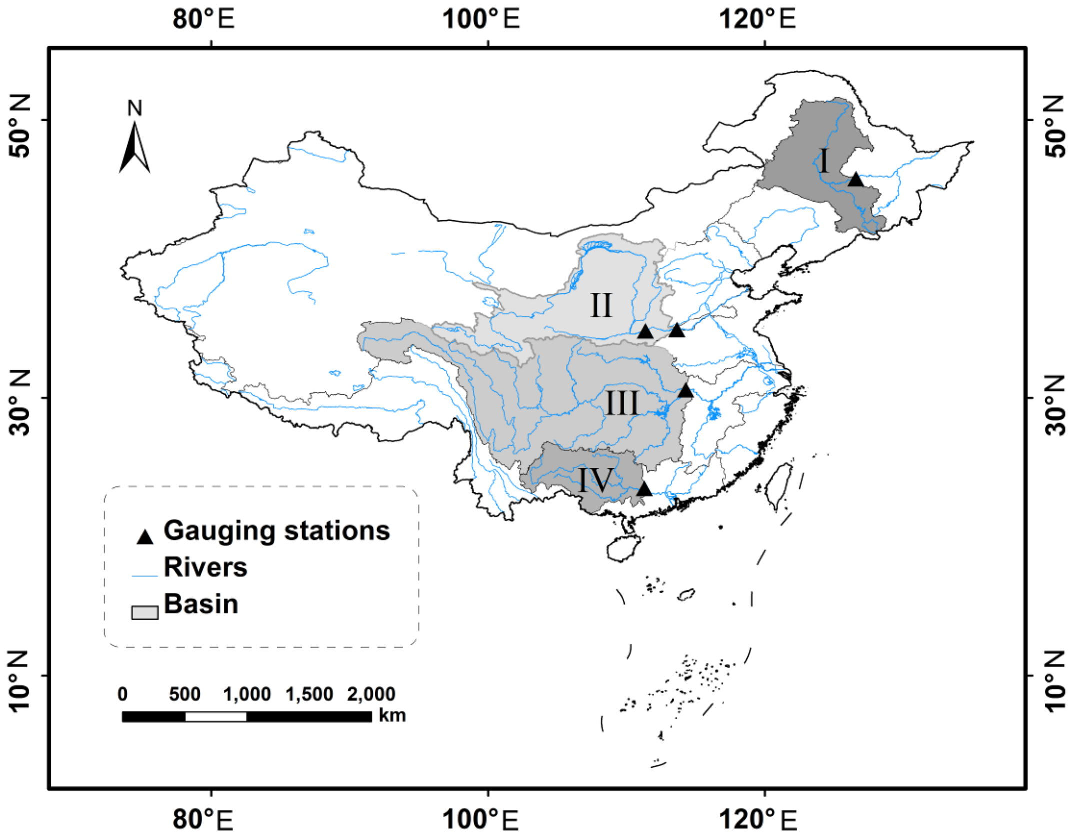


Fig. 2 The definition of ENSO events (El Niño and La Niña) from 5-month running mean series of Niño 3.4 SST index (upper panel) and the partition of warm/cool phase PDO from monthly PDO index (lower panel)

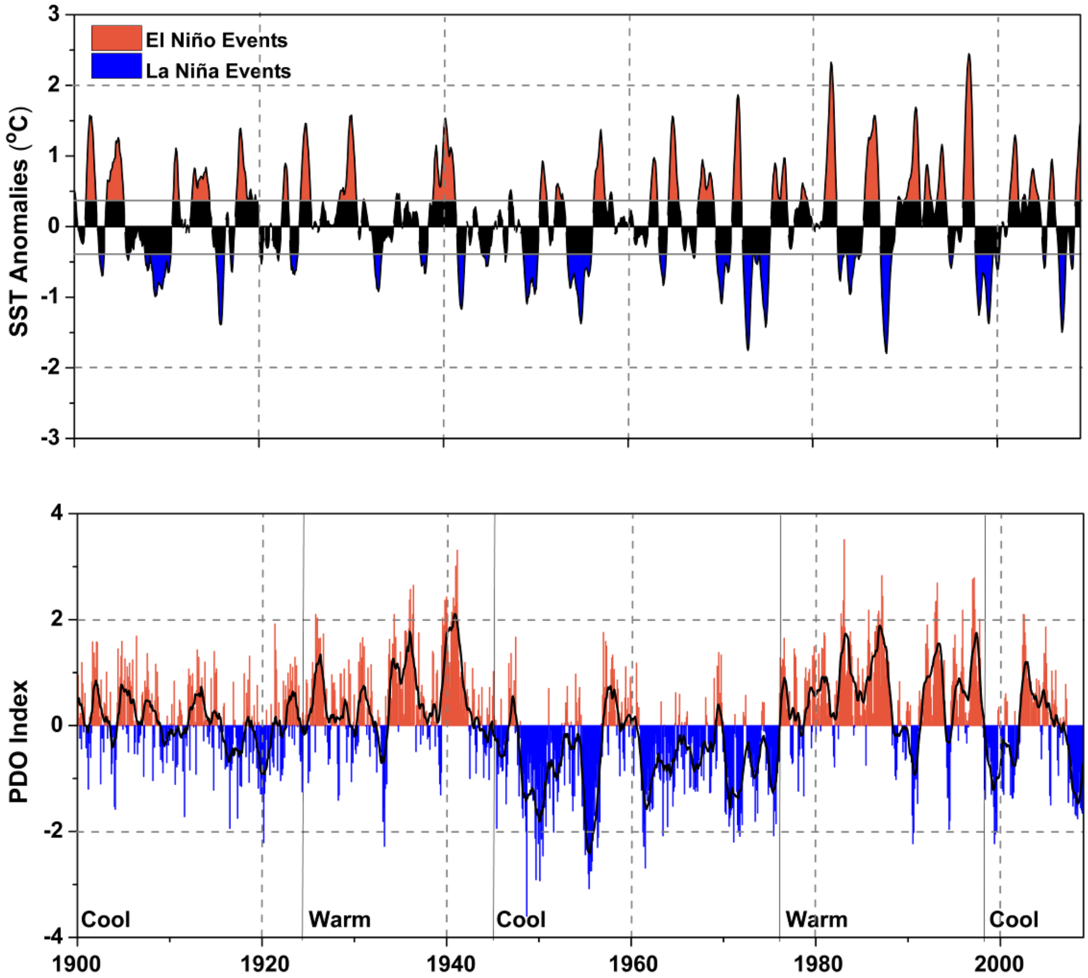


Fig. 3 Percentage changes of annual precipitation in El Niño years and La Niña years over the long-term average (1901-2009): (a) annual precipitation occurred in La Niña events; (b) annual precipitation occurred in El Niño events; and (c) annual precipitation occurred in La Niña events minus that occurred in El Niño events

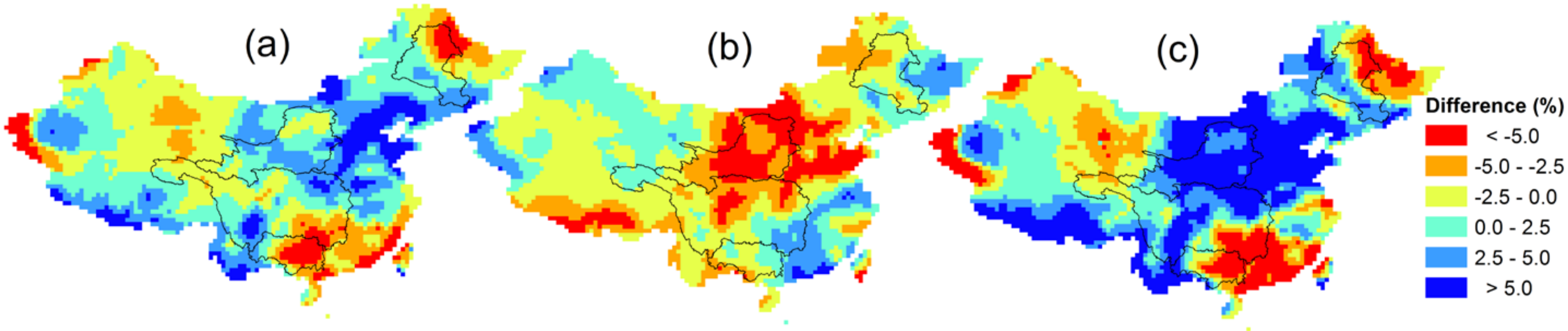


Fig. 4 Monthly precipitation changes in La Niña months compared to El Niño months. Regions change significantly at the 0.05 level based on the Wilcoxon signed ranks test are shown with shadow.

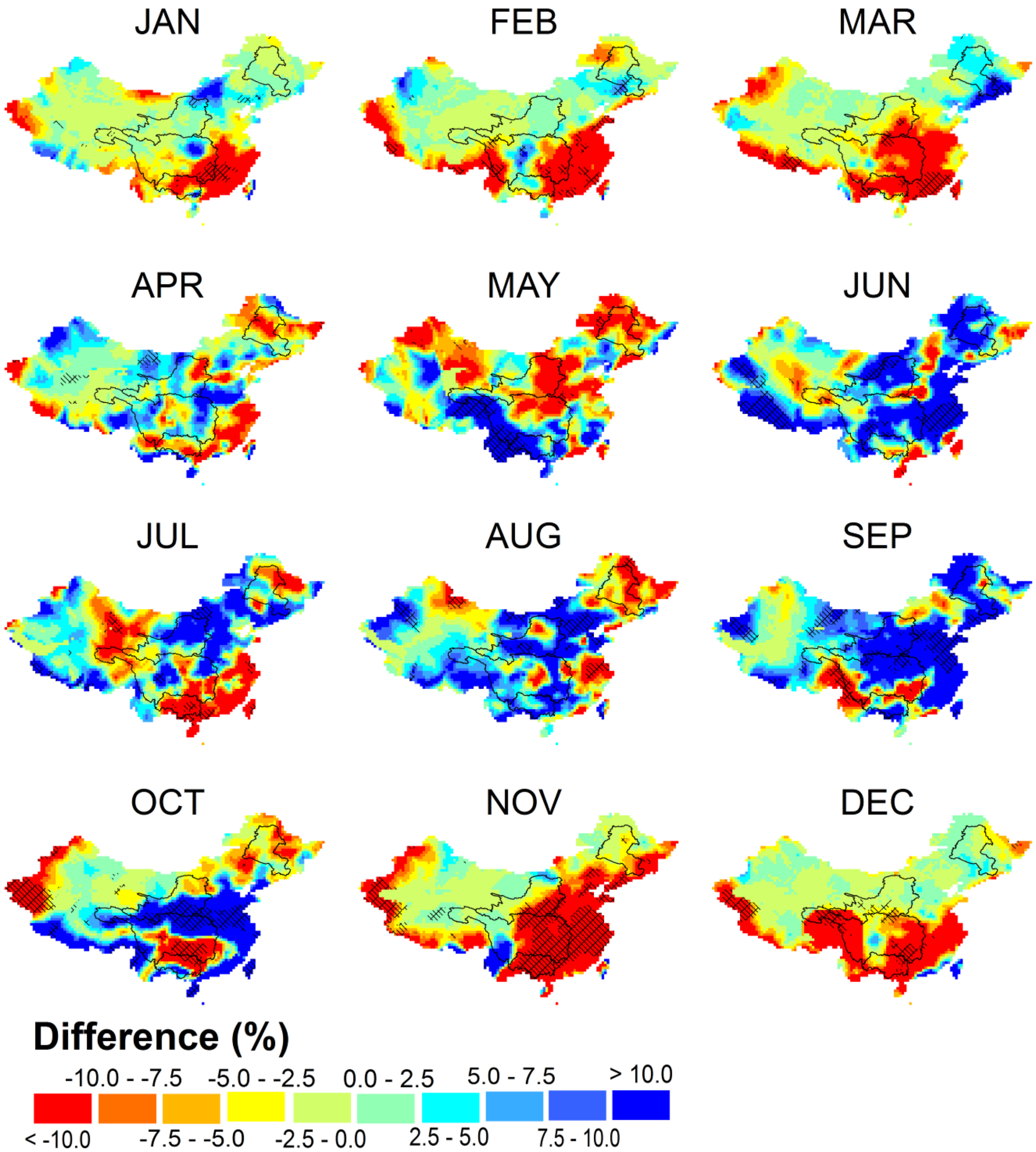


Fig.5 Monthly and "annual" streamflow changes over four major river basins in China in El Niño months and La Niña month over the monthly/annual long-term average (1901-2004). The asterisks indicate the statistical significance based on Wilcoxon Signed Ranks Test (lower than 0.05 is **, lower than 0.10 is * and otherwise is nothing). It should also be noted that the monthly streamflow changes in Yellow River basin and Pearl River basin were only calculated during the period 1950-2004 due to their limited availability of monthly streamflow data

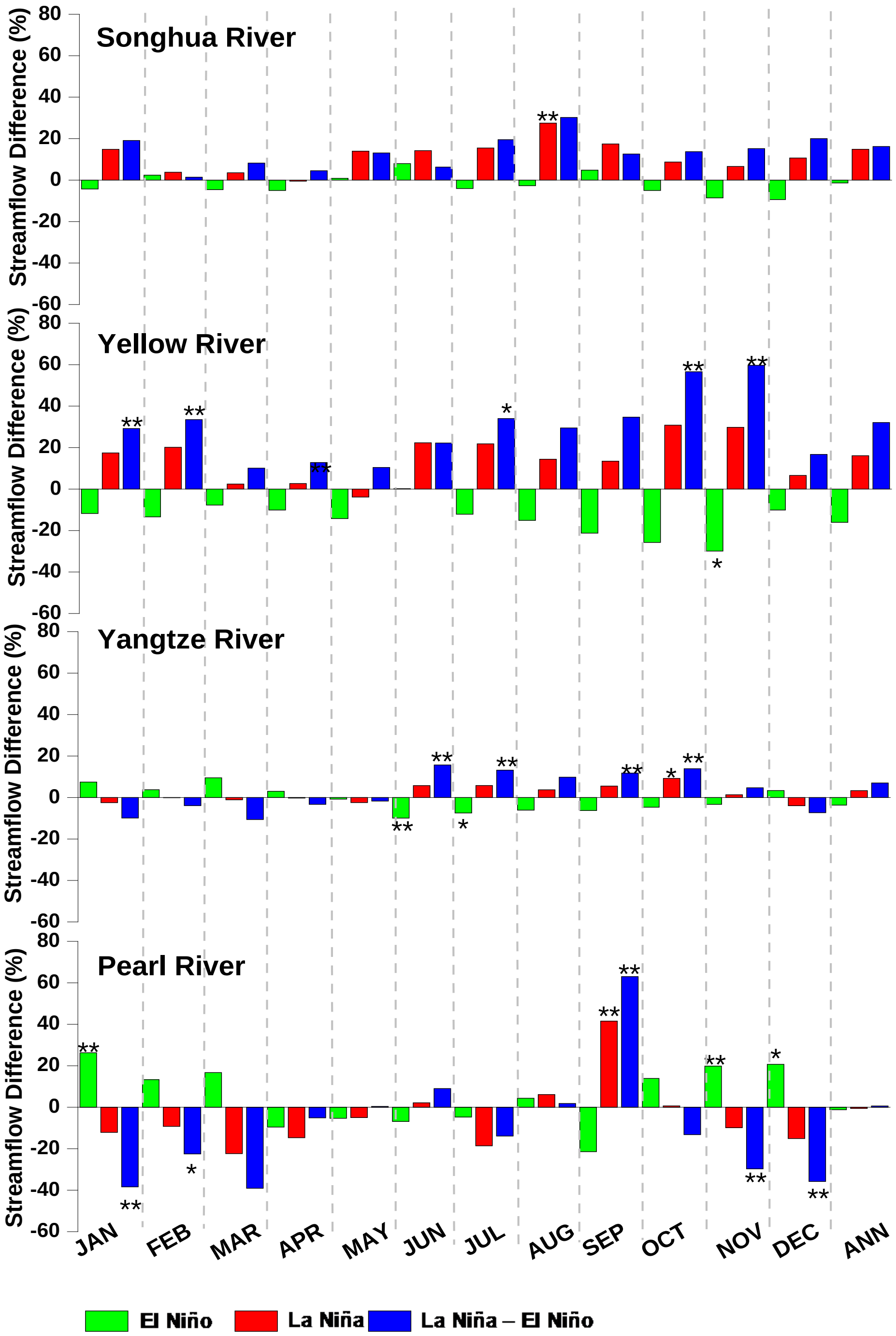


Fig.6 Percentage changes of annual precipitation in PDO warm phase and cool phase over the long-term average (1901-2009): (a) annual precipitation in POD cool phase; (b) annual precipitation in POD warm phase; (c) annual precipitation in POD cool phase minus that in POD warm phase. Regions change significantly at the 0.05 level based on the Wilcoxon signed ranks test are shown with shadow

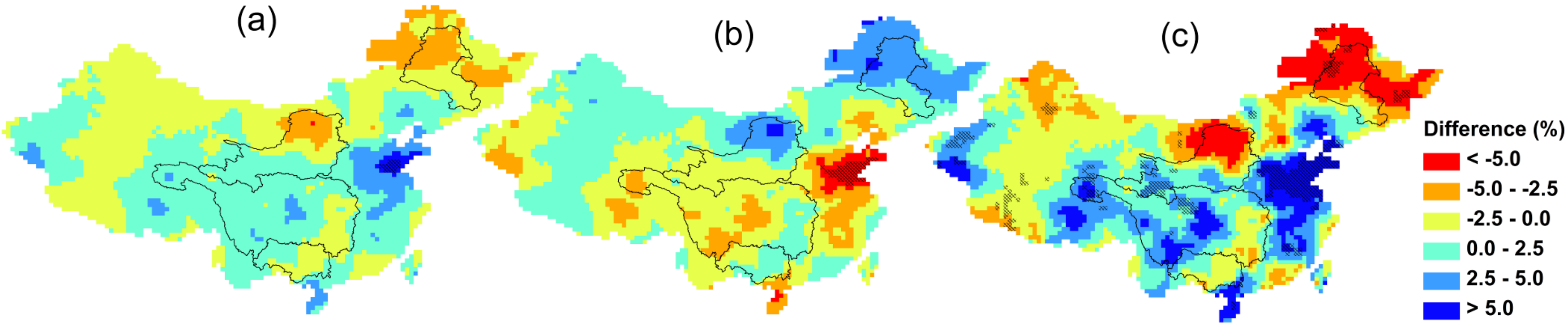


Fig. 7. Percentage changes of annual streamflow over four major river basins in China in PDO warm phase and cool phase over the long-term average (1901-2009). P values based on Wilcoxon signed ranks test are showed on the top/bottom of each bar

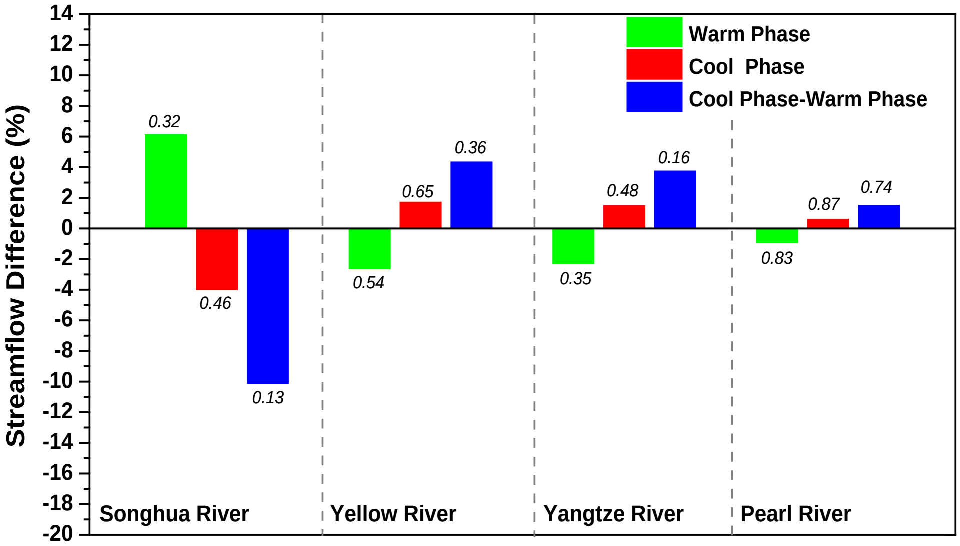
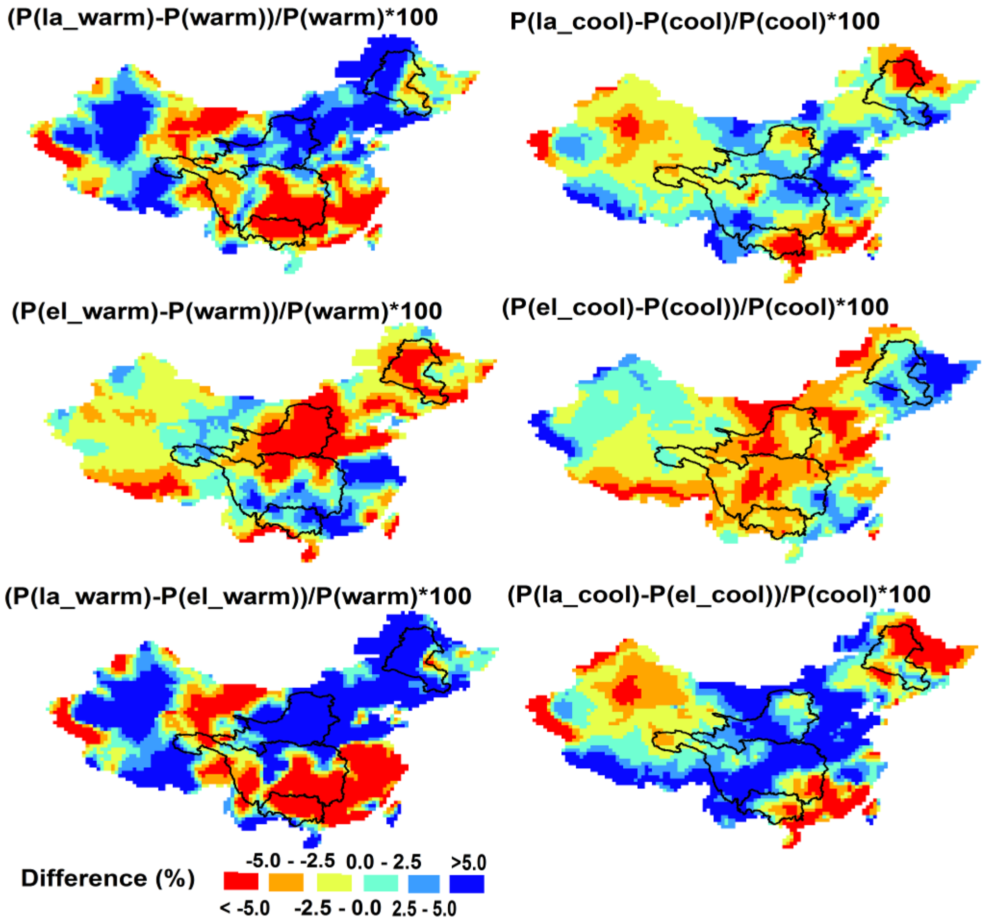
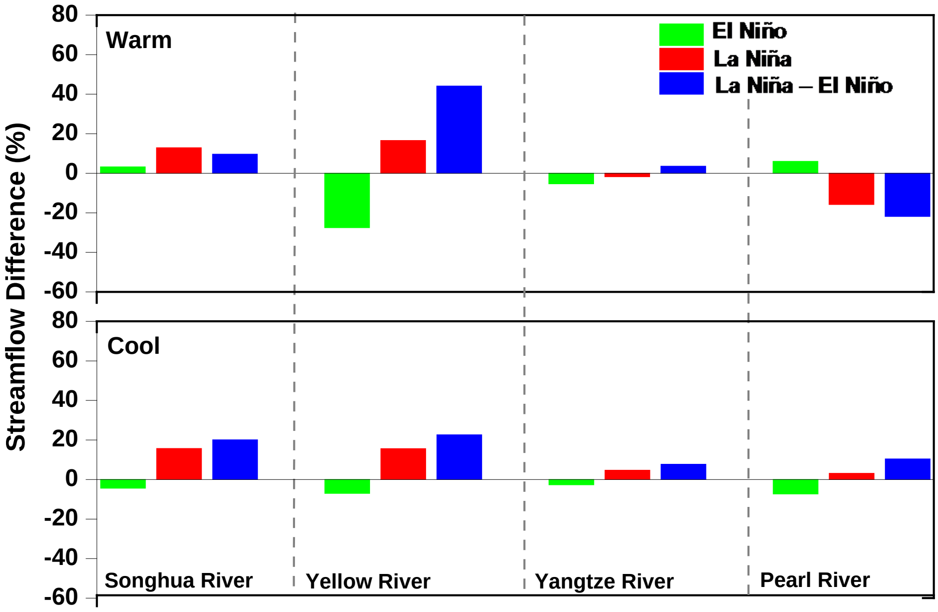


Fig.8. Percentage changes of precipitation between El Niño periods and La Niña periods during the PDO warm phase (left panel) and the PDO cool phase (right panel)



726 **Fig.9.** Percentage changes of streamflow between El Niño period and La Niña periods
727 during the PDO warm phase (upper panel) and the PDO cool phase (lower panel)



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