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Terrestrial water storage changes over the Pearl River Basin from GRACE and connections with Pacific climate variability

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ABSTRACT

Time-variable gravity data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission are used to study terrestrial water storage (TWS) changes over the Pearl River Basin (PRB) for the period 2003–Nov. 2014. TWS estimates from GRACE generally show good agreement with those from two hydrological models GLDAS and WGHM. But they show different capability of detecting significant TWS changes over the PRB. Among them, WGHM is likely to underestimate the seasonal variability of TWS, while GRACE detects long-term water depletions over the upper PRB as was done by hydrological models, and observes significant water increases around the Longtan Reservoir (LTR) due to water impoundment. The heavy drought in 2011 caused by the persistent precipitation deficit has resulted in extreme low surface runoff and water level of the LTR. Moreover, large variability of summer and autumn precipitation may easily trigger floods and droughts in the rainy season in the PRB, especially for summer, as a high correlation of 0.89 was found between precipitation and surface runoff. Generally, the PRB TWS was negatively correlated with El Niño-Southern Oscillation (ENSO) events. However, the modulation of the Pacific Decadal Oscillation (PDO) may impact this relationship, and the significant TWS anomaly was likely to occur in the peak of PDO phase as they agree well in both of the magnitude and timing of peaks. This indicates that GRACE-based TWS could be a valuable parameter for studying climatic influences in the PRB.

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1. Introduction

The Pearl River is the third largest river in terms of drainage area and has the second largest streamflow in China. Due to its importance to the social-economic development of China, many studies [1–9] have been conducted for water security concerns in the Pearl River Basin (PRB), e.g., rainfall regimes, drought and wetness, evapotranspiration, atmospheric water vapor, water discharge and sediment load. Among them, Zhang et al. [3] found that the PRB trends to be dryer in the rainy season and wetter in winter, and moisture content is one among many factors acting on the dry or wet conditions of the basin. Moreover, increased rainfall variability and frequencies of extremely high/low rainfall events related to the weakening Asian monsoon [4] as well as the frequencies of short wet periods with increased total amount of precipitation [1] potentially increase the risk of floods and droughts over the PRB. Furthermore, decreasing evapotranspiration result mainly from increasing aerosol and intensifying urbanization may weaken the hydrological cycle in the basin [2]. These studies have been valuable for the characterization of the PRB's hydrological regime. However, recent strong anthropogenic influences, such as damming effects by the Longtan Reservoir (LTR), have significantly impacted the hydrological cycle of the PRB [8]. In addition, the upper and mid-PRB is formed primarily by a karst geological environment with strong heterogeneities [10,11], making it a great challenge to monitor and simulate water variations in these areas. Therefore, a combination of precipitation and other datasets (e.g., satellite observations and hydrological models) would be beneficial for a more comprehensive analysis.

The twin Gravity Recovery and Climate Experiment (GRACE) satellite mission, a project jointly sponsored by the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR), was launched in March 17, 2002. The spatial-temporal change of the Earth gravity fields mapped by the GRACE satellite provides information directly related to the mass redistribution at or near the surface of the Earth, e.g., changes in terrestrial water storage (TWS), ocean, polar ice sheets and mountain glaciers [12]. Particularly, hydrological applications would be the largest contribution of GRACE among many related studies [13] since TWS changes associated to climate variability and change play a crucial role in regional and global hydrological cycles and water management. GRACE-derived TWS changes, including changes in surface water, soil moisture, groundwater, snow and ice, have been widely used to investigate water balance in many river basins, especially for drought and flood assessment. Examples include the Amazon Basin [14,15], the Yangtze River Basin [16,17], the Mississippi River Basin [18], the Murray Darling Basin [19] and the Nile Basin [20].

In the present study, GRACE-based TWS, in combination with precipitation and in situ water level data of the LTR, along with outputs from two hydrological models: the Global Land Data Assimilation System (GLDAS) and the WaterGAP Global Hydrology Model (WGHM) are used to investigate water variations over the PRB. Possible teleconnections with Pacific climate variability are analyzed by using indices of El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). The objective of this study is to assess the related impacts of human intervention and climate variability on water resources within the PRB.

2. Study region

The PRB ranges from 97°39′E–117°18′E and 3°41′N–29°15′N with an area of ~442,000 km^2 located in China (Fig. 1). In addition to the uneven spatio-temporal precipitation distribution, approximately 80% of the total discharge concentrates in the rainy season (April–September) [4]. The climate is mainly influenced by the eastern Asian monsoon and typhoons as well as the topographic features [9]. Many dams (data available at http://www.fao.org/nr/water/aquastat/dams/index.stm) have been built for irrigation and hydroelectricity. Among them, the LTR which is the second largest dam in China, was built at the midstream of the PRB, Guangxi Province. At its first stage of water impoundment from September 2006 to the end of 2009, the water level reached 375 m with a total storage capacity of 16.2 km^3. This artificial water impoundment has strongly influenced water variations in the PRB [8].

3. Data and methods

3.1. GRACE data

The latest release of CSR RL 05, GFZ RL 05a and GRGS RL03 data for the period 2003 to Nov. 2014 were used to derive TWS for the PRB. GRGS is a regularized solution and no further filtering is required [21]. Both of the CSR and GFZ data were processed following the methods of [22] to obtain monthly TWS anomalies. Firstly, degree-2 zonal C20 time series were replaced by analyzed Satellite Laser Ranging (SLR) data [23]. A hybrid filtering scheme combined de-correlation filter P3M6 [24] and 300 km Fan filter was then employed to reduce noise [25]. A regional scaling factor of 1.48 computed by applying the same filtering techniques (except for de-correlation) to GLDAS-based TWS [26] was obtained to recover the lost signal due to truncation of the gravity coefficients and filtering for both of CSR and GFZ TWS. This scaling factor is close to the value of 1.35 derived from the Community Land Model v4.0 provided by the GRACE Tellus website for the same region. Additionally, Long et al. [17] also shows that scaling factors estimated from six models range from 1.09 to 1.53 for the PRB.

3.2. *Hydrological models*

TWS estimates from two land surface models from GLDAS with time spanning from 2003 to 2014 and WGHM [27–29] covering the period 2003–2013 were used for a comparison with GRACE. Monthly GLDAS-based TWS changes from the NOAH version at a spatial resolution of 1° × 1° used in the analysis are the sum of 4-layer soil moisture, snow water equivalent and plant canopy water. WGHM-based TWS anomalies at a spatial resolution of 0.5° × 0.5° include changes in surface water storage (water in rivers, lakes, reservoirs and wetlands), soil water storage, snow and groundwater.

Additionally, due to large uncertainties may exist in different land surface models, the applications of surface runoff data from four versions of GLDAS (NOAH, CLM, VIC and MOSAIC) with a resolution of 1° × 1° [26] were investigated

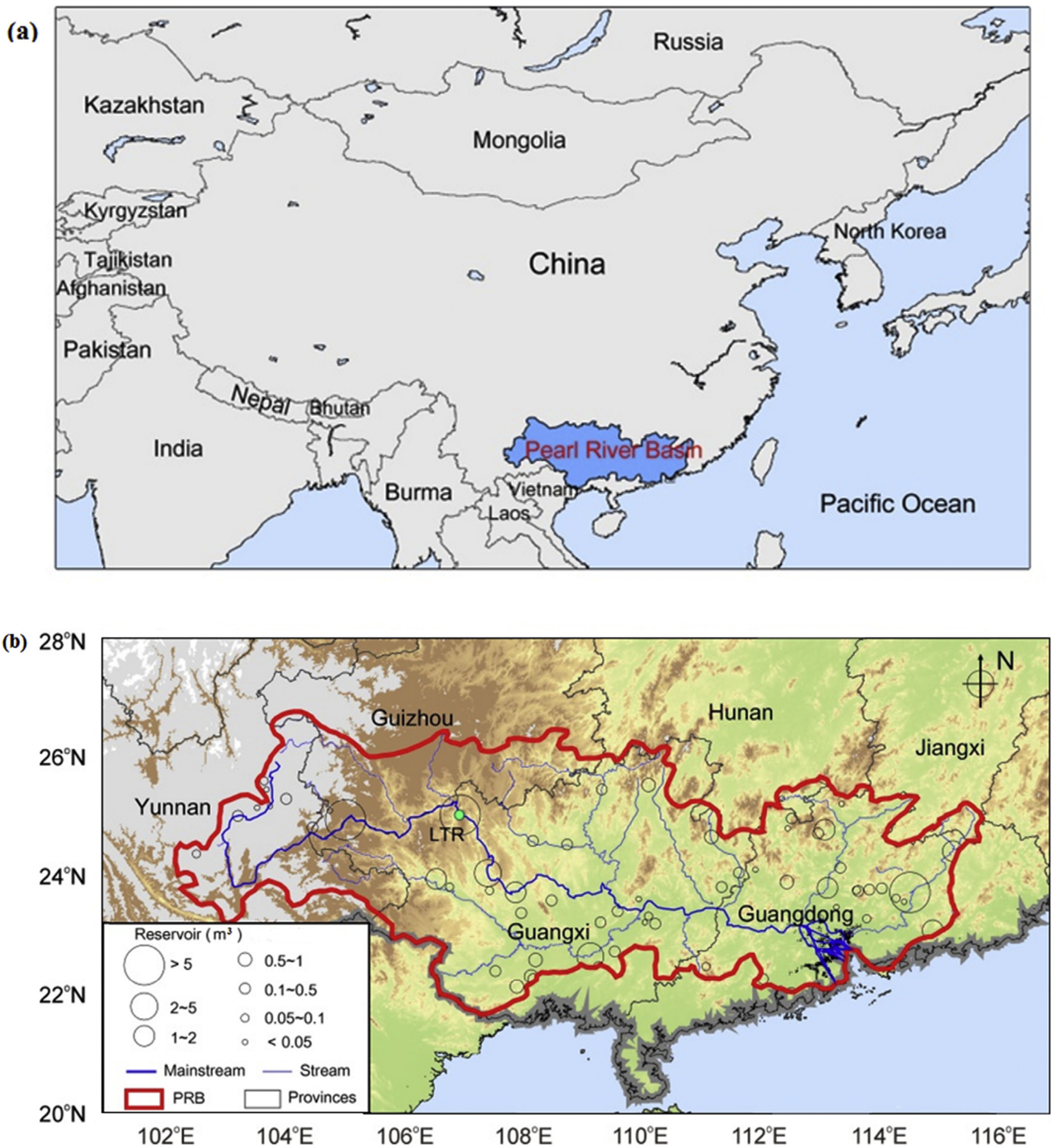

Fig. 1 – a-Location of the Pearl River Basin in China. b-Graph of the study area. Circle represents the location and capacity of reservoirs.

before using them to characterize the hydrological variations in the PRB through examining the correlation between precipitation and runoff data in terms of monthly and annual time scales (Fig. 2, Fig. 3 and Table 1). The highest correlations were found between monthly/annual precipitation from the China Meteorological Administration (CMA) (described in Section 3.4) and runoff data from CLM (Table 1). Moreover, the mean of the annual total runoff from CLM (353.4 mm) is more reasonable as Fekete et al. [30] pointed out that the annual runoff is in the range of 200–400 mm between 20°N and 30°N. Therefore, we selected the CLM to estimate runoff data over the PRB. In addition, evapotranspiration data from the CLM with the same resolution were also used for the analysis.

3.3. *ENSO and PDO*

The Niño 3.4 provided by the Climate Prediction Centre (CPC) is used to represent ENSO index in this study. It represents a mean sea surface temperature (SST) anomaly in the

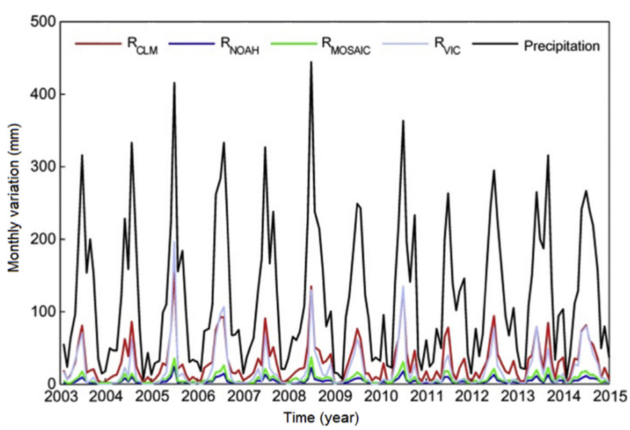

Fig. 2 – Monthly variations of precipitation from CMA and runoff from four models of GLDAS.

region between 5°N and 5°S and 170°W–120°W. As a largely interdecadal oscillation, the PDO provided by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) can modulate the interannual ENSO-related teleconnections [31].

3.4. *Other data sets*

Monthly gridded precipitation from 2003 to 2014 and temperature data spanning for the period 2003-2013 with the same spatial resolution of 0.5° × 0.5° used in the study are provided by the CMA (available at http://cdc.nmic.cn/home.do). Monthly water level data of LTR from January2006 to 2014 were used to investigate anthropogenic influences in the basin.

4. Results

4.1. *Comparison of TWS anomaly from GRACE and hydrological models*

Fig. 4 shows the secular trends of TWS estimates from different GRACE solutions and hydrological models, and precipitation from CMA. Good agreement can be seen among different TWS estimates, as obvious decreasing trends occurred over the upper PRB (except for the CSR solution), while the middle and lower reaches of the PRB mostly show water increases. These long-term trends generally compare well with precipitation. Moreover, water depletions over the upper PRB can be attributed to the recent heavy droughts [11,32] related to the persistent low precipitation [1,3], also can be seen in Fig. 4e. Positive peaks shown in GRGS and GLDAS are believed to be caused by water impoundment by the LTR since precipitation deficits occurred in the same region (Fig. 4e). However, positive peaks of CSR TWS and GFZ TWS occurred in different areas, which could be attributed to strong signal modification caused by spatial smoothing [33]. Moreover, obvious differences in magnitude can be seen between the GRGS-based trends and those of

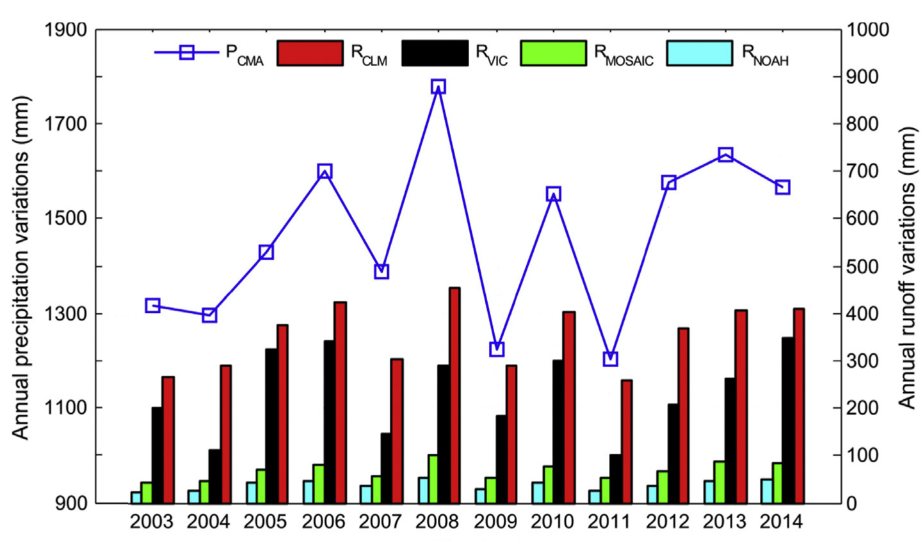

Fig. 3 – Annual variations of precipitation from CMA and runoff from four models of GLDAS.

Table 1 – Correlation coefficients between runoff and precipitation data and the mean of the annual total runoff from different models of GLDAS.

	Correlation with monthly precipitation	Correlation with annual precipitation	Mean of the annual total (mm)
CLM	0.94	0.94	353.4
VIC	0.85	0.72	234.4
NOAH	0.90	0.90	37.4
MOSAIC	0.89	0.92	68.6

CSR and GFZ. These discrepancies can be attributed to various factors, such as the data processing strategies employed by different centers, filtering effects and truncation [33,34]. Previous studies also pointed out that because of substantial differences among various GRACE solutions, it is hazardous to state regional mass loss or gain based on a single dataset [35] and using only one center-specific solution may lead to misinterpretation of geophysical processes in the studied region [33]. In addition, WGHM cannot detect this damming effect possibly due to the underestimated seasonal variability of total TWS in Indochina monsoon controlled areas [36]. Another obvious water increased signal observed by CSR, GFZ, GLDAS and WGHM in the lower reach of the PRB can be explained by the increased precipitation.

Fig. 5 indicates the correlations between different GRACE solutions and GLDAS/WGHM. TWS estimates from CSR, GFZ and GRGS display a strong correlation with GLDAS, with correlations of 0.86, 0.84 and 0.82 respectively. Relative smaller correlation coefficients were found between GRACE and WGHM (0.60, 0.58 and 0.50 for CSR, GFZ and GRGS respectively), suggesting that the possible underestimated seasonal variations by WGHM [36] would affect its performance in simulating TWS variation in the PRB. Similar results were also reported in other regions, e.g., the Yangtze River Basin [16]. In addition, the TWS changes estimated from hydrological models are less variable than those of GRACE, coinciding with the finding in other regions [37], primarily due to WGHM possibly overestimates ground water recharge or runoff [36] and a lack of surface and groundwater in GLDAS [37].

4.2. *Temporal TWS anomaly from GRACE and hydrological models*

The annual signal was removed from the original signal to obtain the non-seasonal anomaly, which can reflect the non-seasonal anomalous dry and wet conditions. The uncertainties of GRACE shown in Fig. 6a were computed from the standard deviation of TWS changes from three solutions. Fig. 6 shows the behaviors of non-seasonal changes in TWS and other water components in the PRB. It was shown that a long-term dry condition from 2004 to mid-2006 (Fig. 6a) corresponds to persistent negative precipitation/surface runoff anomalies from the 5-month mean time series (Fig. 6b). An obvious TWS increase period from mid-2008 to early 2009 (Fig. 6a) can be attributed to positive precipitation anomalies (Fig. 6b) as well as the significant water impoundment by the LTR (Fig. 6c), with water level increased from 332 m to 374 m. While water deficits in the 2009–2010 and 2011 droughts caused largely by the persistent precipitation reduction. In particular, the latter drought has resulted in an extreme low surface runoff and no water impoundment by the LRT in 2011 (Fig. 6c). Large uncertainty in GRACE TWS at early 2003 results mainly from the relative poor quality of GRACE data at its early stage [16].

Additionally, WGHM shows lower non-seasonal variability and reacts more quickly to precipitation changes than GRACE

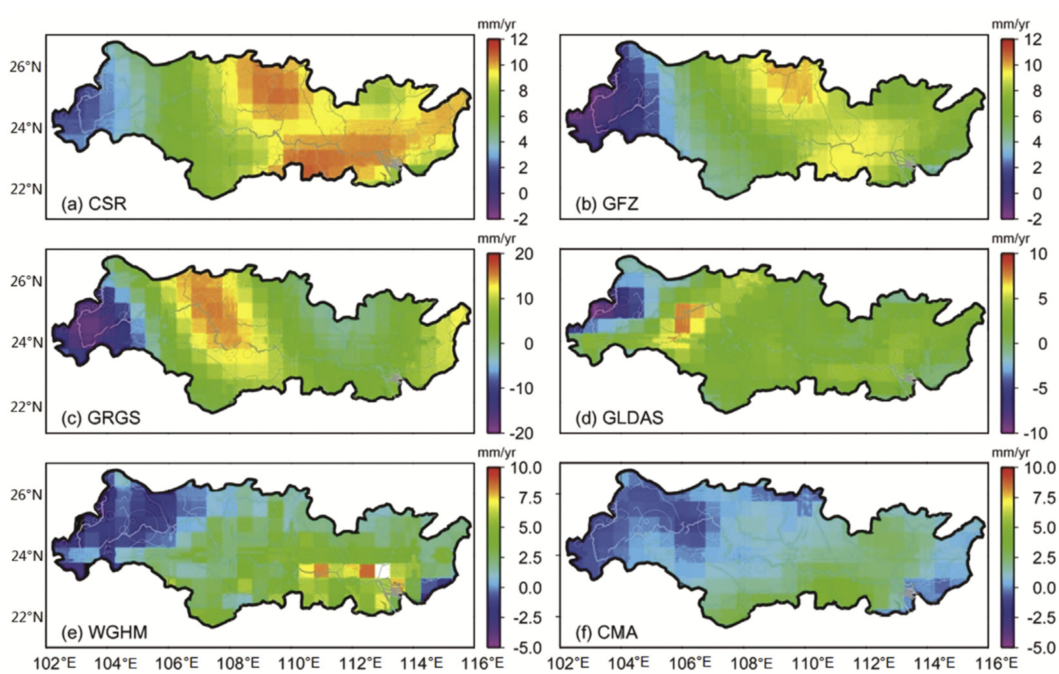

Fig. 4 – Long-term trend distribution of TWS from (a–c) GRACE, (d) GLDAS, (e) WGHM, and precipitation from CMA. Note that trends in WGHM TWS were estimated for the period 2003–2013.

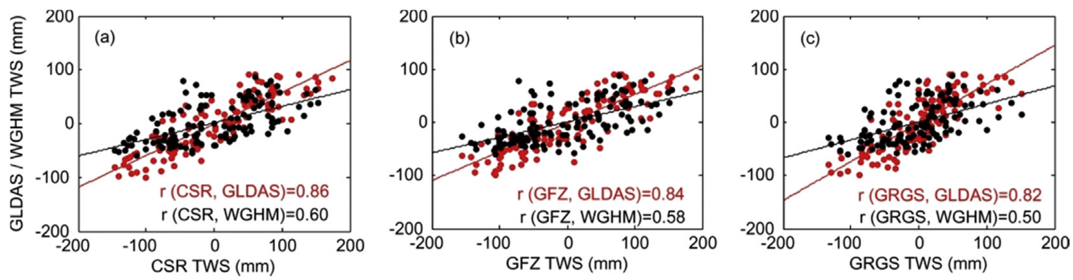

Fig. 5 – Comparison of regional TWS changes from GRACE, GLDAS and WGHM.

and GLDAS in the PRB, such as a quick recovery of TWS in the 2011 drought in response to positive precipitation anomalies. A correlation of 0.88 was found between the 5-month mean time series of precipitation and surface runoff, indicating that rainfall is a main driving force of runoff generation in the basin. Surprisingly, evapotranspiration decreased during the 2009–2010 and 2011 droughts even significant positive temperature anomalies occurred during the former drought (Fig. 6d). This may result from the limited soil moisture and wilting of plants in the extreme drought [38]. Moreover, inconsistency between temperature and evapotranspiration (both positive and negative temperature correspond to

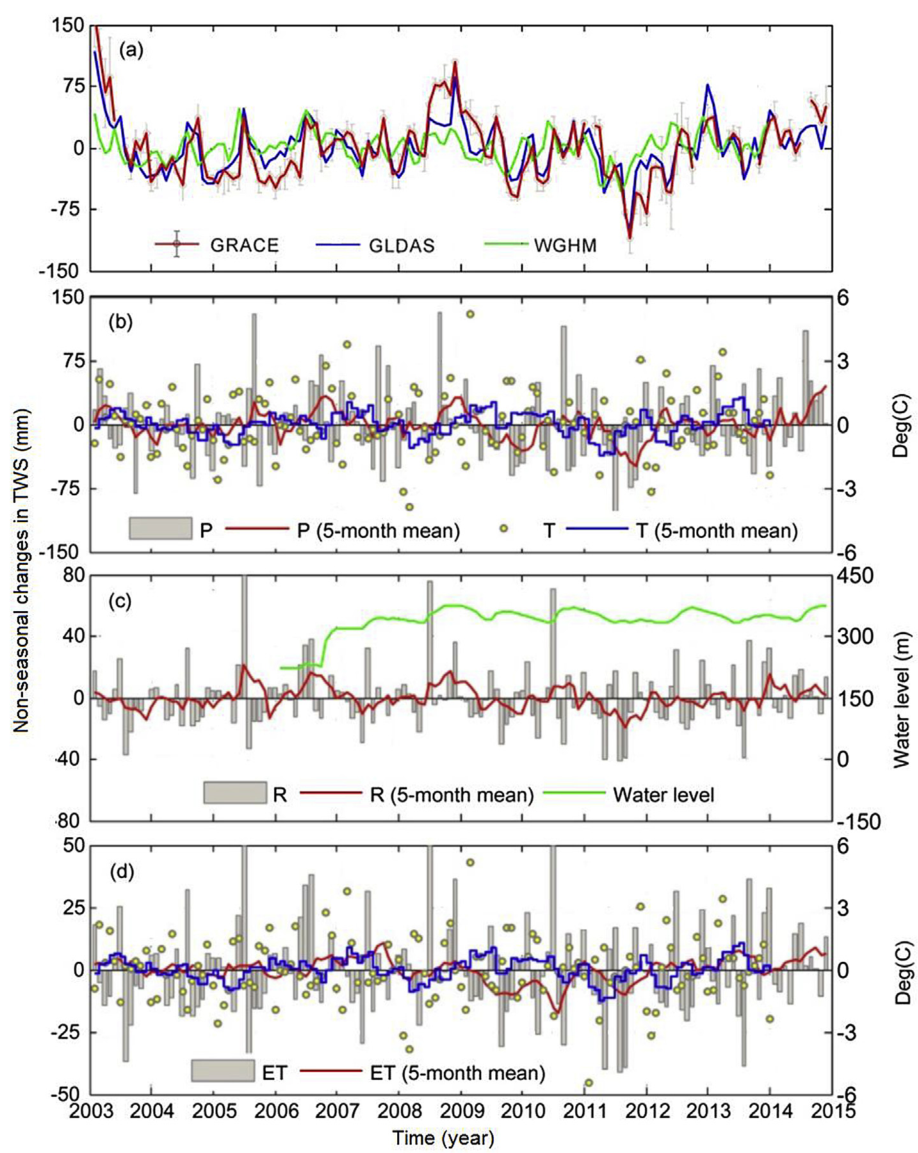

Fig. 6 – Non-seasonal changes in TWS, precipitation (P), surface runoff (R), evapotranspiration (ET), temperature (T), and water level variations of the LTR.

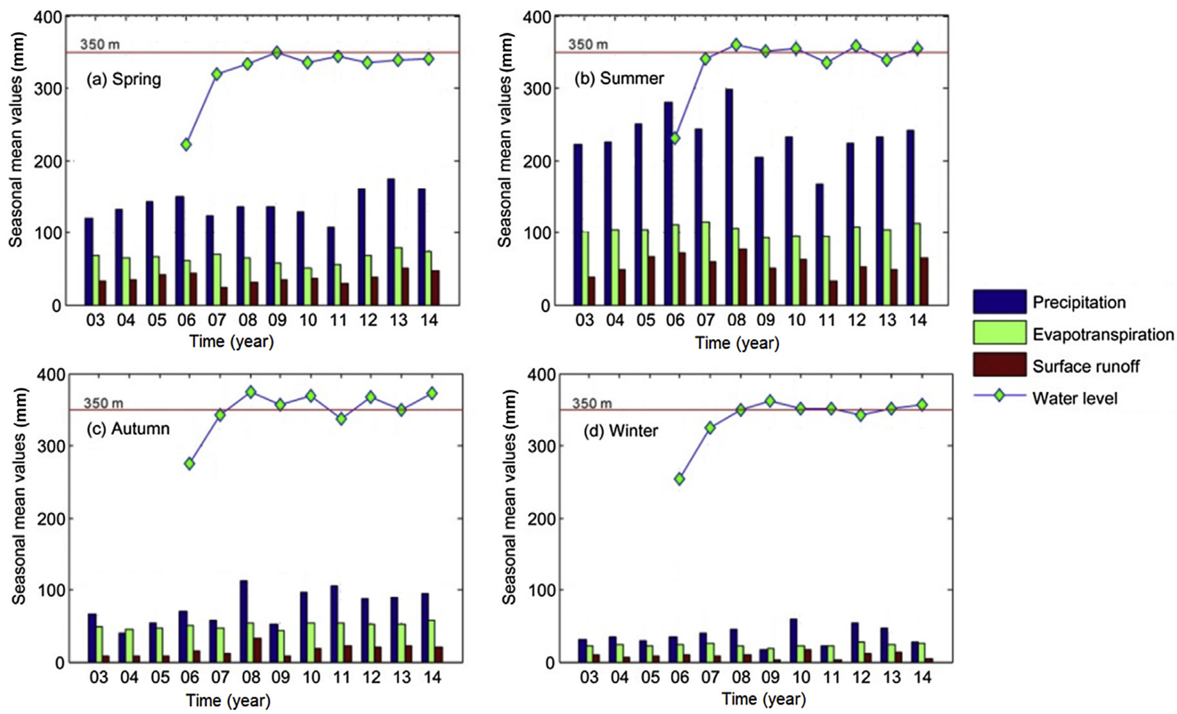

Fig. 7 – Seasonal variations of precipitation, evapotranspiration, surface runoff and water level of the LTR. Note that the unit of water level data is m, and the red line represents the water level of 350 m.

evapotranspiration deficits) implies that droughts are more influenced by precipitation than temperature (reflecting evapotranspiration) in the PRB.

Seasonal changes of different hydrological variables were computed in Fig. 7. We notice that precipitation mainly concentrated in spring (March–May) and summer (June–August) with less rainfall in autumn (September–November) and winter (December–February). An increasing trend in winter precipitation (Fig. 7d) coincides with the finding in Ref. [3]. High variability of summer precipitation has resulted in large variations in surface runoff, and a correlation of 0.89 was found between them. This may easily trigger summer floods and droughts in the basin. Since the LTR generally impounds water in autumn, large variations in summer precipitation strongly impacted the water impoundment of the LTR, especially for the 2011 heavy drought (Fig. 7b). Additionally, evapotranspiration primarily concentrated in summer, and its low variability in all seasons implies once again that precipitation was more important than evapotranspiration for the occurrence of

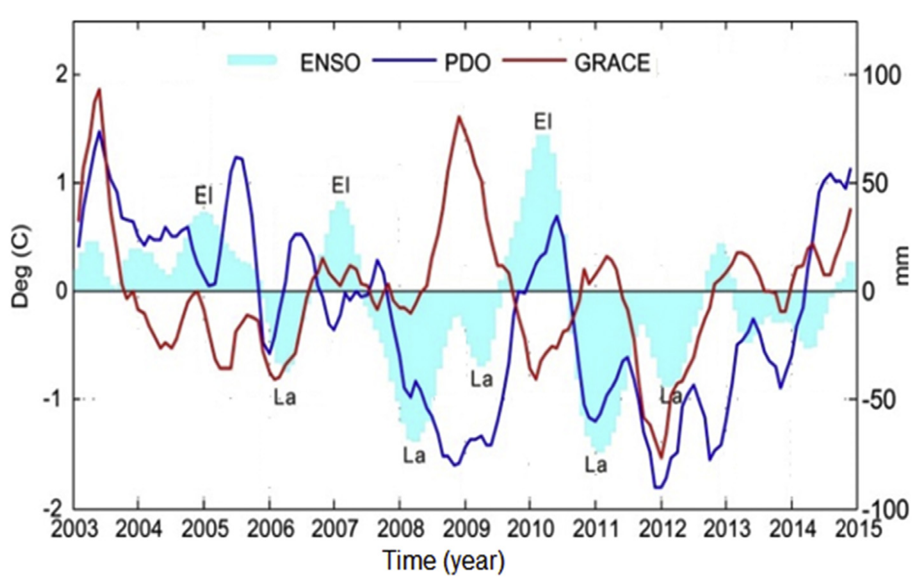

Fig. 8 – Non-seasonal GRACE-based TWS changes and climate indices of ENSO and PDO. Time series of GRACE are superimposed where available, and the missing values were simply interpolated by averaging the values before and after the missing data. All data were smoothed by a 5-month moving window.

summer droughts in the PRB. Similar case was found in Lithuanian river [39] and Syed et al. [37] also pointed out that rainfall dominates TWS changes in the tropics.

4.3. Non-seasonal TWS changes and Pacific climate variability

Studies have found a link between Pacific SST and rainfall in the entire or parts of the PRB [4,40,41]. It is also worth to see how Pacific climate variability influences TWS in the PRB. On Fig. 8 it was shown that the PRB trends to be dry in El Niño and wet in La Niña, consistent with the rainfall-ENSO patterns in Southern China [42]. For instance, long-term negative TWS anomalies at two periods from 2004 to the end of 2005 and from late 2009 to mid-2010 correspond to El Niño events, while positive TWS anomalies for the periods 2008–2009 and 2010–2011 coincide with La Niña events. However, the PDO's modulation of the anomalous Philippine Sea anticyclone may result in the change in the rainfall-ENSO relationship in southern China since ENSO exerts influences on East Asian climate by a teleconnection between the anomalous Philippine Sea anticyclone and anomalous southwesterly winds [40,43]. This may explain positive correlation occurred between ENSO and TWS in the 2006 and 2011–2012 La Niña events, and an El Niño event in 2006–2007. Similar changes in the rainfall-ENSO relationship related to the impact of PDO were also reported in the southern China in different period [40,41]. Moreover, good correspondence between the peaks of TWS anomalies and PDO in 2003, 2008 and 2011–2012 in terms of timing and magnitude indicates that the extreme TWS anomaly in the PRB was likely to be influenced by the peak of PDO phase, including warm and cool phase. But the explanation of their positive or negative relationship needs to incorporate more factors since the PRB is influenced by complex climate systems, such as SST in the South China Sea [44], the Indian Ocean [32]and the Tibetan Plateau heating [45].

5. Conclusions and discussion

In the present study, we have investigated water variability over the PRB from GRACE, hydrological models and in situ water level variations of the LTR. Significant water depletions over the upper PRB and drought-induced water deficits in 2011 as well as strong water impoundment by the LTR are well observed by GRACE. Two heavy droughts in 2009–2010 and 2011 have resulted in extreme low water level of the LTR and surface runoff, especially for the latter one. Precipitation was the primarily contributor for these droughts occurrence in the PRB as evapotranspiration shows low seasonal variability. Moreover, large variability of summer precipitation strongly impacted the regular water impoundment by the LTR and surface runoff, and as a result, this may easily trigger droughts and floods in the basin. This result coincides with the findings in previous studies [1,4]. Results once again show the capability of GRACE in detecting water impoundment by dams in the PRB as was done in previous work by Wang et al. [46]. Additionally, TWS in the basin was negatively correlated with ENSO in general. Occurrence of positive correlations between TWS and ENSO may be attributed to the PDO's modulation, in particular the extreme TWS anomaly was likely to occur in the peak of PDO phase. Our results would be helpful for a more comprehensive analysis of the impacts of climate variability and human activities on the TWS in the PRB.

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