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Spatio-temporal variability of terrestrial water storage in the Yangtze River Basin: Response to climate changes

Yaoguo Wang [a], Zhaoyang Sun [b], Qiwen Wu [c], Jun Fang [c,*], Wei Jia [d]

[a] Luoyang Urban Planning & Architecture Design Research Institute Co., Ltd., Luoyang 471000, China
[b] Luoyang Polytechnic, Luoyang 471000, China
[c] School of Geodesy and Geomatics, Wuhan University, Wuhan 430079, China
[d] The Seventh Engineering Company of CCCC Fourth Harbor Engineering Co., Ltd., Guangzhou 511455, China

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ABSTRACT

The Yangtze River Basin (YRB) is an important region for China's economic development. However, it has a complex terrain layout, most of which is affected by monsoon weather, and the geographical and temporal distribution of water resources is severely unbalanced. Therefore, the detailed analysis of spatio-temporal water mass changes is helpful to the development and rational utilization of water resources in the YRB. In this study, the variation of terrestrial water storage (TWS) is monitored by Gravity Recovery and Climate Experiment (GRACE) satellite gravity. We find that the University of Texas Center for Space Research (CSR) solution shows a notable difference with the Jet Propulsion Laboratory (JPL) in space, but the general trend is consistent in time series. Then the GRACE inferred water mass variation reveals that the YRB has experienced several drought and flood events over the past two decades. Global Land Data Assimilation System (GLDAS) results are similar to GRACE. Furthermore, the overall precipitation trend tends to be stable in space, but it is greatly influenced by the strong El Niño-Southern Oscillation (ENSO), which is the response to global climate change. The upper YRB is less affected by ENSO and shows a more stable water storage signal with respect to the lower YRB.

1. Introduction

The Yangtze River Basin (YRB), which has a length of more than 6300 km and is the longest river in mainland China, rises from the south side of Tanggula Mountain-Goladang Snow Mountain on the Qinghai-Tibet Plateau [1]. From west to east, the YRB flows directly into the East China Sea through eleven provinces (municipalities and autonomous regions), including Qinghai, Sichuan, Tibet, Yunnan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai. And its tributaries extend to eight provinces (autonomous regions), including Guizhou, Gansu, Shanxi, Henan, Zhejiang, Guangxi, Guangdong, and Fujian [2,3]. As one of the mother rivers of Chinese people, the YRB has played a pivotal role in their development. In addition, the YRB is a critical political and economic zone in China, with a total area of about 1.8 million km^2, including 460 million mu of arable land and about 460 million people living and working here. The YRB is rich in water resources, with an annual average of about 995.5 billion m^3 of water resources and more than 200 billion m^3 of water supply, making it the essential strategic water source in China and the most important pillar for maintaining the security of China's water supply [4]. However, with the abnormal global climate change, the water quality variation in the region is in an unbalanced state, especially the drought and flood events caused by extreme climate changes [5].

In the past 20 years, modern space geodesy technology has advanced by leaps and bounds [6]. TOPEX/Poseidon and its successor program Jason accurately measured sea surface topography, AQUA measures soil moisture, and ICESat rigorously monitors polar ice sheet height and its changes. The GRACE satellite, jointly launched by the United States and Germany in March 2002, provided data on the Earth's time-varying gravity field with a temporal resolution of about one month and 120 orders of magnitude [7]. At spatial scales of several hundred kilometers and above, the accuracy of the Earth's time-varying gravity field observed by GRACE is

* Corresponding author
E-mail address: fangjun@whu.edu.cn (J. Fang).

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improved compared with previous satellite gravity measurements. Using GRACE time-varying gravity field data, the inversion accuracy of surface water on seasonal and interannual time scales is less than 1 cm, which provides a broad application prospect for the study of large-scale mass redistribution among geospheres [8,9]. GRACE-modeled time-varying gravity field can be used to retrieve global and regional water mass changes on land, which is important for revealing mass redistribution in mountain glaciers and polar ice caps. In addition, it can quantitatively estimate the spatio-temporal distribution of seawater mass changes in the ocean, contributing to a deeper understanding of the causes of sea level changes [10,11].

Indirect water level time series measurements are needed as hydrological stations have declined [12]. The verified non-seasonal NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) vertical velocities show the agreement with non-seasonal GRACE TWSs [13]. When considering the water mass balance of the YRB region, the Noah, Variable Infiltration Capacity (VIC) and Mosaic tend to be overestimated [14]. Compared with the land surface model (LSM), GLDAS and CPC, GRACE generally has higher correlations and consistent spatial correlation patterns, but there are some differences between GLDAS and CPC [15,16]. Chao et al. estimated the individual TWS components in YRB, showing that the contribution of groundwater is 48% [17].

Besides, the delay of ENSO impact is also noteworthy [18]. The research indicates that ENSO has a positive delay effect of four months on the intra-annual and inter-annual signals [19]. While Zhang finds an ENSO event may result in TWS in the YRB after around 7–8 months, the lagged impact is more active in the lower YRB than the upper YRB [1].

In this study, we more comprehensively investigate the terrestrial water mass change in the upper and lower YRB and the performance of main lakes when ENSO events occurred during 2002–2017. We analyzed and compared the TWS change of the terrestrial hydrological model GRACE on spatiao-emporal scales. At the same time, precipitation and temperature are also considered, trying to reflect the impact of ENSO events on the climate change of the YRB in a more all-sided way. In addition, we also use wavelet spectrum to briefly analyze the periodicity of ENSO events.

2. Materials and methods

2.1. GRACE data

We utilized Spherical harmonic coefficients (SHCs) of GRACE Level-2 Release 06 (RL06) products released by the Center for Space Research (CSR) spanning from April 2002 to June 2017. It is worth noting that degree-1 coefficients (geocentric term) correction using the results estimated by Swenson et al. [20], C_{20} coefficients using the results evaluated from SLR by Cheng et al. [21], followed by the correction using the glacial isostatic adjustment (GIA) model given by Peltier et al. [22]. Furthermore, we performed Gaussian smoothing with a radius of 300 km to attenuate the effect of higher-order noise from the spherical harmonic (SH) coefficients [23]. In addition, monthly GRACE RL06 mascon data from the University of Texas Center for Space Research (CSR) ($0.25° \times 0.25°$) and the Jet Propulsion Laboratory (JPL) ($0.5° \times 0.5°$) were used for comparison with the SHCs solution. The above data were all the same lengths and were interpolated to a spatial resolution of $0.5° \times 0.5°$.

2.2. Surface hydrological model

The Global Land Data Assimilation System (GLDAS) was established by NASA's Goddard Space Flight Center in conjunction with the National Center for Environmental Prediction (NCEP). The system aims to generate land surface state variables and flux data by integrating advanced surface modeling and data assimilation techniques with a framework for water use and availability estimation that combines satellite and ground observations [24]. GLDAS is composed of four main surface models: Mosaic (MOS), Noah, Community Land Model (CLM) and Variable Infiltration Capacity (VIC). The land surface model has a temporal resolution of 3 h to 1 month, a spatial resolution of 0.25° or 1°, and generates equivalent water surface height (EWH) grid data in near real time covering the global land except for Antarctica. As part of a follow-up project funded by NASA's Energy and Water Cycle Research (NEWS) program, GLDAS is implementing data assimilation technologies that include snow water equivalent, soil moisture, surface temperature, and leaf area index. In this study, we use the GLDAS output products of four kinds of surface models, which can be downloaded from https://ldas.gsfc.nasa.gov/gldas/.

2.3. Precipitation data

The Global Precipitation Climatology Center (GPCC) model is one of the most widely used global grid-pointing land surface precipitation products, which supports regional climate monitoring, model validation, climate variability analysis, and water resources evaluation research. This product is a precipitation dataset constructed by sphere map interpolation based on international weather stations published by the German Weather Service [25]. There are more than a dozen GPCC precipitation products, and different precipitation products have different spatial resolutions and periods. In this study, we select Full Data Monthly Version 2020 with a spatial resolution of 0.5°, i.e., FD_M_V2020_ 050 precipitation model, which spans from January 1891 to December 2019. The download address is https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html.

2.4. Temperature data

Using some unique interpolation methods, the CHCN_CAMS model is updated periodically in near real-time, which is obtained from two sizeable single-station observation datasets collected by the Global Historical Climatology Network (GHCN) and the climate Anomaly Monitoring System (CAMS) [26]. This model provides high-resolution (0.5°) monthly global surface temperature change values at 2 m above the surface from 1948 to the present, which can be downloaded from https://psl.noaa.gov/data/gridded/data.ghcncams.html.

2.5. Lake leveling data

The International Data Center on Hydrology of Lakes and Reservoirs (HYDROLARE) was established by Russia at the national institute of hydrology in 2009. The Global Terrestrial Network Hydrology (GTN-H), set by the World Meteorological Organization (WMO) and the Global Climate Observing System (GCOS), operates under the auspices of WMO. The research institution provides hydrological data on the world's lakes and reservoirs (nearly 1200 water bodies to date) [27]. Time series of lake level and area changes can be downloaded from http://hydroweb.theia-land.fr/. We collect level data of three lakes (i.e., Dongting, Poyang, and Taihu) within the YRB, as shown in Fig. 1.

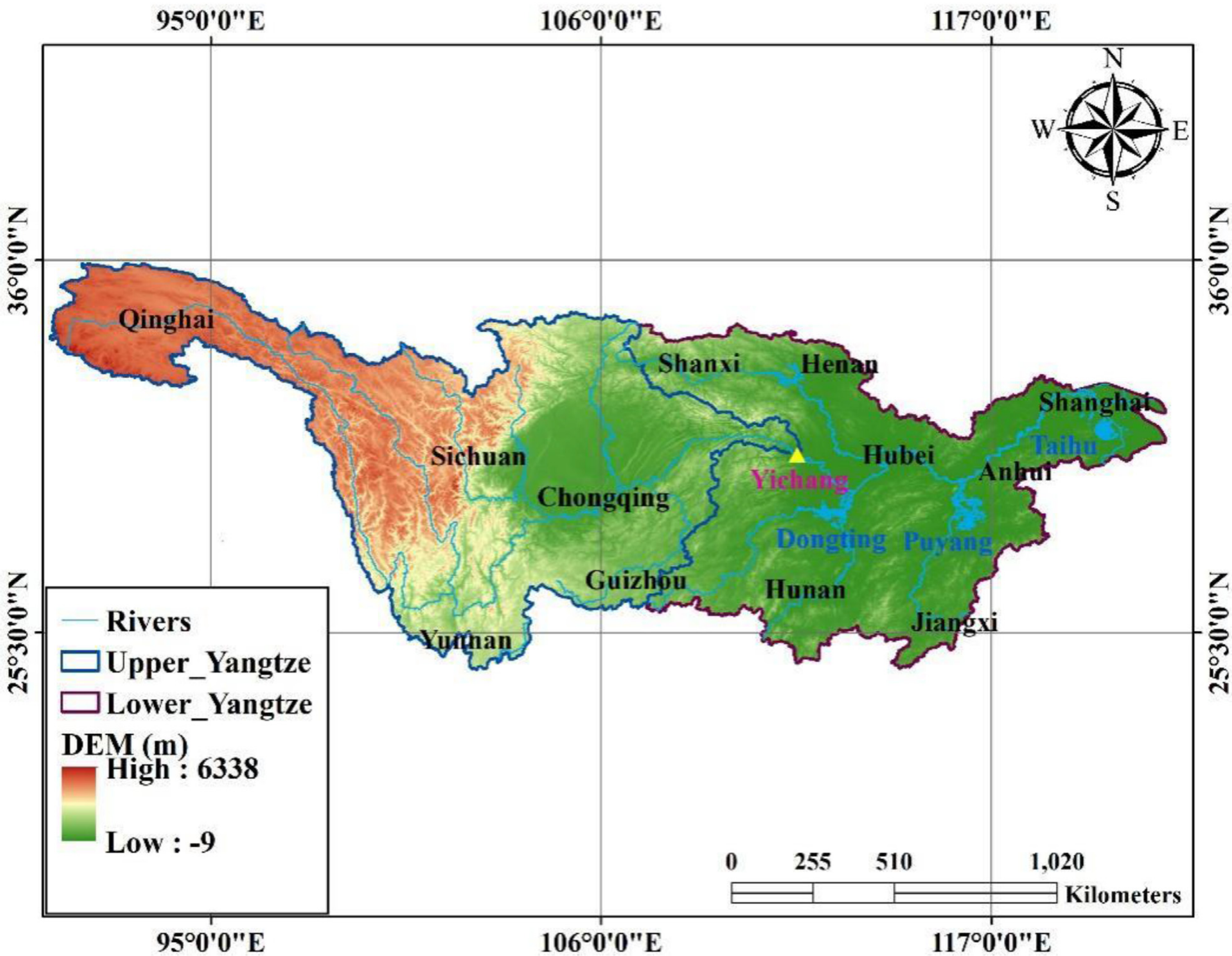

Fig. 1. The Yangtze River Basin and its water distribution. The three large lakes (Dongting, Poyang, and Taihu) are marked in blue. The blue and green lines are the upper and lower boundaries of the YRB, respectively.

3. Results

3.1. Spatial variation of hydrologic mass change in YRB

The spatial characteristics of water storage constrained by the satellite gravity GRACE data (Fig. 2) show an overall trend of increasing in the central and eastern regions and decreasing in the western regions. CSR and spherical harmonic (SH) coefficient solutions show that Chongqing is the center of water quality growth and outward radiation reduction. However, in the JPL solution, the growth center of water storage is in a north-south belt in northern Chongqing, and the three growth centers of water mass can reach more than 20 mm/year. Meanwhile, the water mass loss has been observed in western Sichuan. However, the loss rate of CSR and SH solution is high, ranging from −12 to −17 mm/year and covering a wide area, with only −11 to 8 mm/year using the JPL mascon solution.

Fig. 3 shows that the long-term trend generated by GLDAS is closer to the distribution. In Fig. 2(c), surface water loss is more significant in western Sichuan and southern Henan, while surface water quality in northern Guizhou and northern Chongqing increases more [28]. At the same time, the water volume in Qinghai decreases overall but increases partly, while the water volume in Chongqing increases generally but slightly. However, the long-term trend amplitude of GLDAS is not as obvious as that of GRACE, which ranges from −17 to 24 mm/year, while the former one is from −8 to 12 mm/year. We speculate that this may be because GLDAS can only detect shallow surface water [29].

Precipitation is a key factor driving the change in regional terrestrial water storage. Fig. 4 presents the long-term trend of precipitation variation in the YRB, which is not statistically significant. Only in southern Henan Province and Sichuan Province, the precipitation generally decreases by less than −1 mm/yr. There is a more noticeable trend of increasing precipitation above 2 mm/yr east of Hubei and Hunan, and the rest of the region is slightly growing by about 1 mm/yr. Compared with Figs. 2 and 3, the regions of increase and decrease in the precipitation trend and water mass trend basically coincide. However, the variation trend of precipitation is relatively small, and the amplitude of precipitation is close to the variation of water mass in the east of Hubei and Hunan. The increasing precipitation trend in Chongqing is small, but the increasing trend of water mass is obvious.

3.2. Time variation of hydrological mass change of YRB

The TWS over YRB obtained from CSR, JPL and SH are essentially in agreement with time-varying characteristics (Fig. 5), but the change in SH solution is more significant. The mascon solution of CSR is slightly lower than JPL after 2011. In the first gray area in Fig. 5, the water storage variation in the upper YRB decreased abnormally from mid-2006 to mid-2007 but had no significant impact on the lower YRB. From 2011 to 2012, the water storage in

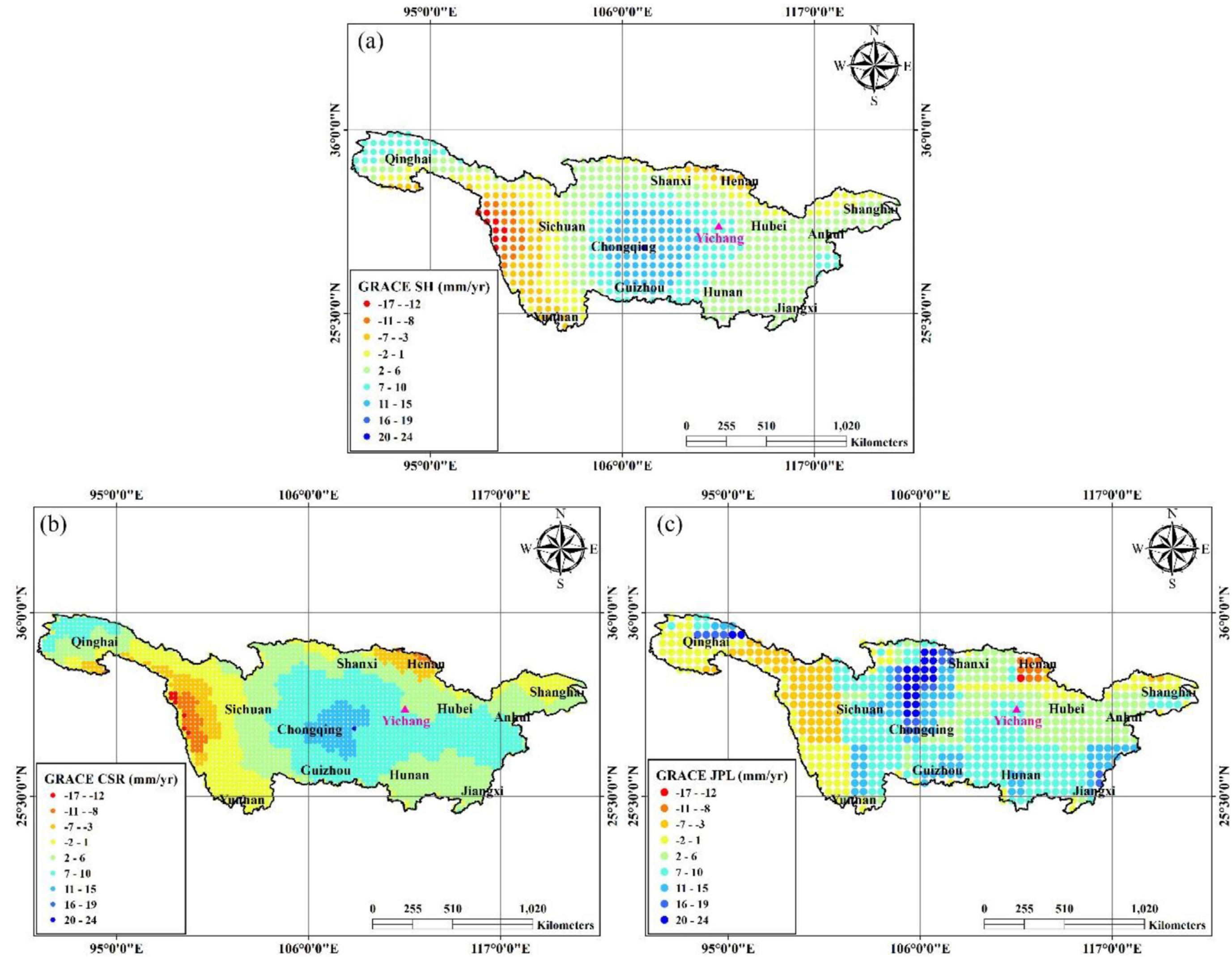

Fig. 2. Long-term trends of surface hydrology in the Yangtze River basin calculated from different data. (a) Spherical harmonic coefficients of GRACE Level-2 Release 06 (RL06) products released by the Center for Space Research (CSR); (b) The mascon solution of GRACE CSR RL06; (c) The mascon solution of GRACE JPL RL06.

the upper YRB decreased abnormally again, and at the same time, it decreased to a greater extent in the lower YRB, resulting in a decrease of the total water storage in the YRB.

The two gray areas in Fig. 5 correspond to distinct El Niño and La Niña events (Fig. 6). From 2002 to 2006, MEI in Fig. 6 shows El Niño, and TWS shows a downward trend in the lower YRB, but not in the upper YRB. This significant decline in TWS also occurred in 2014, which was the start of a strong El Niño year.

However, La Niña years, such as 2005–2006, interrupted the previous downward trend of TWS and made the TWS in 2010–2011 (another strong La Niña years and much larger than other years), but there was a marked drought both the upper and lower after 2011. Before 2002, there was also a strong MEI signal. Although a high TWS value could be found, the lack of GRACE data prevents the display of changes.

Fig. 7 shows the anomalous variation of the surface terrestrial water storage (STWS) in the YRB based on the four land surface models of GLDAS and the corresponding average result. Their average value is highly consistent with the fluctuations (Fig. 5). In contrast, the GLDAS solution has a more significant decrease in the lower YRB from 2006 to 2007. In addition, the elevated level of water storage during 2010–2011 and the primary status of water storage (Fig. 5) during the summer of 2011 and spring of 2012 are generally consistent with terrestrial hydrological models (Fig. 7).

Furthermore, the variation of lake water level in this area was obtained based on satellite altimetry data (Fig. 8). The satellite altimetry shows the lake level changes of the three major lakes in the YRB (Fig. 1). The trends after least-squares fitting can all lead to more obvious trend changes after 2010 (i.e., the La Niña period) when the apparent water mass anomaly decreases in Figs. 5 and 7. Especially, the accelerated lake level change of Poyang Lake was more significant after 2010.

Comparing meteorological data, TWS, and precipitation with seasonal and interannual fluctuations (Fig. 9), we found that 2006 was an El Niño year with significantly reduced precipitation in the upper YRB and the lowest water level in the YRB in the same period, resulting in a long and widespread severe drought of the upper YRB. The significant increased precipitation in the YRB and the local flooding in the YRB were the response to the La Niña event from 2007 to 2009. The precipitation in the YRB decreased significantly from 2009 to early 2010 when an El Niño event induced severe droughts. After that, several high intensities concentrated on prolonged rainfall events and extensive floods in the YRB, mainly in response to the La Niña event from 2010 to 2012. However,

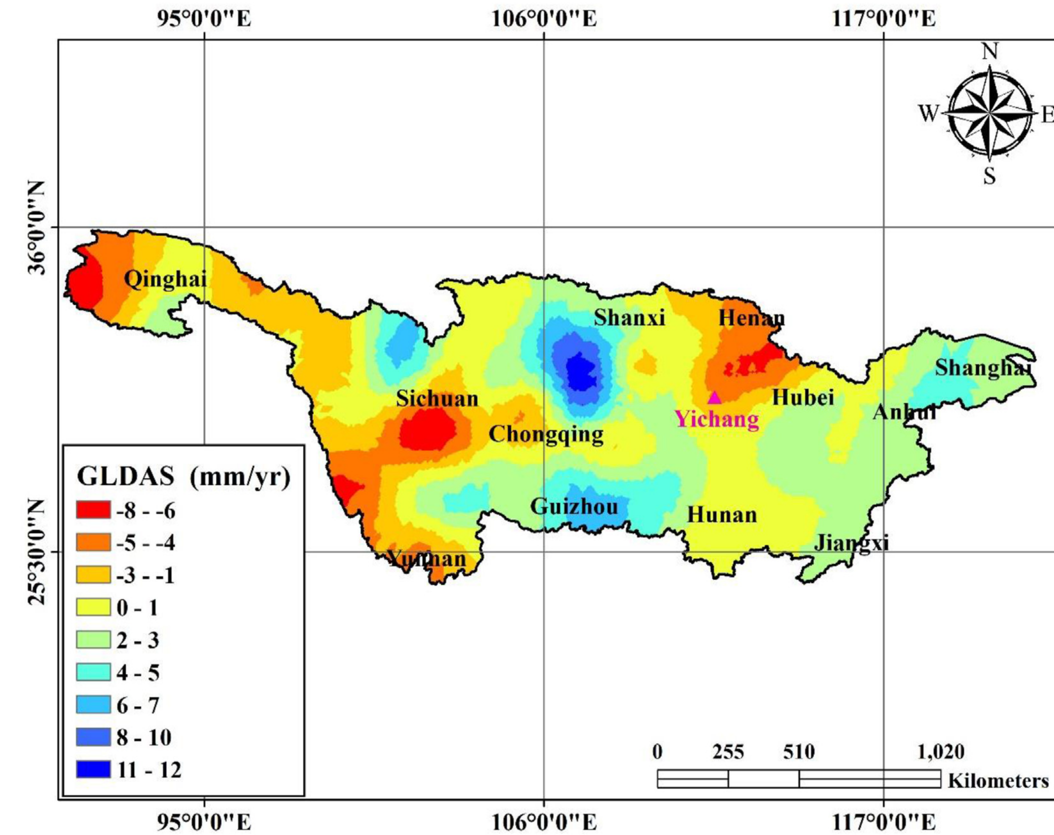

Fig. 3. Long-term trends of surface hydrology in the Yangtze River basin obtained based on the terrestrial hydrological model GLDAS.

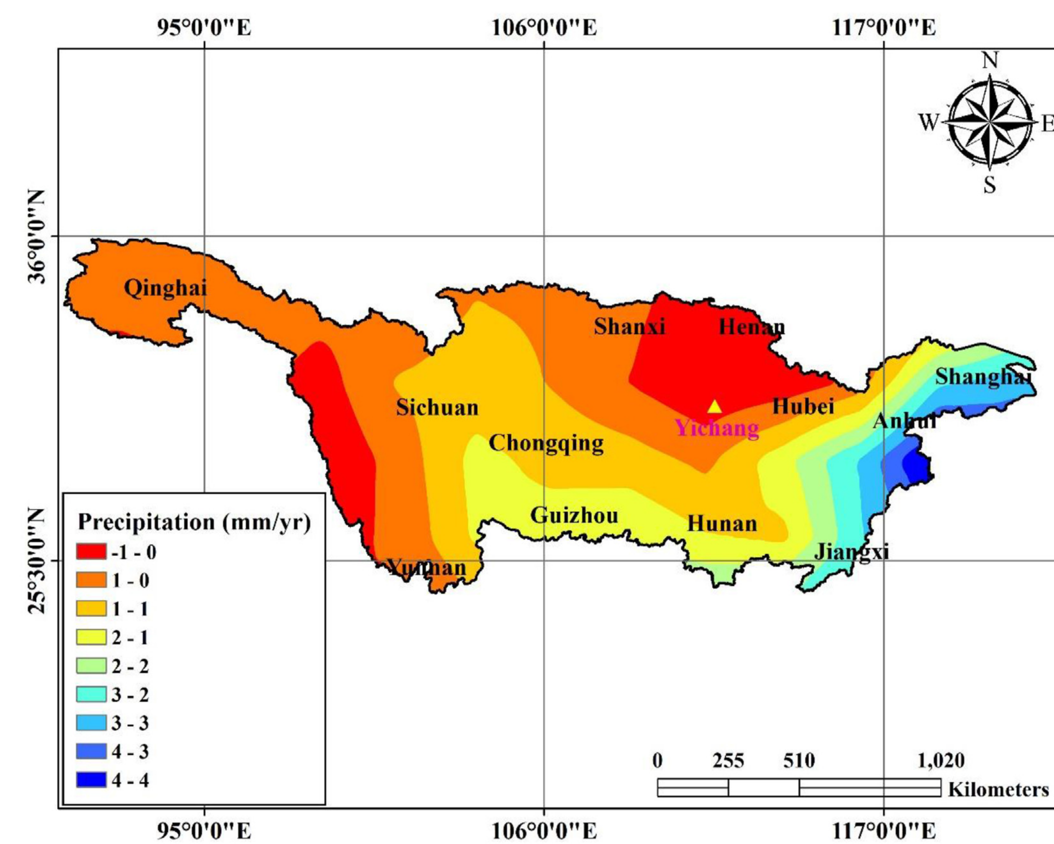

Fig. 4. The trend of precipitation throughout the YRB during 2002–2017.

widespread severe floods occurred in the YRB from 2014 to 2016. We speculate that ENSO is a necessary but not decisive factor affecting surface water in the YRB; El Niño usually decreases surface water in the YRB, and La Niña usually increases the terrestrial water storage in the YRB.

Besides, the climate index indicates that the interannual fluctuations are mainly distributed over the period of 2–7 years. However, the periodicity of MEI before and after 2004 is not consistent. The periodicity of 2–7 years disappeared before 2004, but the 11-year period was always evident. However, this phenomenon may be due to the insufficient length of the time series, and the 11-year cycle also decreased in intensity around 2001. Hence, the signal in the medium and long periods is not obvious.

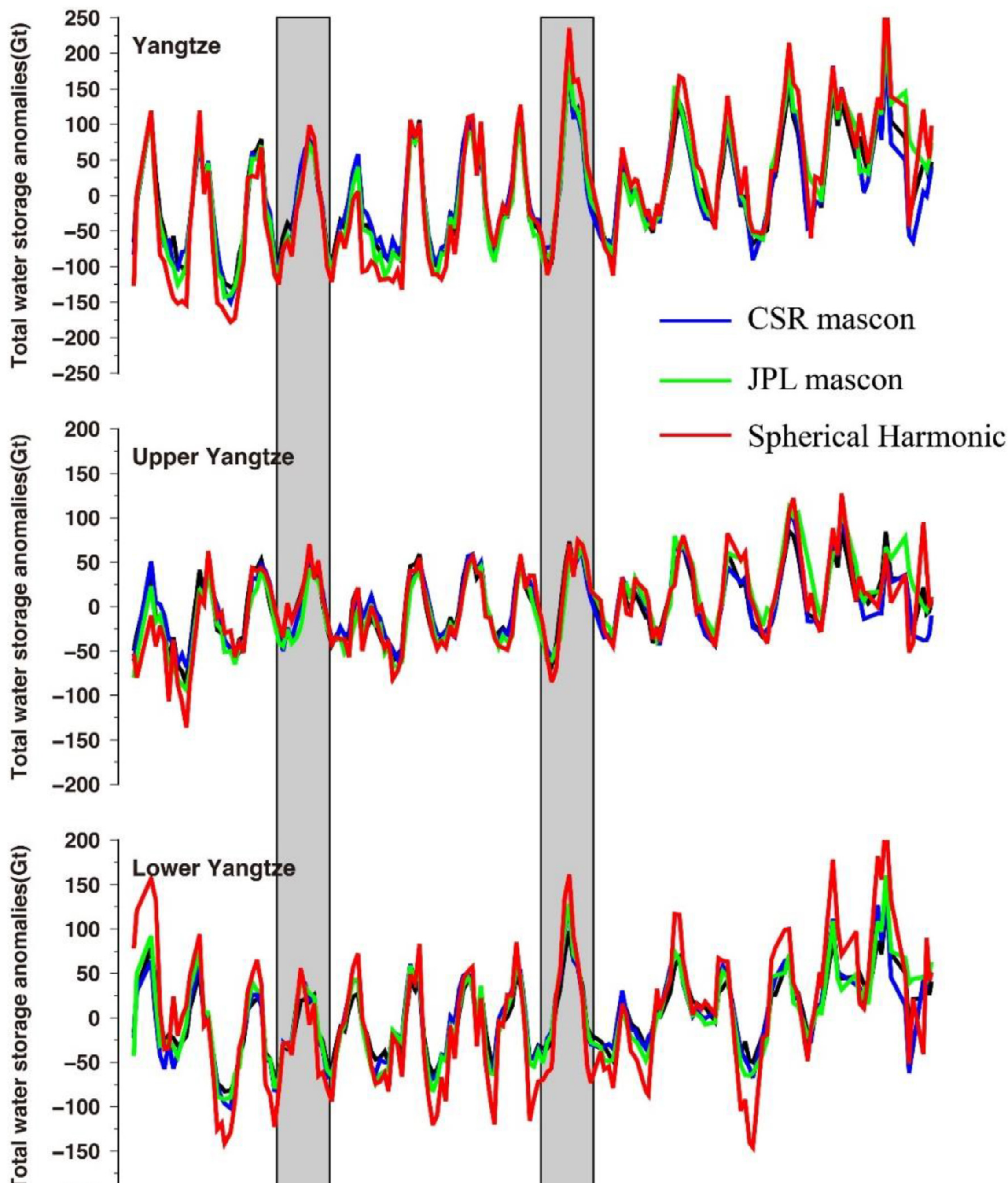

Fig. 5. The terrestrial water storage (TWS) anomaly in the YRB. The whole, upper, and lower TWS are presented.

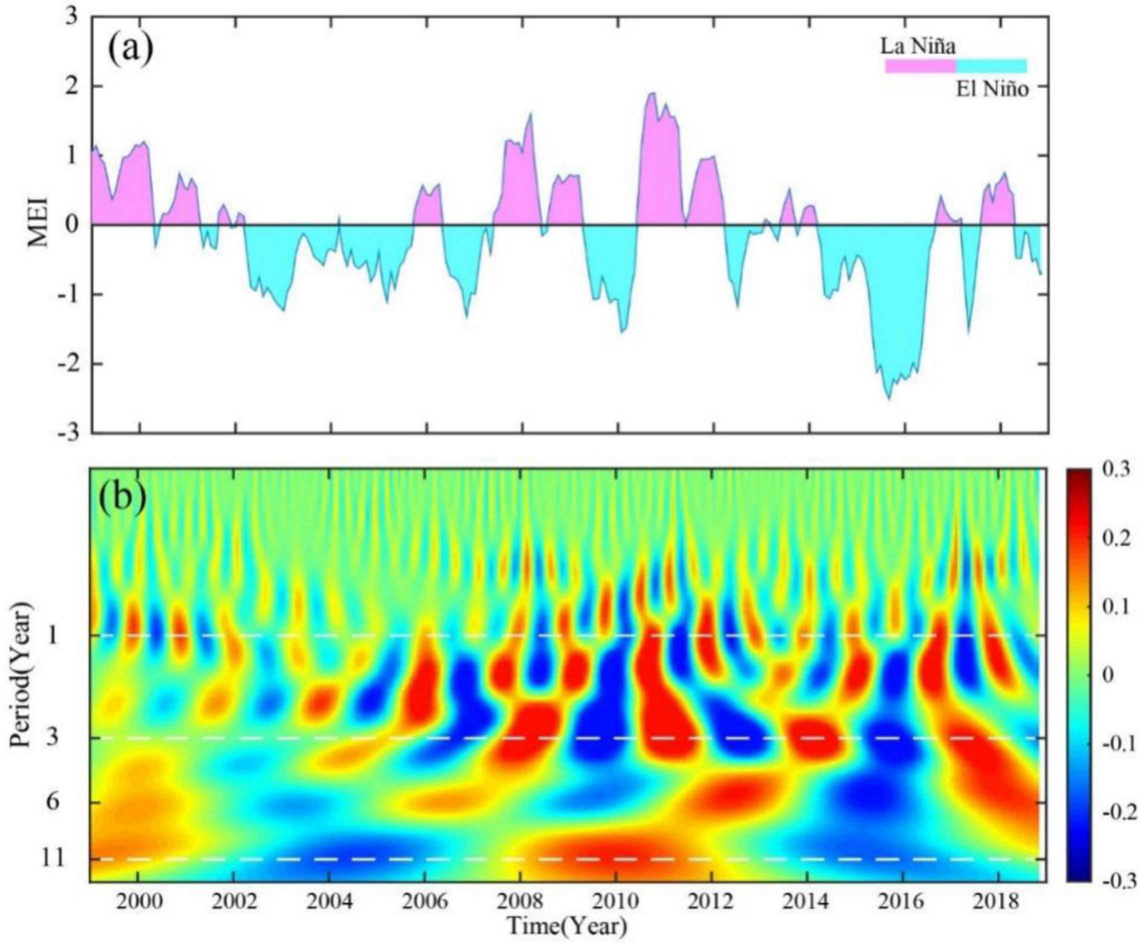

Fig. 6. The climate index of multivariate ENSO and wavelet spectrogram of MEI. (a) The MEI indexes. (b) The Wavelet Spectrum of MEI.

4. Discussion and Conclusion

Seasonal, interannual and long-term trends of Earth's surface mass represent the interaction between solid Earth, oceans, terrestrial water, and atmosphere, mainly in response to the water cycle fluctuations, such as rainfall, evaporation, land water change, ocean currents, glacier and ice cap melting, etc. [30]. The results of water mass changes in the Yangtze River Basin can also be used to enhance and improve the accuracy of global climate models, help understand the causes of natural disasters such as floods and droughts, and help humans explore various natural material cycles. Therefore, it plays a significant role in climate change on a global scale, which is of great value in studying the mechanism of climate worldwide. The YRB experiences heavy precipitation during the annual rainy season, causing surface water mass to exhibit extreme seasonal cycle variations [29]. Due to the influence of the monsoon, the spatio-temporal distribution of annual precipitation in the YRB is uneven, with heavy rainfall occurring mainly from April to October [31,32].

Considering the distribution of population density in the Yangtze River Basin (YRB), the distribution of water resources in the YRB is seriously unbalanced. In addition, the construction of many reservoirs in the YRB has a non-negligible negative effect on the water cycle and ecological environment, making the rational exploitation and management of water resources much more complex [33–35].

In this study, the spatio-temporal characteristics of water storage changes in YRB were derived based on the GRACE satellite dataset, combined with the application of hydrological models. We adopted a suitable processing method to observe and study the surface water mass changes in the YRB and compared them with hydrological models and precipitation data to analyze the spatio-temporal distribution patterns of surface water changes in the YRB. We adopted the GRACE satellite gravity observation to identify the spatio-temporal variation characteristics of terrestrial water storage of the YRB from April 2002 to June 2017. The spatial patterns of water mass distribution and the seasonal (interannual) variations of surface water mass are significantly different in the climate response.

We compared the spatio-temporal distribution of CSR, JPL and SH solutions based on GRACE satellite data in the YRB. Although the three solutions show the same performance in TWS time series, there are significant differences in the spatial distribution between CSR and JPL, and the SH solution is more like CSR. Among the four GLDAS models, the apparent amplitude of STWS reflected by MOS is large, while the amplitude of CLM is relatively small. Therefore, it is recommended to comprehensively consider the GLDAS model for analysis. However, the long-term precipitation trend is not obvious in the YRB, only in the range of -1 - 4 mm/yr, and the precipitation increase occurs more in the middle and lower reaches of YRB, which indicates that the ENSO events may have an insignificant impact on the long-term trend and the peak of precipitation in one ENSO year.

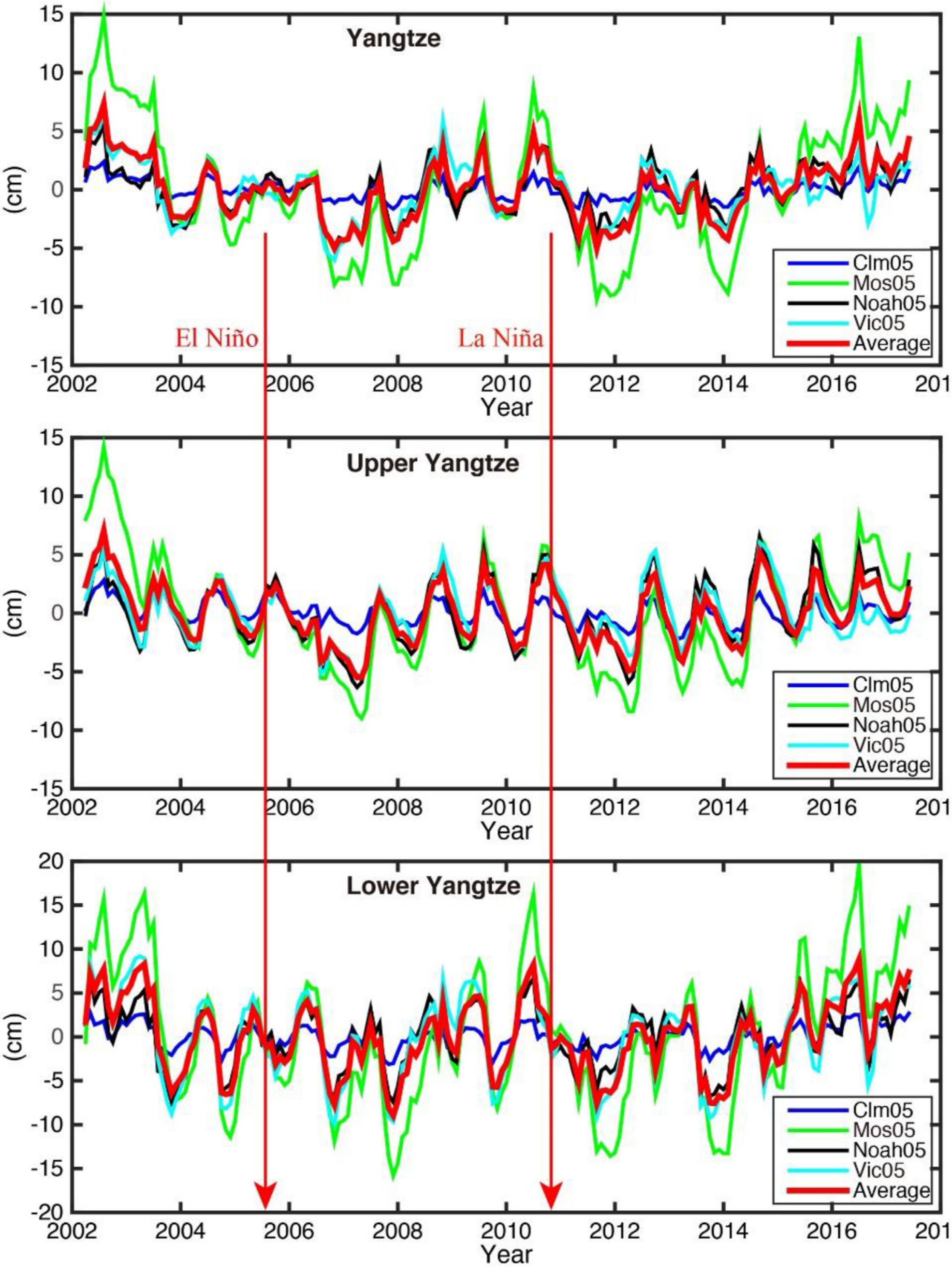

Fig. 7. The surface terrestrial water storage (STWS) anomaly obtained by GLDAS in the YRB. The STWS of the whole, upper, and lower YRB, respectively. MOS (Mosaic), Noah (Noah), CLM (Community Land Model) and VIC (Variable Infiltration Capacity) are four land surface models of GLDAS.

The influence of ENSO event is obvious. In the case of a typical La Niña year in 2010, GRACE data shows a clear peak in that year, followed by a large decrease in amplitude in the next year. In the STWS obtained from GLDAS, there was also a significant decrease in water level in the following year. The water level of the three lakes calculated by Satellite altimetry shows significant changes around 2010, especially in Poyang Lake, but the lake water level increased. In 2011, the peak rainfall in the lower YRB increased, while the total rainfall in that year decreased sharply. Totally, the lower is more sensitive than the upper YRB, especially on GRACE data and precipitation. Meltwater from the Tibetan Plateau may have helped stabilize the TWS of upper YRB, and it is harder for the monsoon to influence the upstream than the downstream. Besides, we analyzed the MEI's periodicity, which was unstable between 2000 and 2004. But this case may be limited by sequence length.

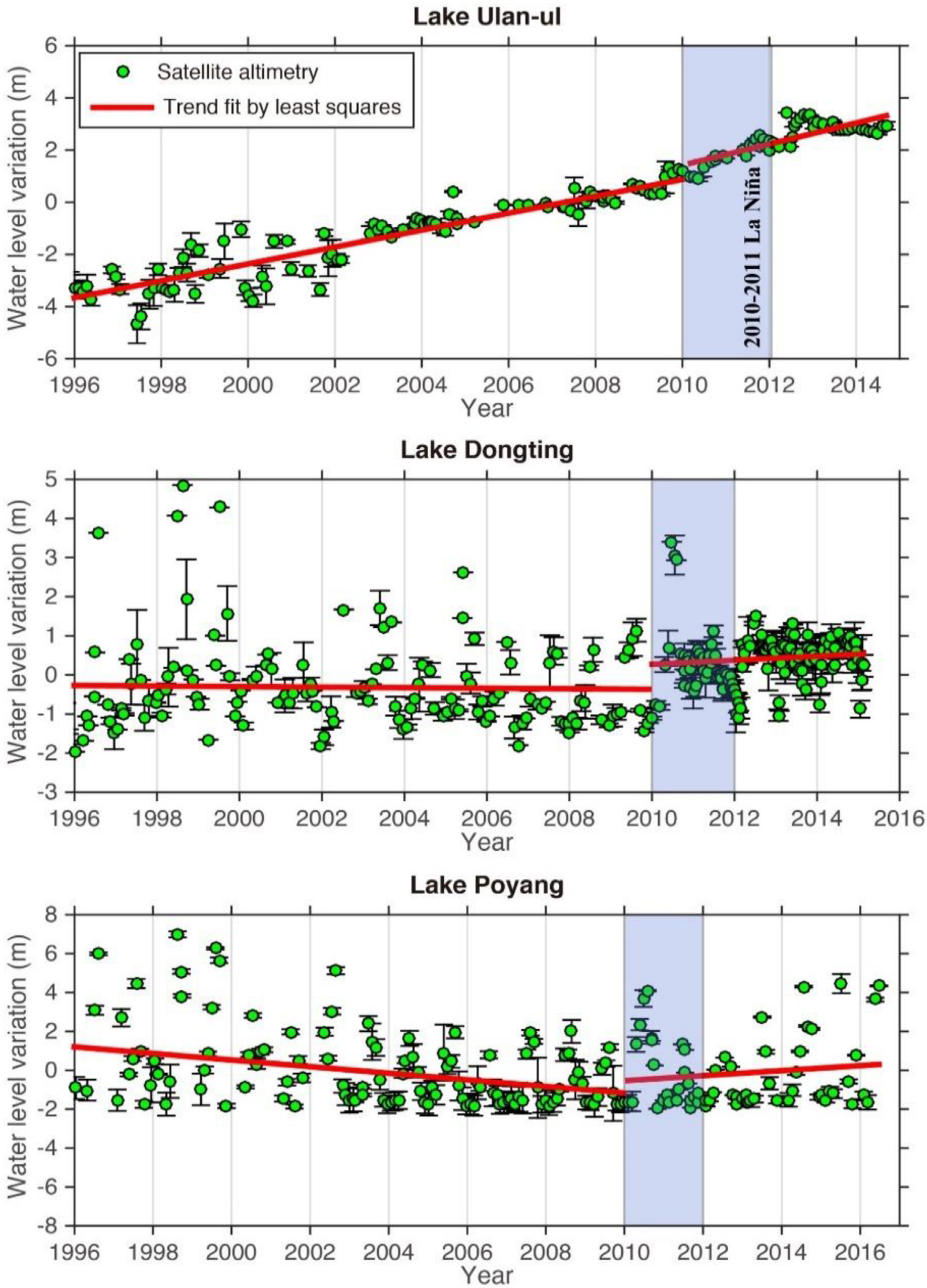

Fig. 8. Satellite altimetry reveals the water level anomaly of the three lakes in YRB.

However, this study focuses on the relationship between total water storage variation and climate change, ignoring the human factor of the variation in water volume. Therefore, the obtained results do not reflect the monthly variation of each region in wholeness, and we will make further exploration in future research work.

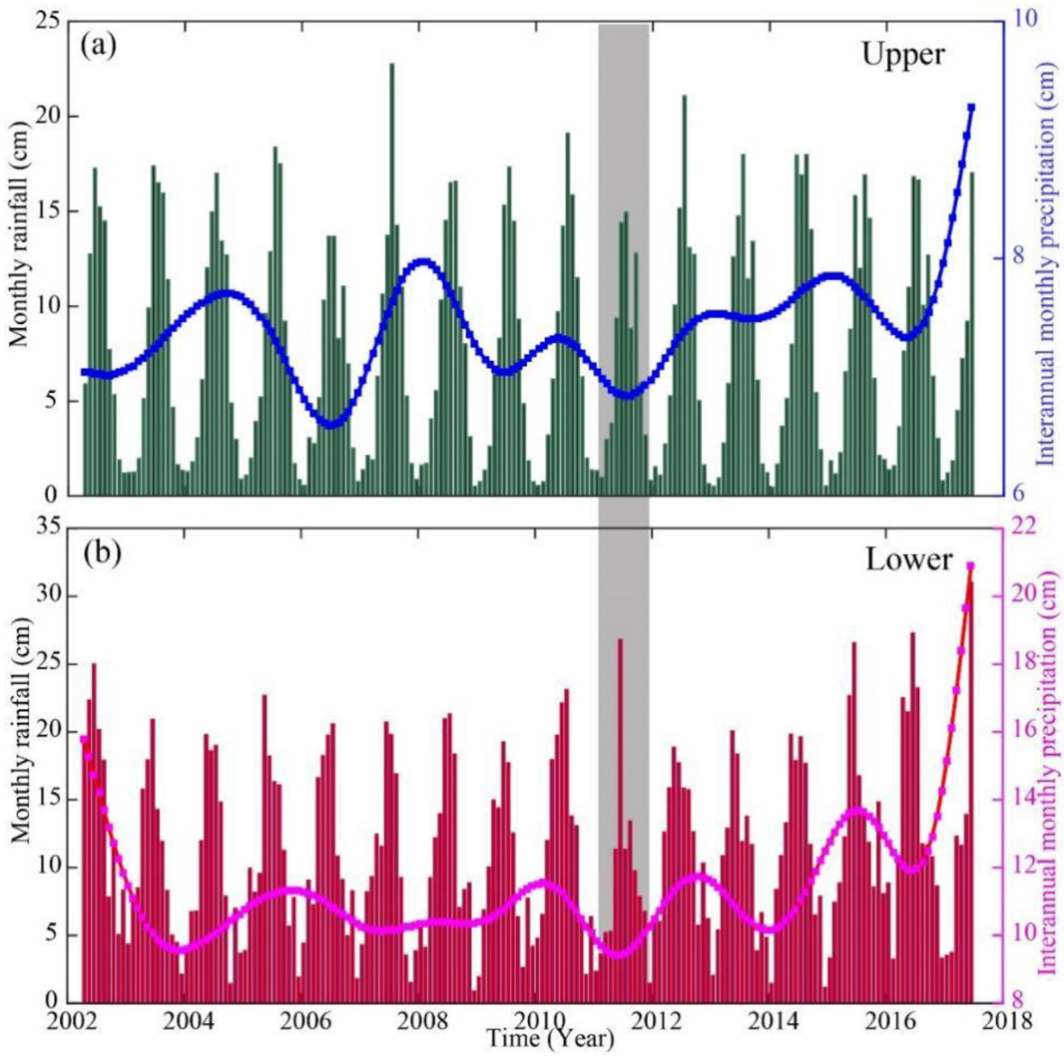

Fig. 9. Precipitation and temperature changes in the YRB from 2002 to 2017. (a) and (b) are the precipitation of the upper and lower YRB, respectively. The right vertical axis shows the interannual precipitation using the low pass filter (<0.5 cpy).

Author statement

Yaoguo Wang: Data curation, Writing-Original draft preparation.
Zhaoyang Sun: Conceptualization, Methodology.
Qiwen Wu: Software, Visualization, Investigation, Validation.
Jun Fang: Writing-Reviewing and Editing.
Wei Jia: Software, Validation.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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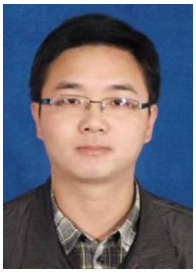

Yaoguo Wang received the bachelor's degree in School of Surveying and Geodesy, the PLA Information Engineering University from 2006 to 2010, and the master's degree in College of Earth Science and Engineering, Shandong University of Science and Technology from 2010 to 2012. Mainly engaged in geodesy and engineering surveying.

Zhaoyang Sun graduated from Henan University of Science and Technology in 2004 and graduated from Zhengzhou University in 2012. Mainly focused on building energy efficiency.

Qiwen Wu was born in Huangshan, Anhui, China in 1995. He received the M.S. degree in Surveying and Mapping from the East China University of Technology, Nanchang, Jiangxi, China in 2021 and is currently pursuing the Ph.D. degree in geodesy and survey engineering from the Wuhan University, Wuhan, Hubei, China. His research interests mainly focus on GNSS data processing and analysis.

Jun Fang studied at the School of Geodesy and Geomatics, Wuhan University, and is studying for a master's degree in Resources and Environment, School of Geodesy and Geomatics, Wuhan University. Mainly focused on geodesy and surface deformation fields.

Wei Jia works for the Seventh Engineering Company Of CCCC Fourth Harbor Engineering CO., Ltd. Mainly engaged in geodesy.