Hydrological variability and loading deformation in the Yangtze river basin based on modern geodetic means

Ding Ren, Lilong Liu, Liangke Huang and Lv Zhou

College of Geomatics and Geoinformation, Guilin University of Technology, Guilin, China; Guangxi Key Laboratory of Spatial Information and Geomatics, Guilin, China

ABSTRACT

The complex process of water storage change in the Yangtze River Basin (YRB) includes strong feedbacks and connections with global climate change. This study adopted Global Positioning System (GPS) observations and Gravity Recovery and Climate Experiment (GRACE) and Follow-On (FO) data from 2002 to 2021, along with Global Land Data Assimilation System (GLDAS) model outputs and Satellite Altimetry data, to analyse changes in hydrological mass in the YRB. Singular Spectrum Analysis (SSA) was used to analyse the missing data of GRACE/GRACE-FO from 2017 to 2018. GRACE/GRACE-FO and GLDAS derived terrestrial water storage (TWS) show different spatial distributions in the different river sections of YRB, and the long-term positive trend is due to increased mass, mainly in the late upstream and middle-lower reaches. Principal component analysis (PCA) was used to separate the common-mode components (CMC) in the YRB’s continuous GPS network, and it was found that several of these periodic oscillation signals are connected to hydrology. In addition, it was discovered that changes in hydrological mass in the YRB are influenced by precipitation and temperature and TWS anomalies may be associated with El Niño/Southern Oscillation (ENSO) events. These findings increase our understanding of the complex climate and dynamic hydrological processes of YRB.

ARTICLE HISTORY

Received 24 March 2022
Accepted 1 July 2022

KEYWORDS

Yangtze river basin; GPS; GRACE/GRACE-FO and GLDAS; satellite altimetry data; water storage anomalies; interannual fluctuations of hydrology; ENSO events

1. Introduction

Mass changes have occurred in the water cycle of the Yangtze River Basin (YRB) due to global climate changes (Immerzeel et al., 2010). The YRB, as the China’s and Asia’s longest river, originates from the Tibetan Plateau, the world’s ‘third pole’, and flows through eleven provincial administrative regions from west to east through central China (L. Wang et al., 2021). The YRB includes a multi-step topography with mountains, plateaus, basins, hills, plains, and several freshwater lakes such as Poyang Lake and Dongting Lake, providing abundant hydrological resources (Du et al., 2011). In recent years, global warming has accelerated the melting of glaciers in highland, directly leading to the large expansion of lakes, disrupting the YRB’s water mass balance, and eventually leading to a rise in the sea level (Kang et al., 2010; Pepin et al., 2015). Furthermore, increased precipitation can produce an immediate water mass changes in the YRB and cause flooding in extreme circumstances, endangering human life and property (W. Wang et al., 2013). In addition, the East Asian monsoon and the Indian monsoon, are formed by the significant differences in thermal properties between land and ocean, which bring a large amount of water vapour from the Pacific and Indian oceans to the continent and produce a large amount of rainfall in the monsoon area, resulting in the changes of hydrological quality of YRB (Wang & Chen, 2012).

Since the YRB spans eastern, western, and central China, climate changes vary from one section of the YRB to another, and the corresponding hydrological changes are also different. The annual maximum flow of the YRB is mainly influenced by climate change over a long period, according to data from three major gauging stations representing the upper, central, and lower portions of the YRB (i.e. Yichang, Hankou, and Datong; Q. Zhang et al., 2007). The East Asian monsoon and summer flood in the YRB are closely related to extreme weather (e.g. El Niño; W. Zhang et al., 2016). Sun et al. (2017) employed Gravity Recovery and Climate Experiment (GRACE) data to investigate terrestrial water storage (TWS) anomalies in the YRB. The results demonstrated that GRACE data can be used to monitor and analyse floods in the YRB and other regions effectively. Zhang et al. (2015) quantified drought in the YRB based on GRACE satellite and hydrological modes and discovered that El Niño/La Niña events were significantly correlated with TWS and the downstream was more sensitive to ENSO changes than the upstream. Xiao et al. (Yan et al., 2021) used GRACE measurements and surface model outputs to quantify the TWS in eastern China in 2019, and concluded that the insufficient precipitation in the second half of 2019 was the main cause of drought. At the source of the YRB, it is estimated that the...
reduction rate of glacier mass in the Tibetan Plateau region is $-28 \pm 6$ Gt/yr between 2003 and 2019 based on GRACE/GRACE-Follow-On (FO) data (Wang et al., 2021), which to some extent causes changes in the hydrological mass of the YRB. In addition, the TWS time series contains multi-year oscillation signals and its geophysical processes have not been fully elucidated.

The inversion of land water storage changes by GRACE satellite allows the analysis of the response of hydrological mass variability to climate change. However, satellite formations and solution strategies affect the GRACE/GRACE-FO method, and its inversion results are limited in spatial resolution. By contrast, the Global Navigation Positioning System (GPS) can better show detailed signal features of the region. Saji et al. (2020) analysed the ground deformation owing to changes in hydrologic quality in the Himalayas and North India based on GPS measurements and GRACE data, and concluded that this region shows prominent changes in hydrologic mass. Furthermore, continuous GPS (CGPS) observation time series provides a variety of geophysical signals which may be related to dynamic activities in several Earth domains. Since hydrology and atmospheric mass loading are the main seasonal changes of CGPS, and it can also be noticed by GRACE/GRACE-FO, the combined CGPS and GRACE/GRACE-FO observation can more accurately detect the dynamic processes of hydrological changes (Fang et al., 2021).

In this study, GPS and GRACE/GRACE-FO measurements combined with Global Land Data Assimilation System (GLDAS) model outputs were used to assess the geographical and temporal variability of terrestrial hydrological loading in and around the YRB between 2002 and 2021. Furthermore, we analysed the water level changes in the YRB using altimetry data. The hydrological signal of YRB were analysed and the elastic loading displacement were estimated based on different methods.

| Data   | Source  | Brief description                                                                 | URL                                                                 |
|--------|---------|----------------------------------------------------------------------------------|----------------------------------------------------------------------|
| GPS    | CMONOC  | Continuous GPS stations’ daily positions.                                        | ftp.cgps.ac.cn/products/position/gamit/RL06mascons.html              |
| GRACE/GRACE-FO Mascons (0.25° × 0.25°) | CSR     | The monthly GRACE/GRACE-FO RL06 Mascon Solutions (version 02).                  | http://www2.csr.utexas.edu/grace/RL06mascons.html                    |
| GRACE/GRACE-FO SHCs (1.0° × 1.0°) | CSR     | The monthly GRACE/GRACE-FO RL06 spherical harmonic coefficient solutions.       | http://www2.csr.utexas.edu/grace/RL06mascons.html                    |
| GLDAS (Noah, Catchment, and VIC) | NASA    | Three GLDAS monthly Land Surface Models (LSMs) V2.1.                            | https://gpcp.nsstc.noaa.gov/Global/GLDAS/RL06mascons.html             |
| DAHITI | DGFIT-TUM | The Database for Hydrological Time Series of Inland Waters.                      | http://www2.csr.utexas.edu/grace/RL06mascons.html                    |
| GPCP   | NOAA    | Global Precipitation Climatology Project monthly product.                        | https://gpcp.nsstc.noaa.gov/Global/DAHITI/RL06mascons.html            |
| CHCN_CAMS | NOAA   | CHCN_CAMS Gridded 2m Temperature (Land) Data.                                    | https://gpcp.nsstc.noaa.gov/Global/GPCP/RL06mascons.html             |
| Climate Index | NOAA | Version 2 of the ENSO index.                                                      | https://gpcp.nsstc.noaa.gov/Global/CHCN_CAMS/RL06mascons.html        |

2. Materials and methods

2.1. GPS data

This study adopted 59 continuous GPS (CGPS) stations (Figure 1) generated from the Crustal Movement Observation Network of China (CMONOC-I and CMONOC-II). Note that all the used time series have at least 10-year duration, with 5 long-term stations spanning the years 2002 to 2021 and 54 short-term stations spanning the years 2010 to 2021. Daily positions were calculated based on GAMIT/GLOBK10.40 software (Herring et al., 2010a, 2010b). The first-order term of the ionosphere is eliminated by a linear combination (LC) observations. The tropospheric mapping function and tropospheric gradients are calculated based on the Global Mapping Function (GMF). The finite element solutions 2004 (FES2004) model was utilised for ocean tide correction and International Earth Rotation and Reference System (IERS) 2010 conventions for the solid Earth tide and polar tide corrections (Pan et al., 2016). The geophysical fluid loading products, developed by the Earth System Modelling group at Deutsches GeoForschungsZentrum (ESMGFZ), are used to remove the non-tidal atmospheric and oceanic loading displacements in the centre-of-figure (CF) frame (Dill & Dobslaw, 2013). In addition, we utilised the extensive TSAnalyzer tool to remove outliers, offsets, and postseismic deformation in the CGPS time series (Wu et al., 2018).

2.2. GRACE and GRACE-follow-on (FO) data

GRACE/GRACE-FO data have played an important role in detecting changes in continental water and mass transport in the Earth system caused by global climate change since 2002 (Tapley et al., 2019). This study utilised CSR GRACE/GRACE-FO RL06 Mascon Solutions (0.25° × 0.25°) from April 2002 to July 2021 to derive the TWS in the YRB. In addition, the vertical hydrological loading displacement caused by mass change is obtained by inverting the spherical harmonic
coefficient of gravity signal. We utilised the spherical harmonic coefficients (SHCs) derived from CSR GRACE/GRACE-FO Level-2 products from April 2002 to July 2021 to calculate elastic loading displacements in the YRB. The C20 coefficients were replaced by satellite laser ranging (SLR) data (Cheng et al., 2013). Note that the degree-1 coefficients of geocenter motion were replaced by the Stokes coefficients derived by Swenson et al. (2008). In order to eliminate the influence of North-South stripes, this study adopted the GRACE/GRACE-FO data for post-processing based on the de-stripping and Gaussian smoothing filters as suggested by Swenson and Wahr (2006). A glacial isostatic adjustment (GIA) based on the ICE6G-D model was applied to SHCs and mascon solutions (Peltier et al., 2015). The vertical loading displacement caused by surface elastic loading variation can be calculated as (Pan et al., 2018):

\[
V = R \sum_{l=1}^{\infty} \sum_{m=0}^{l} \hat{P}_l^m(\cos \lambda) \cdot \left[ \Delta C_{lm} \cos(m\theta) + \tilde{S}_{lm} \sin(m\theta) \right] \frac{h_l}{1 + k_l}
\]

where \( R \) and \( \lambda \) are the mean radius of the Earth and colatitude; \( \hat{P}_l^m(\cos \lambda) \) is the Legendre function of degree \( l \) and order \( m \) has been fully normalized; \( C_{lm} \) and \( S_{lm} \) are the gravity field’s spherical harmonic coefficients; \( h_l \) and \( k_l \) are the adopted load Love numbers provided by Farrell (Farrell, 1972), which are calculated according to the solid Earth’s centre of mass (Blewitt, 2003).

2.3. GLDAS model

Global Land Data Assimilation System (GLDAS) integrates satellite and ground observation data products by generating optimal fields of surface state and fluxes using advanced surface modelling and data assimilation techniques (Rodell et al., 2004). Three GLDAS monthly Land Surface Models (LSMs) V2.1 have a spatial resolution of 1.0° × 1.0° and range from 2002 to 2021: Noah, Catchment, and Variable Infiltration Capacity (VIC). GLDAS inferred shallow surface water storage includes soil moisture, snow depth water equivalent, and plant canopy surface water. Furthermore, the three GLDAS LSMS were averaged.

2.4. Satellite altimetry data

The inversion results of satellite altimetry data from Database for Hydrological Times Series of Inland Waters (DAHITI) were adopted to reflect the water level changes of lakes in the YRB (the locations of the lakes are shown in Figure 1). DAHITI is an online database for inland water level time series derived from satellite altimetry observations that is maintained by the Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM). Furthermore, DAHITI is global time-series water level database of large lakes, reservoirs, and rivers, which is established by combining TOPEX/Poseidon, Jason-1, Jason-2, ERS-2, Envisat, and SARAL/AltiKa radar altimeter data and waveform detection using Kalman filtering (Schwatke et al., 2015). Note that DAHITI
includes 7103 water level time series that are scattered throughout all continents except Antarctica. The download address is https://dahiti.dgf.tum.de/en/.

2.5. Meteorological data

2.5.1. GPCP combined precipitation data

Global Precipitation Climatology Project (GPCP) monthly product integrates several satellite datasets over land and ocean and gauges analysis overland, to offer a consistent study of global precipitation. GPCP monthly rainfall has been estimated on a 2.5-degree worldwide grid based on data from rain gauge stations, satellites, and sounding observations since 1979, which can be downloaded from https://psl.noaa.gov/data/gridded/data.gpcp.html (Adler et al., 2018; Adler et al., 2003). To be consistent with other data coverage dates, we used the combined precipitation data set of GPCP version 2.3 from 2002 to 2021.

2.5.2. CHCN_CAMS gridded 2 m temperature (land) data

CHCN_CAMS is a high resolution (0.5°×0.5°) analysis on global surface temperature from 1948 to now and can be downloaded from https://psl.noaa.gov/data/gridded/data.gchncams.html. CHCN_CAMS combines two big independent station observation datasets from the Global Historical Climatology Network version 2 and the Climate Anomaly Monitoring System (GHNC + CAMS), allowing a large number of stations to be used and updated regularly with some unique interpolation methods (Fan & van den Dool, 2008). CHCN_CAMS monthly data from 2002 to 2021 were taken.

2.5.3. Climate index

The possible ties with the El Niño/Southern Oscillation (ENSO), which was the most well-known indicator of global interannual climate variability, was studied to better understand the climate drivers of hydrological changes in the YRB (Adusumilli et al., 2019). Version 2 of the ENSO index from 2002 to 2021 was adopted Table 1.

2.6. Methods

Since atmospheric and non-tidal oceanic loading has been removed from the GPS coordinate time series, the seasonal oscillation signals in the GPS observations of the Yangtze River basin are most likely from hydrological loading variations (He et al., 2021). This study adopted Empirical Orthogonal Function (EOF) to analyse GPS common-mode signals in the YRB. The EOF analysis, as a Principal Component Analysis (PCA), decomposes the relevant spatial and temporal changes of time variable field into a linear combination of vertical oscillation orthogonal ‘modes’ (Chang & Chao, 2014). Dong et al. introduced the details of EOF algorithm (Dong et al., 2006).

In this study, to interpolate missing data between GRACE and GRACE-FO, we adopt a non-parametric and data-adaptive implementation based on Singular Spectrum Analysis (SSA; Yi & Sneeuw, 2021). The basic principle of SSA is to sample time series into time-lagged segments, extract the correlation information between components, then reconstruct the time series using the temporal correlation information (Schoellhamer, 2001). The method excels in inferring missing data from the long-term and oscillatory waves of existing observations (Kondrashov & Ghil, 2006). In addition, the Fourier spectrum and wavelet time-frequency spectrum were used to evaluate the hydrological oscillation signal in the YRB.

To ensure that CGPS and GRACE/GRACE-FO have the same sampling interval, we convert the daily sampling interval of all the CGPS stations’ vertical coordinate time series to a monthly average sampling interval. Meanwhile, we calculated the vertical elastic loading displacement from the GRACE/GRACE-FO solution according to equation (1), as shown in Figure 6. Then, we calculated the Pearson correlation coefficients between GRACE/GRACE-FO inferred elastic loading displacements and 59 monthly CGPS time series, as shown in Figure 7(a). The WRMS reduction is often utilised to measure the effect of elastic deformation (GRACE signals) on tectonic deformation (GPS signals; Van Dam et al., 2007).

\[ \text{WRMS reduction} = \frac{\text{WRMS}_{\text{GPS}} - \text{WRMS}_{\text{GPS-GRACE}}}{\text{WRMS}_{\text{GPS}}} \]  

where \( \text{WRMS}_{\text{GPS}} \) is the WRMS value of the monthly GPS time series; \( \text{WRMS}_{\text{GPS-GRACE}} \) refers to the WRMS value of the monthly GPS time series minus the GRACE/GRACE-FO inferred elastic loading displacement.

3. Results

3.1. The surface mass balance over the YRB

GRACE/GRACE-FO can detect changes in the gravitational field at the Earth’s surface caused by mass loading redistribution. Changes in terrestrial water storage (TWS), which represent changes in water stored in the soil, snow on land, and groundwater reservoirs, are an essential for the water cycle (Cazenave & Chen, 2010). This study calculated the long-term trend, annual amplitude, and annual phase of TWS from GRACE/GRACE-FO and GLDAS in the YRB and its surroundings, respectively, as shown in Figure 2. GRACE/GRACE-FO and GLDAS TWS changes show sound consistency.
Figures 2(a,b) show that the mass increase distributions are mainly concentrated at the end of the upper reaches, and middle-lower reaches of the YRB (C. Wang et al., 2018); the rising trend in water storage is mainly caused by a large number of lakes in this region and the monsoonal precipitation. In the southwest of the YRB (i.e. the eastern part of the Himalayas), the water storage decreases in the long run, which is related to the glaciers there. The intensity of the long-term trend of TWS for GRACE/GRACE-FO is greater than that of GLDAS, which are possible due to GRACE/GRACE-FO detecting changes in groundwater and surface water components (e.g. rivers and lakes) that GLDAS does not.

Figures 2(c,d) indicate that TWS shows significant changes in the middle-lower reaches of the YRB, which may be due to southeast monsoon precipitation and numerous curved river systems that facilitate water storage (Z. Jiang et al., 2021). In addition, the large annual amplitude of TWS in the eastern Himalayas and Yunnan may be related to glacial changes and the South Asian monsoon (W. Jiang et al., 2017). Furthermore, abundant rivers and dense vegetation in Yunnan help with water retention throughout the yearly season. Meanwhile, we discover that the annual phase of the YRB has geographical distribution differences: the middle-lower reaches of the YRB occur primarily in early summer, may be influenced by the Meiyu rainy season (Zhu et al., 2016); the upper reaches of YRB mainly occur in late summer, possibly impacted by Indian monsoon precipitation (Wei et al., 2014), as shown in Figure 2(e,f).

Figure 3 depicts the monthly time series of the TWS from GRACE/GRACE-FO and GLDAS for middle-lower reaches, upper reaches and the overall in the YRB. The dashed box part in Figure 3 is the GRACE/
GRACE-FO solution interpolated with SSA. By comparing the signal of the same period with the GLDAS solution and the Fourier amplitude spectra before and after interpolation in Figure 4, we find that the TWS after SSA interpolation has recovered the signal characteristics of the missing part. Meanwhile, we discover that the periodic change in the upper reaches of the Yangtze River is more significant and regular than that in the mid-lower reaches. Compared with the upper reaches of the YRB, the mid-lower reaches of the YRB have many oscillatory signals of modest amplitude mixed in with the annual cycle signals. Furthermore, Figure 5 shows the water level changes at 4 locations within the YRB from DAHITI. We noticed abnormal abrupt fluctuations in TWS and lake levels in some years (as shown in grey in Figures 3 and 5), which are associated with abnormal changes in climate.

3.2. The elastic deformation observed by GPS and GRACE/GRACE-FO in YRB

In Figure 7, in the vertical direction of the 59 CGPS stations, the Pearson correlation coefficients of 0 to 0.4, 0.4 to 0.6, and 0.6 or more accounted for 11.9%, 20.3%, 67.8% of the total number, respectively; WRMS reduction rates of 0 to 10.0%, 10.0% to 20.0% and 20% or more accounted for 13.6%, 32.2% and 54.2% of the total number, respectively. The mean values of the Pearson correlation coefficient and WRMS reduction rate for 59 sites in the YRB were 0.6 and 22.0%, respectively. Therefore, the GPS displacements is closely related to the GRACE/GRACE-FO elastic loading displacements in the vertical direction, as shown in Figures 6 and 7, and the significant WRMS reduction rates for the stations indicate high consistency between the GPS and GRACE/GRACE-FO displacements in term of the hydrologic quality impact at these locations. Furthermore, we found that the YRB's

![Figure 3](image-url)  Figure 3. TWS changes in each section of the Yangtze River basin and its overall as inferred by GRACE/GRACE-FO Mascon Solutions and GLDAS, respectively. The dashed box is the part of SSA interpolation. (a) is the TWS changes in the middle-lower of the YRB. (b) is the upper of the YRB. (c) is the whole YRB.

![Figure 4](image-url)  Figure 4. Fourier amplitude spectra of the GRACE/GRACE-FO Mascon Solutions before and after interpolation with SSA.
southwestern sites have greater Pearson correlation coefficients and WRMS reduction rates, which are mostly due to the more significant seasonal TWS mass change shown in Figure 2.

There is a substantial seasonal variation in the GPS vertical time series, which is the response of mass loading changes to climate change. In this study, we use the PCA method to extract the common-mode seasonal terms for long-term and short-term stations of the CGPS in the YRB, respectively, as shown in Figure 8. Before applying PCA, we deleted the long-term trend of each site, but retained the seasonal items. Here, we chose the scaled first PC as the common-mode seasonal

---

**Figure 5.** Lake level change data from DAHITI inversions. The locations of the lakes can be found in Figure 1.

**Figure 6.** Example of comparison between GPS and GRACE/GRACE-FO observations. The blue line represents the daily GPS vertical observations with the trend term removed, the black line represents the corresponding monthly average GPS observations, and the red line represents the monthly average mass loading displacement of GRACE/GRACE-FO after SSA interpolation and removal of the trend term. The shaded part is the part of GRACE/GRACE-FO interpolated with SSA between 2017 and 2018. The locations of the six GPS time series can be found in Figure 1.
term for the YRB due to the only consistent spatial response (Pan et al., 2019). Figure 8 shows that the seasonal variation of hydrological mass loading displacement in the YRB is noticeable, especially during the annual and semi-annual cycles. Simultaneously, we discovered anomalous abrupt shifts in the common-mode seasonal term displacement of GPS during 2010–2012, 2015–2016, and 2020–2021 (shaded part in Figure 8), which is consistent to the findings in Figures 3 and 5, and these abrupt shifts are related to climate change.

In the dense GPS networks, common-mode components (CMC) are connected with interannual signals related to the Earth’s climate response and internal dynamic process (Pan et al., 2019). Therefore, based on the removal of long-term trends in the early stage of this study, we removed the annual and semi-annual signals of the CGPS stations’ vertical time series in the entire YRB, and extracted the CMC based on the PCA approach. We also chose the scaled first PC as the CMC of the YRB due to the only consistent spatial response, as shown in Figures 9 (a,b). In Figure 9(c), the wavelet time-frequency spectrum of the YRB’s CMC shows many interdecadal oscillatory signals, which are mainly connected to the variation of hydrological mass loading in the YRB, which corresponds to the results in Figure 4. Therefore, we processed the first daily PC as a monthly average, as shown in Figure 9(b). As a result, we found significant abrupt changes in amplitude between 2012 and 2014, between 2015 and 2016, and between 2020 and 2021, respectively. This phenomenon can also be seen in the variations of TWS and water level in Figures 3 and 5, mainly related to changes in hydrological mass loading and climate changes. Meanwhile, we found there was no amplitude abrupt changes in the TWS around 2018, which may be due to the interpolation of GRACE/GRACE-FO.

3.3. Long-term and interannual climate changes in the YRB during 2002-2021

In this study, we analysed the changes of precipitation and surface air temperature in the YRB to study the relationship between hydrological mass loading
balance and climate change, as shown in Figure 10. In Figure 10a, we found that the long-term precipitation tended to increase in the second half of the YRB's upper reaches and the YRB's lower reaches, while it was decreasing or even was prone to zero in the first half of the YRB's upper reaches (i.e. high-altitude glaciated areas). Furthermore, precipitation in the southwest of the YRB (i.e. the eastern part of the Himalayas) is decreasing in a long term. These findings are consistent with TWS long-term trend changes for GRACE/GRACE-FO and GLDAS in Figures 2(a,b).

Precipitation directly affects lake volume and glacier mass, whereas temperature affects hydrological mass via evaporation. In Figure 10(b), we found that the temperature tends to increase in a long-term trend in the central part of the upper YRB (i.e. the southwestern part of the YRB). Therefore, the changes in the quality of lakes and glaciers controlled by precipitation and temperature lead to significant seasonal changes in the hydrological quality of the region, which can be seen in Figures 3 and 7.

Furthermore, we used precipitation and temperature changes (i.e. monthly and yearly average) in the YRB to check the reaction of hydrological mass changes in the YRB to global extreme climate events (i.e. El Niño and La Niña), as shown in Figures 11 and 12. We discovered that the average annual precipitation and temperature in the YRB's upper reaches are lower than those in the middle-lower reaches, which is directly related to altitude. Around 2008, the low temperature of the whole YRB (the most obvious in the upstream area) and the increase of rainfall (i.e. La Niña extreme weather phenomenon) led to a significant increase in the displacement of hydrological loading in YRB (see, Figure 3). During 2013–2014, the average annual temperature in the YRB began to rise, leading to the melting of glacier in the upper parts and the increase of the lakes across the region, which leads to the improvement in the YRB's hydrological mass (consistent with the change of TWS in Figure 3, the change of water level in Figure 5, and the change of CMC in Figure 9). Although the annual average precipitation in 2018 was low, there were several months with higher than usual rainfall near the end of the year, which could have contributed to the abrupt changes in amplitude of the CMC in Figure 9(b). From Figures 11 and 12, it can be seen that around 2019, the decrease in rainfall and the increase in temperature, especially in the middle-lower reaches of the YRB, caused the drought, which is consistent with the changes in Figures 3, 5, 8, and 9(b). However, in 2020, a surge in precipitation creates a sudden rise in the YRB's hydrological mass, resulting in floods (Xue et al., 2022), which corresponds to transient changes in the prior TWS, water level, and CMC. In addition, we observe that during El Niño years, or transition years between El Niño and La Niña (e.g. 2010, 2016, and 2020), the average precipitation is abnormally high, resulting in the sudden increase in lake water volume, and abrupt changes in hydrological mass loading displacement in the YRB (see, Figures 3, 5, 8, and 9).

The elastic loads inferred by GPS and GRACE/GRACE-FO are highly connected with climate change, especially during periods of excessive precipitation, according to the results of the above analysis. We discover that the annual average temperature of the YRB has been relatively high since 2013, particularly in the middle-lower...
Figure 9. The spatial pattern of scaled principal components (PCs) in the YRB. The arrows represent the positive response to the scaled PC. (a) is the vertical component’s normalised spatial eigenvector from PC1. (b) Time series of PC1 after scaling. (c) Spectrum analysis of PC1.
High temperatures will lead to changes in glacier mass at high altitudes, and the total amount of water in the lake, which affect changes in hydrological loading near the surface. The climatic component (MEI) also represents the interannual variation of extreme weather over the last 20 years, as seen in Figure 11(d). We observe that La Niña occurs more frequently and with greater intensity than El Niño. The temperature in the YRB is often lower during La Niña occurs than during El Niño, and precipitation in the YRB is substantially more significant when El Niño changes to La Niña, as shown in Figures 11 and 12. Therefore, extreme weather changes are one of the main factors leading to abnormal changes of terrestrial water in YRB.

4. Discussion

From west to east, the YRB has diverse topographies and climates and the response of hydrological mass changes to climate variation differs from one region to another (Cao et al., 2011). Accelerated global warming will result in an imbalance in the mass of glaciers in the high-altitude mountains in the upper reaches of YRB and affect the changes in water storage across the basin (Pepin et al., 2015; Wang et al., 2017). The YRB can easily form a monsoon climate due to the thermal differential between land and sea. The East Asian monsoon influences the middle-lower reaches of the YRB, while the Indian monsoon affects the upper reaches (Q. Zhang et al., 2007). The monsoon transports vast amounts of water vapour from the Pacific and Indian Oceans to the mainland, resulting in large volumes of rain and snow, which further improves the capacity of rivers in the basin, and alters the hydrological mass (Wang & Chen, 2012). We can better detect the dynamic process of TWS changes in the YRB based on contemporary geodetic technologies (Chen et al., 2017). In terms of long-term trends, annual amplitudes, and annual phases, the fluctuation of TWS derived from GRACE/GRACE-FO and GLDAS models shows the temporal and spatial changes of hydrological mass in the YRB, as shown in Figure 2.
In addition, as shown in Figure 10, the YRB tends to have the long-term temperature increase, particularly in the middle part of the upper YRB (i.e. high altitude areas), which will inevitably accelerate glacier melting and affect the YRB’s hydrological mass balance (Wang et al., 2021). Furthermore, the YRB experiences growing rainfall, and accordingly the volume of lakes and the capacity of groundwater reservoirs throughout the basin increase. As a result, TWS changes (T. Jiang et al., 2008; Su et al., 2008).

As demonstrated in Figures 3, 5, 8, and 9, extreme climate change would result in abrupt abnormal changes in elastic displacements of hydrological loading inferred by modern geodetic means (He et al., 2021; Sun et al., 2017; Z. Zhang et al., 2015). This is proved by the large-
scale drought and flood in YRB in 2019 and 2020 respectively (L. Wang et al., 2021; Yan et al., 2021). Moreover, there are strongly seasonal and interannual signs of water storage changes in the YRB. Therefore, analysing changes in the features of these signals can help us understand the YRB’s dynamic hydrological processes and climate change (Medina et al., 2008; Song et al., 2013). We discovered that the hydrological fluctuations in the CMC signal in GPS coordinates are substantially connected with ENSO occurrences and climate variables such as temperature and precipitation (W. Zhang et al., 2016; Q. Zhang et al., 2007; see, Figure 9). However, it is essential to realise that the GPS coordinate time series contains numerous other sources that may influence our results and analysis (Van Dam et al., 2007). These sources may include systematic mistakes in data processing, incorrect modelling, model residuals from non-tidal atmospheric and oceanic effects, unmodeled inelastic processes, and other non-geophysical signals.

5. Conclusions

Complex change processes in hydrological mass of the YRB respond to global climate variation. In this study, we used GPS observations and GRACE/GRACE-FO data in combination of GLDAS model outputs and Satellite Altimetry data to assess hydrologic loading changes and interannual hydrologic oscillation changes in the YRB from 2002 to 2021. In the long term, the TWS in the YRB shows a different spatial distribution in each section of the YRB. Due to the abundance of lakes in these areas and the influence of monsoon climate, the end of the upper reaches, and middle-lower reaches of the YRB show an increasing quality trend. We found that the correlation between GPS and GRACE/GEACE-FO inferred hydrological elastic displacements presents well in the YRB, especially in the southwestern part of the YRB. The interdecadal oscillatory signals associated with hydrological mass changes may be highly related to climate changes. By evaluating the regional distribution and interannual oscillation of the long-term trend of precipitation and surface temperature in YRB, it is found that the change of hydrological loading in YRB is basically consistent with climate change. In addition, the seasonal and interannual fluctuations of YRB water storage and the inferred elastic displacement are mainly related to climate changes such as ENSO events.

Acknowledgments

We are grateful to National Key Scientific Projects “Tectonic and Environmental Observation Network of Mainland China” (CMONOC I and II) for providing the GPS data. We appreciate the International GNSS Service (IGS) for providing global GPS data products, and Massachusetts Institute of Technology (MIT) for providing the GAMIT/GLOBK software.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was funded by National Natural Science Foundation of China (grant number: 42064002), and Guangxi Science and Technology Plan Project (grant number: 2019110107).

Author contributions

Conceptualization, D.R. and L.L.; methodology, D.R. and L.L.; data analyses and field investigation, D.R. and L.L.; formal analysis, D.R.; investigation, D.R., L.L. and L.H.; writing—original draft preparation, D.R.; writing—review and editing, D.R., L.L. and L.H.; visualization, D.R., L.L. and L.Z.; supervision, L.L., L.H. and L.Z.; project administration, LL. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The geophysical fluid loading products can be downloaded from http://rz-vm115.gfz-potsdam.de:8080/repository The URLs of the other data used in this paper can be found in Table 1.

ORCID

Ding Ren http://orcid.org/0000-0002-5924-0987

References

Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, -P.-P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J., Arkin, P., & Nelkin, E. (2003). The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). Journal of Hydrometeorology, 4(6), 1147–1167. https://doi.org/10.1175/1525-7541(2003)004<1147:TVGCP>2.0.CO;2

Adler, R. F., Sapiano, M. R. P., Huffman, G. J., Wang, -J.-J., Gu, G., Bolvin, D., Chiu, L., Schneider, U., Becker, A., Nelkin, E., Xie, P., Ferraro, R., & Shin, D.-B. (2018). The Global Precipitation Climatology Project (GPCP) monthly analysis (new version 2.3) and a review of 2017 global precipitation. Atmosphere, 9 (138), 138. https://doi.org/10.3390/atmos9040138

Adusumilli, S., Borsa, A. A., Fish, M. A., McMillan, H. K., & Silveri, F. (2019). A decade of water storage changes across the contiguous United States from GPS and satellite gravity. Geophysical Research Letters, 46(22), 13006–13015. https://doi.org/10.1029/2019GL085370

Blewitt, G. (2003). Self-consistency in reference frames, geocenter definition, and surface loading of the solid earth. Journal of Geophysical Research: Solid Earth, 108(B2), 2103. https://doi.org/10.1029/2002JB002082

Cao, L., Zhang, Y., & Shi, Y. (2011). Climate change effect on hydrological processes over the Yangtze river basin. Quaternary International, 244(2), 202–210. https://doi.org/10.1016/j.quaint.2011.01.004
Cazenave, A., & Chen, J. (2010). Time-variable gravity from space and present-day mass redistribution in the earth system. Earth and Planetary Science Letters, 298(3–4), 263–274. https://doi.org/10.1016/j.epsl.2010.07.035

Chang, E. Y., & Chao, B. F. (2014). Analysis of coseismic deformation using EOIF method on dense, continuous GPS data in Taiwan. Tectonophysics, 637, 106–115. https://doi.org/10.1016/j.tecto.2014.09.011

Chen, X., Long, D., Hong, Y., Zeng, C., & Yan, D. (2017). Improved modeling of snow and glacier melting by a progressive two-stage calibration strategy with GRACE and multisource data: How snow and glacier meltwater contribute to the runoff of the upper Brahmaputra river basin? Water Resources Research, 53(3), 2431–2466. https://doi.org/10.1002/2016WR019656

Cheng, M., Tapley, B. D., & Ries, J. C. (2013). Deceleration in the Earth’s oblateness. Journal of Geophysical Research: Solid Earth, 118(2), 740–747. https://doi.org/10.1002/jgrb.50058

Dill, R., & Dobslaw, H. (2013). Numerical simulations of global-scale high-resolution hydrological crustal deformations. Journal of Geophysical Research: Solid Earth, 118(9), 5008–5017. https://doi.org/10.1002/jgrb.50353

Dong, D., Fang, P., Bock, Y., Webb, F., Prawiroirdijono, L., Kedar, S., & Jamason, P. (2006). Spatiotemporal filtering using principal component analysis and karhunen-loeve expansion approaches for regional GPS network analysis. Journal of Geophysical Research: Solid Earth, 111(B3), 405. https://doi.org/10.1029/2005JB003806

Du, Y., Xue, H., Wu, S., Ling, F., Xiao, F., & Wei, X. (2011). Lake area changes in the middle Yangtze region of China over the 20th century. Journal of Environmental Management, 92(4), 1248–1255. https://doi.org/10.1016/j.jenvman.2010.12.007

Fan, Y., & van den Dool, H. (2008). A global monthly land surface air temperature analysis for 1948–present. Journal of Geophysical Research, 113(D1), 103. https://doi.org/10.1029/2007JD008470

Fang, J., He, M., Luan, W., & Jiao, J. (2021). Crustal vertical deformation of amazon basin derived from GPS and GRACE/GFO data over past two decades. Geodesy and Geodynamics, 12(6), 441–450. https://doi.org/10.1016/j.geog.2021.09.002

Farrell, W. E. (1972). Deformation of the Earth by surface loads. Reviews of Geophysics, 10(3), 761–797. https://doi.org/10.1029/RG010i003p00761

He, M., Shen, W., Jiao, J., & Pan, Y. (2021). The Interannual Fluctuations in Mass Changes and Hydrological Elasticity on the Tibetan Plateau from Geodetic Measurements. Remote Sensing, 13(21), 4277. https://doi.org/10.3390/rs13214277

Herring, T., King, R., & McClusky, S. (2010a). GAMIT/GLOBK reference manuals, release 10.4. Massachusetts Institute of Technology Cambridge MA USA. http://geoweb.mit.edu/gg/docs.php.

Herring, T., King, R., & McClusky, S. (2010b). GLOBK Reference Manual. Global Kalman Filter VLBI and GPS analysis program. release 10.4. Massachusetts Institute of Technology Cambridge MA USA. http://geoweb.mit.edu/gg/docs.php.

Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. Science, 328(5984), 1382–1385. https://doi.org/10.1126/science.1183188

Jiang, T., Kundzewicz, Z. W., & Su, B. (2008). Changes in monthly precipitation and flood hazard in the Yangtze river basin, China. International Journal of Climatology, 28 (11), 1471–1481. https://doi.org/10.1002/joc.1635

Jiang, W., Yuan, P., Chen, H., Cai, J., Li, Z., Chao, N., & Sneeuw, N. (2017). Annual variations of monsoon and drought detected by GPS: A case study in Yunnan, China. Scientific Reports, 7(1), 5874. https://doi.org/10.1038/s41598-017-06995-1

Jiang, Z., Hsu, Y.-J., Yuan, L., Cheng, S., Li, Q., & Li, M. (2021). Estimation of daily hydrological mass changes using continuous GNSS measurements in Mainland China. Journal of Hydrology, 598, 126349. https://doi.org/10.1016/j.jhydrol.2021.126349

Kang, S., Xu, Y., You, Q., Flügel, W.-A., Pepin, N., & Yao, T. (2010). Review of climate and cryospheric change in the Tibetan plateau. Environmental Research Letters, 5(1), 015101. https://doi.org/10.1088/1748-9326/5/1/015101

Kondrashov, D., & Ghil, M. (2006). Spatio-temporal filling of missing points in geophysical data sets. Nonlinear Processes in Geophysics, 13(2), 151–159. https://doi.org/10.5194/npg-13-151-2006

Medina, C. E., Gomez-Enri, J., Alonso, J. J., & Villares, P. (2008). Water level fluctuations derived from ENVISAT radar altimeter (RA-2) and in-situ measurements in a subtropical waterbody: Lake Izabal (Guatemala). Remote Sensing of Environment, 112(9), 3604–3617. https://doi.org/10.1016/j.rse.2008.05.001

Pan, Y., Shen, W.-B., Hwang, C., Liao, C., Zhang, T., & Zhang, G. (2016). Seasonal mass changes and crustal vertical deformations constrained by GPS and GRACE in Northeastern Tibet. Sensors, 16(8), 1211. https://doi.org/10.3390/s16081211

Pan, Y., Shen, W.-B., Shum, C. K., & Chen, R. (2018). Spatially varying surface seasonal oscillations and 3-D crustal deformation of the Tibetan plateau derived from GPS and GRACE data. Earth and Planetary Science Letters, 502, 12–22. https://doi.org/10.1016/j.epsl.2018.08.037

Pan, Y., Chen, R., Ding, H., Xu, X., Zheng, G., Shen, W., Xiao, Y., & Li, S. (2019). Common mode component and its potential effect on GPS-inferred three-dimensional crustal deformations in the Eastern Tibetan Plateau. Remote Sensing, 11 (17), 1975. https://doi.org/10.3390/rs11171975

Peltier, W. R., Argus, D. F., & Drummond, R. (2015). Space geodesy constrains ice age terminal deglaciation: the global ICE-6G_C (VM5a) model. Journal of Geophysical Research: Solid Earth, 120(1), 450–487. https://doi.org/10.1002/2014JB011176

Mountain Research Initiative Edw Working GroupPepin, N., Bradley, R. S., Diaz, H. F., Baraer, M., Caceres, E. B., Forbesythe, N., Fowler, H., Greenwood, G., Hashmi, M. Z., Liu, X.D., Miller, J.R., Ning, L., Ohmura, A., Palazzi, E., Rangwala, I., Schörner, W., Severskiy, I., Shahgedanova, M., Wang, M.B., Williamson, S.N., and Yang, D.Q. (2015). Elevation-dependent warming in mountain regions of the world. Nature Climate Change, 5, 424–430. https://doi.org/10.1038/nclimate2563

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D., & Toll, D. (2004). The global land data assimilation system. Bulletin of the American Meteorological Society, 85(3), 381–394. https://doi.org/10.1175/BAMS-85-3-381

Saji, A.P., Sunil, P.S., Sreeljith, K. M., Gautam, P. K., Kumar, K. V., Ponraj, M., Amirtharaj, S., Shaju, R. M., Begum, S. K., Reddy, C. D., & Ramesh, D. S. (2020). Surface deformation and influence of hydrological mass over Himalaya and North India revealed from a decade of continuous GPS
and GRACE observations. *Journal of Geophysical Research: Earth Surface*, 125(1), e2018JF004943. https://doi.org/10.1029/2018JF004943

Schoellhamer, D. H. (2001). Singular spectrum analysis for time series with missing data. *Geophysical Research Letters*, 28(16), 3187–3190. https://doi.org/10.1029/2000GL012698

Schwatke, C., Detto, M., Bosch, W., & Seitz, F. (2015). DAHITI – An innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrology and Earth System Sciences*, 19(10), 4345–4364. https://doi.org/10.5194/hess-19-4345-2015

Song, C., Huang, B., & Ke, L. (2013). Modeling and analysis of lake water storage changes on the Tibetan Plateau using multi-mission satellite data. *Remote Sensing of Environment*, 135, 25–35. https://doi.org/10.1016/j.rse.2013.03.013

Su, B., Gemmer, M., & Jiang, T. (2008). Spatial and temporal variation of extreme precipitation over the Yangtze river basin. *Quaternary International*, 186(1), 22–31. https://doi.org/10.1016/j.quaint.2007.09.001

Sun, Z., Zhu, X., Pan, Y., & Zhang, J. (2017). Assessing terrestrial water storage and flood potential using GRACE data in the Yangtze river basin, China. *Remote Sensing*, 9(10), 1011. https://doi.org/10.3390/rs9101011

Swenson, S., & Wahr, J. (2006). Post-processing removal of correlated errors in GRACE data. *Geophysical Research Letters*, 33(8), L08402. https://doi.org/10.1029/2005GL025285

Swenson, S., Chambers, D., & Wahr, J. (2008). Estimating geocenter variations from a combination of GRACE and ocean model output. *Journal of Geophysical Research: Solid Earth*, 113(B8)410. https://doi.org/10.1029/2007JB005338

Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., Sasaki, I., Famiglietti, J. S., Landerer, F. W., Chambers, D. P., Reager, J. T., Gardner, A. S., Save, H., Ivins, E. R., Swenson, S. C., Boening, C., Dahle, C., Wiese, D. N., Dobslaw, H., Velicogna, I. (2019). Contributions of GRACE to understanding climate change. *Nature Climate Change*, 9(5), 358–369. https://doi.org/10.1038/s41558-019-0456-2

van Dam, T., Wahr, J., & Lavallée, D. (2007). A comparison of annual vertical crustal displacements from GPS and gravity recovery and climate experiment (GRACE) over Europe. *Journal of Geophysical Research*, 112(B3), 404. https://doi.org/10.1029/2006JB004335

Wang, H., & Chen, H. (2012). Climate control for southeastern China moisture and precipitation: Indian or East Asian monsoon? *Journal of Geophysical Research Atmospheres*, 117(D12), 109. https://doi.org/10.1029/2012JD017734

Wang, W., Xing, W., Yang, T., Shao, Q., Peng, S., Yu, Z., & Yong, B. (2013). Characterizing the changing behaviours of precipitation concentration in the Yangtze river basin, China. *Hydrological Processes*, 27(24), 3375–3393. https://doi.org/10.1002/hyp.9430

Wang, Q., Yi, S., Chang, L., & Sun, W. (2017). Large-scale seasonal changes in glacier thickness across high mountain Asia. *Geophysical Research Letters*, 44(10), 427–10,435. https://doi.org/10.1002/2017GL075300

Wang, C., Jia, M., Chen, N., & Wang, W. (2018). Long-term surface water dynamics analysis based on Landsat imagery and the google earth engine platform: A Case study in the Middle Yangtze river basin. *Remote Sensing*, 10(10), 1635. https://doi.org/10.3390/rs10101635

Wang, L., Peng, Z., Ma, X., Zheng, Y., & Chen, C. (2021). Multiscale gravity measurements to characterize 2020 flood events and their spatio-temporal evolution in Yangtze river of China. *Journal of Hydrology*, 603(10), 127176. https://doi.org/10.1016/j.jhydrol.2021.127176

Wang, Q., Yi, S., & Sun, W. (2021). Continuous estimates of glacier mass balance in high mountain Asia based on ICESat-1,2 and GRACE/GRACE follow-on data. *Geophysical Research Letters*, 48(11), e2020GL090954. https://doi.org/10.1029/2020GL090954

Wei, W., Chang, Y., & Dai, Z. (2014). Streamflow changes of the Changjiang (Yangtze) river in the recent 60 years: impacts of the East Asian summer monsoon, ENSO, and human activities. *Quaternary International*, 336, 98–107. https://doi.org/10.1016/j.quaint.2013.10.064

Wu, D., Yan, H., & Yuan, S. (2018). L1 regularization for detecting offsets and trend change points in GNSS time series. *GPS Solutions*, 22(3), 1–5. https://doi.org/10.1007/s10291-018-0756-4

Xue, F., Gao, W., Yin, C., Chen, X., Xia, Z., Lv, Y., Zhou, Y., & Wang, M. (2022). Flood monitoring by integrating normalized difference flood index and probability distribution of water bodies. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 15, 4170–4179. https://doi.org/10.1109/JSTARS.2022.3176388

Yang, X., Zhang, B., Yao, Y., Yang, Y., Li, J., & Ran, Q. (2021). GRACE and land surface models reveal severe drought in eastern china in 2019. *Journal of Hydrology*, 601, 126640. https://doi.org/10.1016/j.jhydrol.2021.126640

Yi, S., & Sneeuw, N. (2021). Filling the data gaps within GRACE missions using singular spectrum analysis. *Journal of Geophysical Research: Solid Earth*, 126(5), e2020JB021227. https://doi.org/10.1029/2020JB021227

Zhang, Q., Xu, C., Jiang, T., & Wu, Y. (2007). Possible influence of ENSO on annual maximum streamflow of the Yangtze river, China. *Journal of Hydrology*, 333(2–4), 265–274. https://doi.org/10.1016/j.jhydrol.2006.08.010

Zhang, Z., Chao, B. F., Chen, J., & Wilson, C. R. (2015). Terrestrial water storage anomalies of Yangtze River basin droughts observed by GRACE and connections with ENSO. *Global and Planetary Change*, 126, 35–45. https://doi.org/10.1016/j.gloplacha.2015.01.002

Zhang, W., Jin, -F.-F., Stuecker, M. F., Wittenberg, A. T., Timmermann, A., Ren, H.-L., Kug, J.-S., Cai, W., & Cane, M. (2016). Unraveling El Niño’s impact on the East Asian monsoon and Yangtze river summer flooding. *Geophysical Research Letters*, 43(11), 375–11,382. https://doi.org/10.1002/2016GL071190

Zhu, J., Huang, D., & Yang, T. (2016). Changes of Meiyu system in the future under A1B scenario simulated by MIROC_hires model. *Theoretical and Applied Climatology*, 123(3–4), 461–471. https://doi.org/10.1007/s00704-015-1371-8