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ORIGINAL PAPER

MONITORING TERRESTRIAL WATER STORAGE CHANGES AND DROUGHT IN JIANGXI PROVINCE USING GRACE AND GRACE FOLLOW-ON-DATA

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ABSTRACT

Drought incidents often occur which have the non-negligible impact on human living and social economic development. In recent years, Jiangxi Province suffered from some drought disasters especially the Poyang Lake drought bottoming incident in year 2021. Thus, choosing the Jiangxi Province for studying area and April 2002 to December 2022 as studying period and using the Water Storage Deficit Index (WSDI) derived from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-on data to analyze and identify the drought incidents during the study period. Fourteen drought incidents occurred in the study period and the longest drought incident was in 2003-2004, which lasted eight months whose total water deficit is 100.68 km^3. Especially, to deeply analyze the Poyang Lake bottoming drought event, the period from April 2022 to December 2022 is selected as the research interval. It demonstrates that the drought began in August 2022 from the northeastern region spread southwest and expanded to the entire area in October 2022 and November 2022, and then retreated to the northwestern region and drought severity of the Poyang Lake is in peak in November 2022 which led to the lake bottoming and severity of drought reaches the peak in whole province. To comprehensively verify accuracy of the WSDI, the self-calibrating palmer drought severity index (scPDSI) and Standardized Precipitation Evapotranspiration Index (SPEI) are adopted for comparison, the relation between precipitation and TWSA (Terrestrial Water Storage Anomaly) shows apparent periodicity and the correlation coefficient between them is 0.59, which indicates that precipitation is a vital factor affecting TWSA of the Jiangxi Province.

1. 1 INTRODUCTION

Due to the global warming, the extreme climatic events become more and more frequent. Such as flood and drought and so on, which have a great impact on the global water cycle and regional hydrological process (Harder et al., 2015; Ummenhofer and Meehl, 2017; Yang et al., 2021). Greenhouse gases and population growth are important factors in the drought in southern China, and the areas prone to drought will gradually increase (Yuan et al., 2019). Especially, the burning of fossil fuels and human use of land cover which can produce greenhouse gases and seriously affect precipitation (Huang et al., 2013). Jiangxi Province locates in Southeast China and the largest freshwater lake in China is located in the province (Guo et al., 2008; Huang et al., 2013). Poyang Lake is located in Jiangxi Province, Zhou et al. (2018) used multi-source data to identify flood events between 2003 and 2016 and effectively explain the mechanisms by which they occurred and which can effectively play an important role in local economy, humanity life (Zhou et al., 2018). From 2008 to 2017, there are two extreme floods and several drought events in Jiangxi Province (Dai et al., 2021) which plays an important role in agriculture and animal husbandry. Therefore, analyzing the occurring factors of flood and drought contribute to the local economy and future development and provides the scientific basis for disaster prevention.

The ways of monitoring drought and floods in tradition are mainly precipitation and evapotranspiration, but it has limitations in near-surface or groundwater zones (Creutzfeldt et al., 2012). The development of Remote sensing provides a new method to monitor the global or regional drought situation which can achieve unprecedented spatial and temporal resolution and precision (Thomas et al., 2014). For example, adopting the MODIS product to effectively monitor rice drought situation in Jiangxi Province from 2000 to 2008 (Xiu-Ping et al., 2011). Since the GRACE (Gravity Recovery and Climate Experiment) was launched in April 2022, it can provide a large scale hydrology monitoring and from the GRACE data can achieve the monthly

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Terrestrial Water Storage Changes (TWSC), which includes the surface stream, soil moisture and groundwater, through it can derive the Equivalent Water Height (EWH) in centimeter level accuracy (Wahr et al., 2004). The GRACE data have been applicated in many fields, such as freshwater discharge (Wang, 2019), regional flood potential (Sun et al., 2017), drought monitoring (Cao et al., 2015; Wang et al., 2021), and terrestrial water storage change (Chen et al., 2016).

Events such as droughts and floods can often be quantified using the drought index and nowadays the drought index become more and more diversified which are based on different environmental conditions (Byun and Wilhite, 1999; Deo et al., 2017; Pandey et al., 2008). A great number of the hydro-meteorological drought indices can be achieved from different labs (Meresa et al., 2016; Zargar et al., 2011), which mainly includes the standardized streamflow index (Shukla and Wood, 2008), the standardized precipitation and evapotranspiration index (Beguería et al., 2010), the palmer drought severity index and self-calibrating palmer drought severity index (van der Schrier et al., 2013; Palmer, 1965). The common drought indices only take several hydrometeorological elements into account, which hardly explain the actual reasons and conditions of droughts and floods (Nigatu et al., 2021; Yi and Wen, 2016). Drought indices including hydrometeorological variables and methods for calculating drought indices are different which will lead the difference in monitoring period of droughts and floods (Cao et al., 2015). Besides, the hydrometeorological variables of the indices can be obtained from the field survey and hydrological model, which is limited by environmental factors and sparse stations. So much so that, in sparse stations areas, the spatial characteristics of runoff variation are rarely studied (Creutzfeldt et al., 2012; Sun et al., 2017). Since, the launching of GRACE, the situation is improved which compensates the shortcomings in traditional hydro-meteorological drought indices and the drought indices of deriving from the GRACE have been adopted in many scientific research about droughts and floods (Cao et al., 2015; Sun et al., 2017; Thomas et al., 2014; Yi and Wen, 2016). Such as, the total storage deficit index (TSDI) and the hydrological drought index (GHDI) which have been adopted for drought monitoring in arid Northwestern China and the continental United States (Cao et al., 2015; Yi and Wen, 2016). In this study, we adopt the water storage deficit index (WSDI) for evaluating the occurring periods of droughts and floods (Thomas et al., 2014) and the WSDI has the dimensionless and seasonless properties that will be further adopted for many research. Such as, the WSDI is used in the Nile River Basin for evaluating major floods and droughts (Nigatu et al., 2021).

Based on above researches, some factors working together on TWS changes. Therefore, in this paper, we will further study extreme drought events in Jiangxi Province and its features from GRACE-derived WSDI. The structure is as follows. Section 2 introduces study region and datasets, section 3 describes the investigated methods and section 4 explores the reliability of WSDI and the features of the extreme drought event in Jiangxi Province. Section 5 demonstrates the conclusions.

2. DATASETS AND STUDY REGIONS

2.1. DATASETS

2.1.1. GRACE DATA

The GRACE and GRACE Follow-on (GRACE-FO) Mascon RL06 version products which are released by three research centers including the Center for Space Research at University of Texas (CSR), NASA Jet Propulsion Laboratory (JPL) and Goddard Space Flight Center (GSFC). The CSR Mascon data is in 0.25° spatial resolution and the GSFC, JPL Mascon data which are in 0.5° spatial resolution. The Mascon data don't require further processing and provide high resolution with almost no striping error (Sun et al., 2018). These Mascon data all added back the degree-one term according to the Technical Note 13 (Landerer, 2019) and the C_{20} coefficients were also replaced (Loomis et al., 2020). The glacial isostatic adjustment (GIA) effects are also adjusted based on the ICE6G_D model (Peltier et al., 2018). The studying period of the data is from April 2002 to December 2022.

2.1.2. HYDROLOGY DATA

The hydrological model adopted in this study is the GLDAS Noah model which is in 0.25° spatial resolution and can be obtained from the website (https://daac.gsfc.nasa.gov/datasets?keywords=Noah. The system uses surface observations and satellite remote sensing observations to drive CLM, MOSAIC, NOAH, VIC and CLSM land surface models, and generates global surface state variables (soil moisture and surface temperature) and flux (evaporation and sensible heat flux) data through model simulation and data assimilation. Time spanning of GLDAS Noah data is from April 2002 to December 2022. The precipitation data which we adopted are Global Precipitation Measurement (GPM) products. GPM is an international satellite mission launched by NASA and the Japan Aerospace Exploration Agency (JAXA) which is next generation of high-quality Global Rain and Snow Satellite observation network after TRMM. The data can be downloaded from the official website (https://gpm.nasa.gov/data/directory), whose spatial resolution is 0.25° after resampling and the temporal resolution is one month. The studying period of the product is same as the above data in this section.

2.1.3. SCPDSI DATA

The scPDSI is a variant on the original PDSI of Palmer (1965), with the aim to make results from different climate regimes more comparable. As with the PDSI, the scPDSI is calculated from time series of

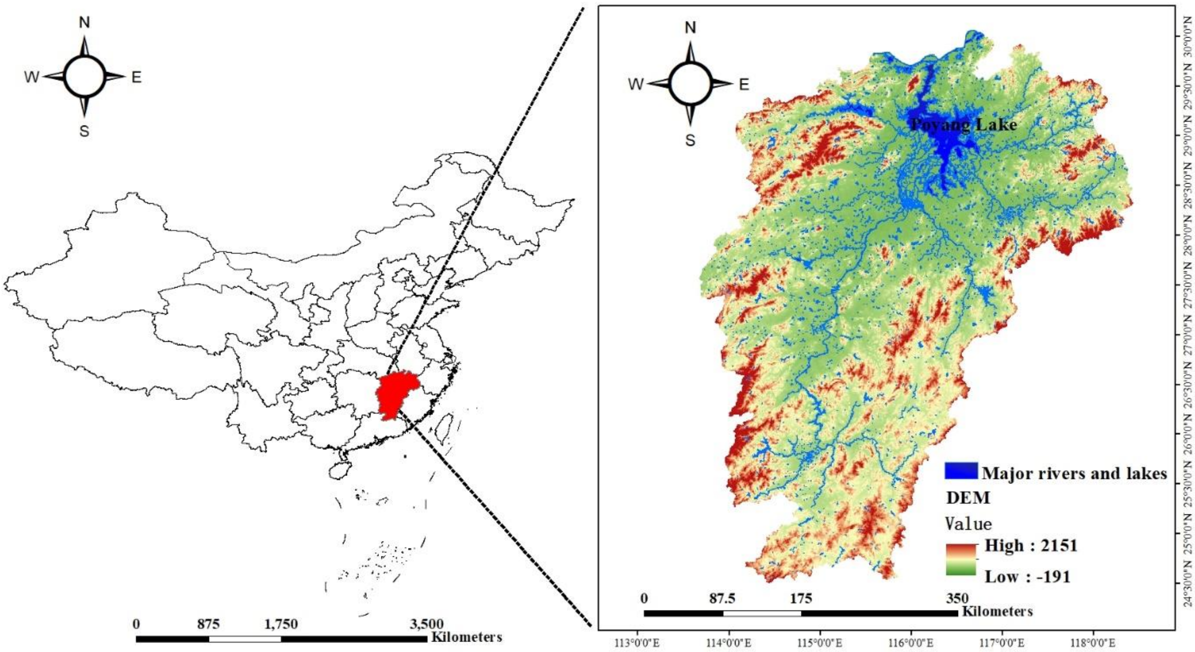


Fig. 1 The location and lakes, rivers of the Jiangxi Province.

precipitation and temperature, together with fixed parameters related to the soil/surface characteristics at each location. In this study, the scPDSI which is in 0.5° and one month spatial-temporal resolution, whose available period is from January 2002 to December 2021.

2.2. STUDY REGIONS

Jiangxi Province is located in the southeast of China, on the south bank of the middle and lower reaches of the Yangtze River, between latitudes 24°29'14" to 30°04'43" north and longitudes 113°34'18" to 118°28'56" east, adjacent to Zhejiang Province and Fujian Province in the east, Guangdong Province in the south, Hunan Province in the west, and Hubei and Anhui Province in the north beside the Yangtze River. Ganjiang River, Fuhe River and Xinjiang River are the major rivers of the province. Poyang Lake is the largest fresh water lake in China. Ganjiang River, Fuhe River, Xinjiang River, Raohe River and Xiuhe River play an important role in the water resources balance of Poyang Lake. In addition, the Yangtze River also plays an indispensable role in the water resources balance of Poyang Lake (Hu et al., 2007). Figure 1 shows the location and rivers, lakes distribution of Jiangxi Province.

3. METHODOLOGY

The residual TWSA after deducting the mean value of each month of TWSA of all research period is used to estimate the water storage deficit (WSD), which is calculated as follows (Thomas et al., 2014),

$$WSD_{i,j} = TWSA_{i,j} - \overline{TWSA_j} \quad (1)$$

where, $TWSA_{i,j}$ represent the terrestrial water storage anomaly in jth month of the ith year, and $\overline{TWSA_j}$ represent the mean value of the TWSA time series in jth month of all research period. The WSD of negative and positive respectively denote different hydrological incident, when WSD of negative and positive last more than three months which can be identified as a drought or flood incident.

$$S(t) = \overline{M(t)} \times D(t) \quad (2)$$

where, $S(t)$ denotes total severity of drought/flood period t and $\overline{M(t)}$, $D(t)$ respectively denotes the mean WSD values and duration for a drought/flood period.

The WSDI can be derived from WSD using a zero-mean normalization method, aiming to better compare with other drought indices (Sinha et al., 2017; Thomas et al., 2014),

$$WSDI_{i,j} = \frac{WSD_{i,j} - \mu}{\sigma} \quad (3)$$

where μ and σ represent the mean and the standardized deviation of the WSD time series. Table 1 displays drought and flood grades of the WSDI.

4. RESULTS AND ANALYSIS

The Mascon data is compared with other GRACE data which has less leakage error in inversion of regional water storage. Considering the long-term data gap between GRACE and GRACE follow-on products and the time range of available data provided by global models, we finally choose April 2002 to December 2022 period for the following research. Because the Mascon data from different labs which

Table 1 Drought and Flood levels based on WSDI.

Values	Categories	Values	Categories
<-2	Extreme drought	>2	Extreme flood
[-2, -1.5]	Severe drought	[1.5, 2]	Severe flood
[-1.5, -1]	Moderate drought	[1, 1.5]	Moderate flood
[-1, 0]	Light drought	[0, 1]	Light flood

Table 2 Summary of features of fourteen drought incidents.

Time period	Duration (months)	Peak value (km^3)	Total Severity (km^3)
2003.09-2004.04	8	-20.56	-100.68
2004.10-2005.03	6	-14.58	-46.97
2005.10-2006.02	5	-10.90	-36.37
2006.11-2007.03	5	-9.99	-32.04
2007.10-2008.03	6	-12.11	-47.46
2008.12-2009.03	4	-11.89	-27.77
2009.10-2010.01	4	-7.96	-23.69
2010.11-2011.04	6	-4.89	-13.93
2011.09-2012.01	5	-6.31	-18.33
2013.10-2014.01	4	-9.40	-29.47
2019.10-2020.01	4	-14.53	-36.68
2020.11-2021.03	5	-10.77	-18.59
2021.10-2022.01	4	-12.39	-25.43
2022.08-2022.12	5	-18.55	-42.32

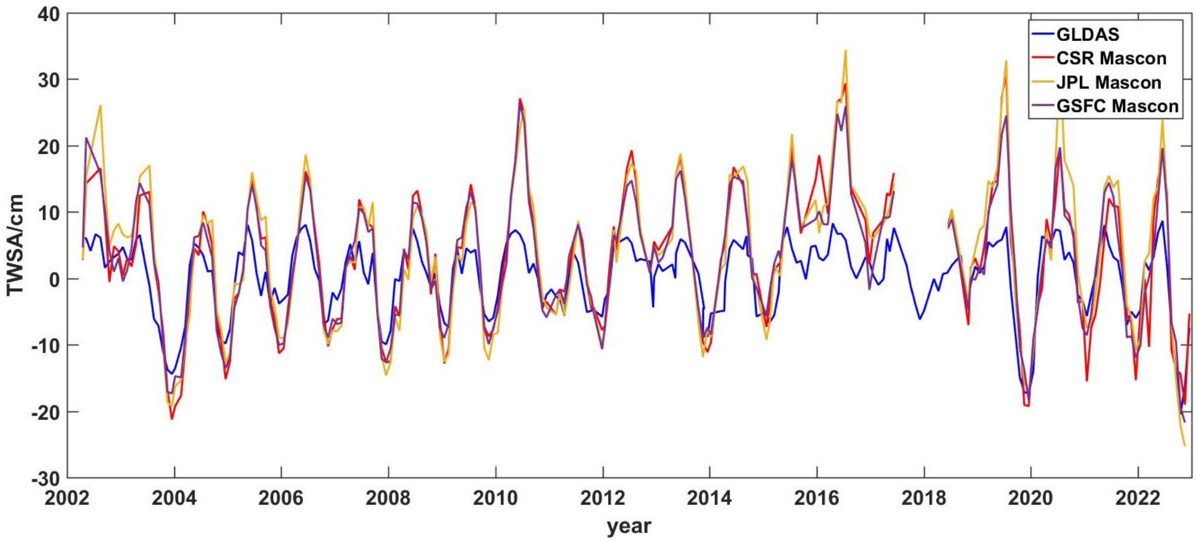


Fig. 2 Comparison of three Mascon solutions and GLDAS data.

have various characteristics, thus, we compared Mascon data with the GLDAS data. Figure 2 shows comparison of a variety of the Mascon data and the GLDAS data and the Table 2 shows the WSDI for the different grades of the flood and drought events. In order to improve the accuracy of the adopted data and reduce its uncertainty, the mean value of three type Mascon data is adopted for follow-up analysis in the research.

4.1. COMPARISON OF PRECIPITATION, RUNOFF AND EVAPOTRANSPIRATION WITH TWSA

Precipitation is the essential processing of hydrological processing and it is also the basic source in Inland terrestrial water. Figure 3 illustrates the change of precipitation and TWSA over all studying period. The peak rainfall occurs from June to August, and the least rainfall occurs from November or December to February of the next year. The regional

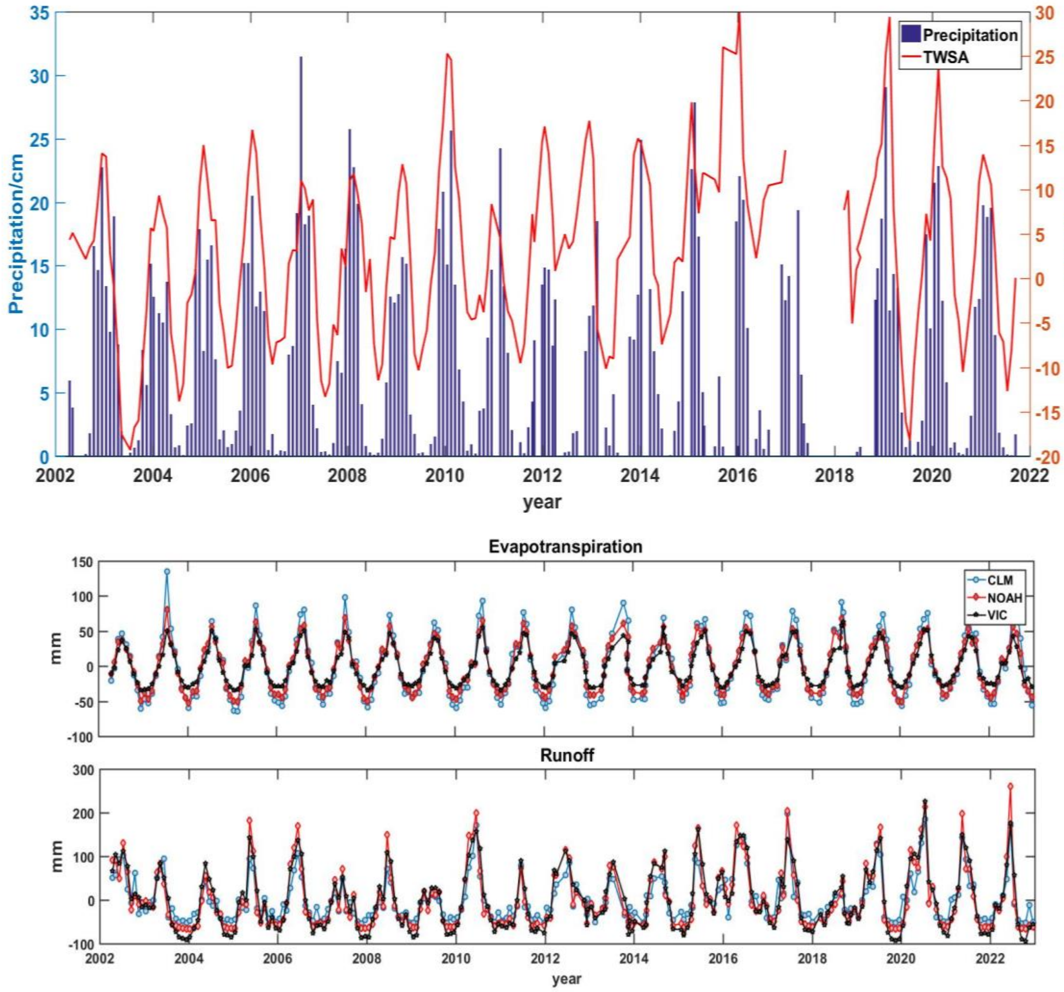


Fig. 3 TWSA and precipitation changes and comparison of the runoff and evapotranspiration over studying period in Jiangxi Province.

rainfall in Jiangxi Province showed obvious periodicity in time-wise. Precipitation is well correlated with TWSA and the two showed a good positive correlation. The correlation coefficient between them is 0.59 which reflects precipitation is the major factor of influencing terrestrial water storage changes in Jiangxi Province. The weighted latitude series of Runoff and evapotranspiration is also shown in Figure 3, it demonstrates three type products are very similar in periodic regularity of the weighted latitude series and the correlation of runoff and evapotranspiration with TWSA is very high. This shows that evapotranspiration and runoff are also important factors affecting the change of TWSA.

4.2. WSDI COMPARED WITH SCPDSI AND SPEI

Figure 4 shows the latitude-weighted time series of WSDI and scPDSI, SPEI over the period of 2002 to 2021. Considering the characteristic of the scPDSI and for convenience of the comparison between WSDI and scPDSI (when the scPDSI value is less than negative 1, drought is defined). Thus, we adjust the scPDSI value up by one digit. The overall trend and fluctuation range of WSDI and scPDSI are more consistent and correlation coefficient of two indexes is 0.78 which reflects well correlation of them in an extent (Here, removed the annual signals of WSDI). In some stages, the beginning time of drought and flood is slightly different and this may be because WSDI is primarily associated with water storage changes, but scPDSI is mainly related to precipitation and temperature related to other meteorological elements (van der Schrier et al., 2013). The Figure 4 shows SPEI index are well correlated with the WSDI, for different time scales SPEI-Z ($Z = 1, 3, 6, 12.$), the correlation between them is very high. In the last subgraph in the first column of Figure 4, SPEI-12 index and WSDI show a certain lag, which may be related to the meteorological data used, calculation method and other factors.

4.3. DROUGHT INCIDENTS ANALYSIS IN STUDYING PERIOD

The WSD series and drought period of April 2002 to December 2022 are shown in Figure 5. There are fourteen drought incidents in whole research period according to WSD series, the longest drought

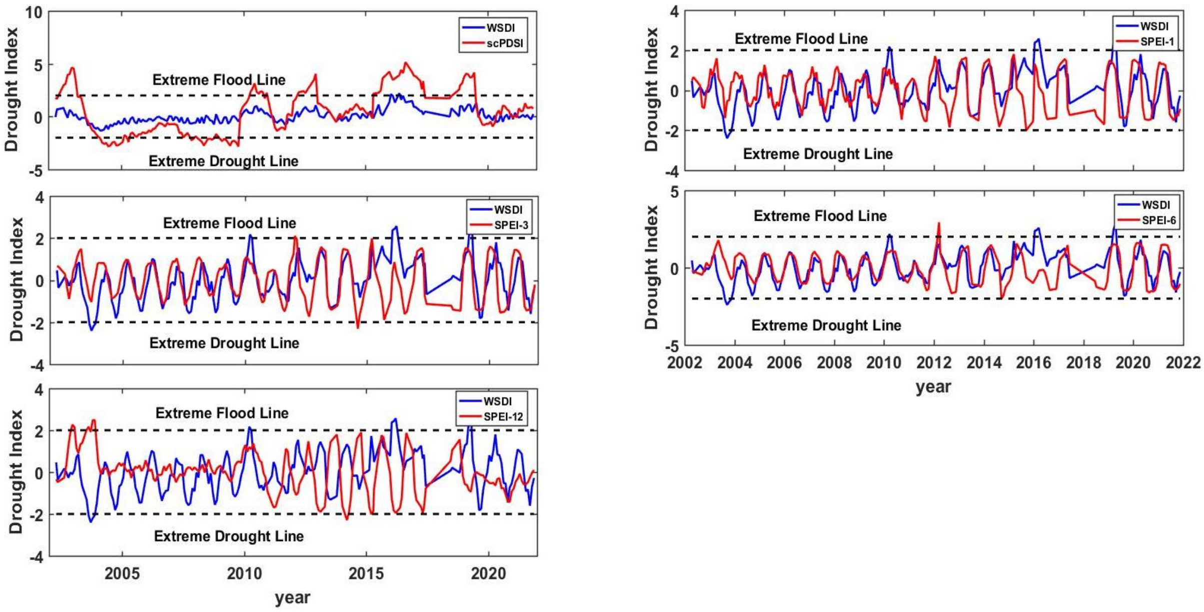


Fig. 4 The latitude-weighted time series of WSDI and scPDSI, SPEI.

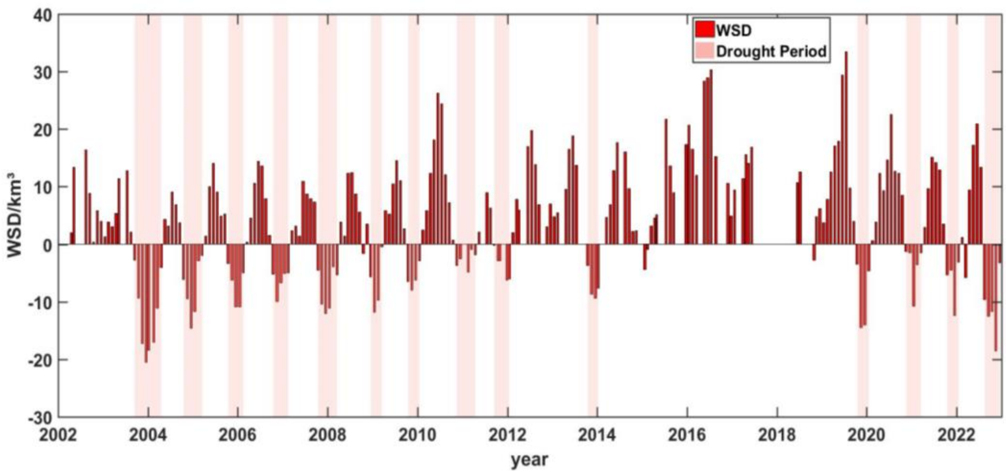


Fig. 5 The WSD and drought period in Jiangxi Province from April 2002 to December 2022.

lasted for eight months after August 2003 and the mean duration of drought incidents in whole research period is 4.8 month. And these drought incidents can be one-to-one corresponded to hydrological data from the network. Through Figure 4, which can be found two drought indexes reached a minimum value around September 2003 to February 2004, it can be matched with Figure 5 and the drought incidents major occur in 2003 to 2011 and which can be well matched in Figures 4 and 5. The periods, durations, peak values, total severities of the fourteen droughts are summarized in Table 1.

To further investigate the spatial evolution of April 2022 to December 2022 drought incidents in Jiangxi Province and consider Poyang Lake drought bottoming event. The spatial distribution of WSDI is shown in Figure 6 and the spatial distribution of precipitation, runoff and evapotranspiration is displayed in Figure 7. It demonstrates precipitation is in a very low state from May 2022 to October 2022 and gradually increased from November 2022 to December 2022. And at same time, the volume of runoff gradually decreased from June 2022, between August and December 2022, the runoff has been in a state of loss. It also shows that the evapotranspiration is at a positive value from April 2022 to September which indicates more water is transported from the atmosphere to the surface than is lost from the surface. The evapotranspiration is at negative value level in whole period of October 2022 to December 2022 which demonstrated water is constantly being transported from the surface to the atmosphere, which corresponds to other meteorological factors above. From April 2022 to July 2022, the terrestrial water storage of Jiangxi Province increased first and then decreased, and reached an extreme value in June, with

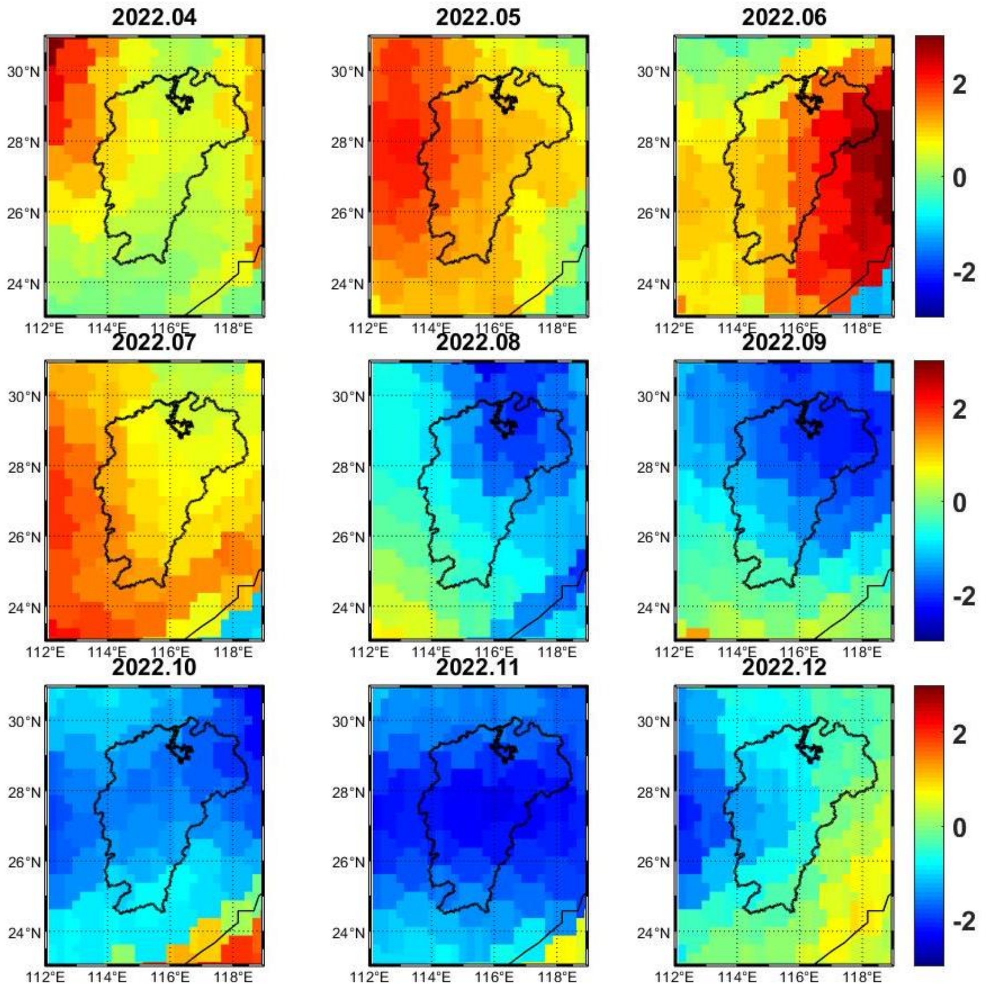
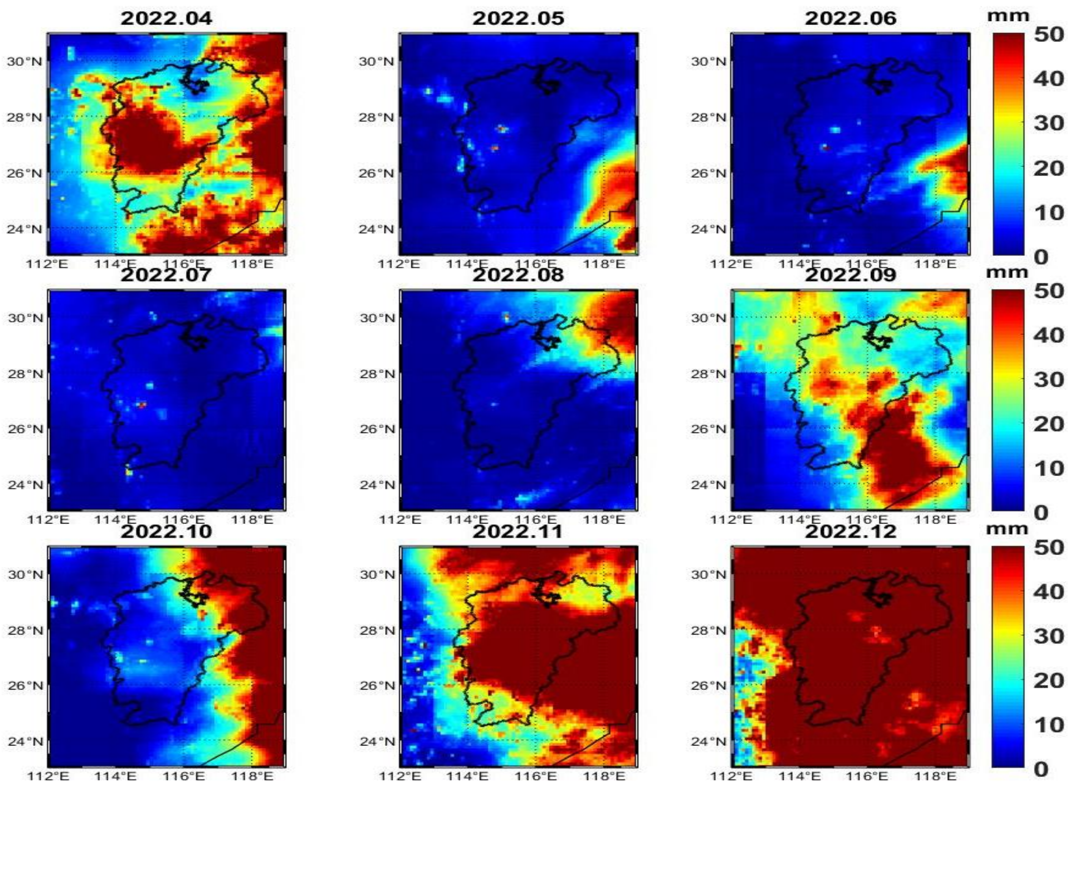


Fig. 6 The spatial distribution of WSDI from April 2022 to December 2022.



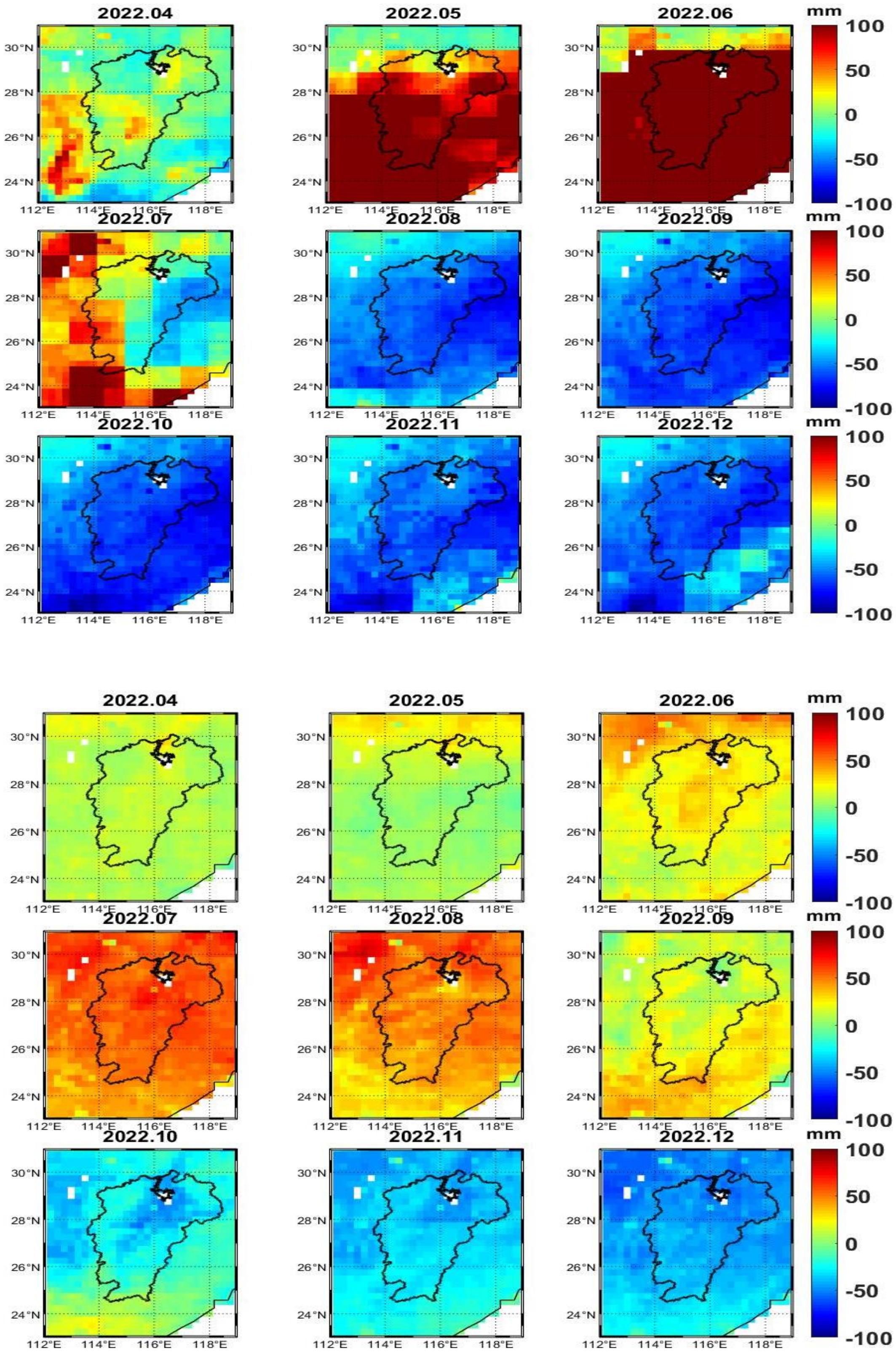


Fig. 7 The spatial distribution of precipitation, runoff and evapotranspiration from April 2022 to December 2022 (First three rows: Precipitation; Middle three rows: Runoff; Last three rows: Evapotranspiration).

some parts of Jiangxi Province in the stage of extreme flooding. From August 2022 to December 2022, the whole Jiangxi Province has been dealing with the drought phase which originated from the northeastern region in August 2022 spread southwest and then expanded to the entire area in October and November 2022, and then retreated to the northwestern region. Likewise, Poyang Lake started drought in August, drought conditions abated in October and reached extreme drought conditions in November.

5. CONCLUSIONS

Basing on GRACE derived WSDI successfully identifies drought incidents in Jiangxi Province. For comprehensive analyzing WSDI, the scPDSI and SPEI drought indexes are adopted to compare with WSDI, and the WSDI with scPDSI, SPEI indexes show a good positive correlation, the correlation coefficient between WSDI and scPDSI is 0.78 and the WSDI with SPEI show a high correlation in different time-scale which reflects the WSDI can effectively monitor drought of the Jiangxi Province. And there are fourteen drought incidents in studying period and almost drought incidents concentrate on 2003 to 2011. The longest drought occurred in 2003 and 2004, lasting eight months. Given that extreme drought incident in 2022 and Poyang Lake drought bottoming event, drought process of 2021 to 2022 period is also analyzed in spatio-temporal based on WSDI, which indicates drought started in August from northeast of Jiangxi Province, spreading southwest and expanded to the entire area in October 2022 and November 2022, and then retreated to the northwestern region. And Poyang Lake also occur the driest conditions in November 2022 which lead to the lake bottoming. There is an obvious seasonal relationship between precipitation and terrestrial water storage in Jiangxi Province, and the peak of precipitation is about 20 cm in summer, and the peak of terrestrial water storage is about 25 cm in July and August every year. The correlation coefficient between precipitation and terrestrial water storage is 0.59. And to precisely analyze the TWSA changing rule, the runoff, evapotranspiration are taken into account and spatio-temporal domains results which shows the correlation of TWSA with runoff and evapotranspiration is very high and the two factors are vital for TWSA changing.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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