Using GRACE and hydrological data to estimate changes of evapotranspiration in the Three Gorges Reservoir

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Abstract. The Three Gorges Project (TGP) has driven changes in water storage, which directly affected the migration and redistribution of land water in the Yangtze River Basin. As a result, a new water balance is established, regional or local evapotranspiration fluctuates, and it may change the climate and weaken geological stability. In this study, we use data from GRACE gravity satellites, hydrological models, remote sensing, and in-situ observations to monitor the spatiotemporal evolution of terrestrial water changes and in the Three Gorges Reservoir (TGR) area, and then to estimate the evapotranspiration induced by water storage fluctuations in the TGR. We calculated the downscaled GRACE results based on the Land Surface Models (LSMs) and scale factor method, which can improve the signal amplitude and spatial differences in the study area and its surrounding areas. Combining the scaled GRACE-derived total water storage changes, precipitation and surface runoff, our estimated evapotranspiration (ET) in the TGR area is highly consistent with the MOD16 global ET results from 2002 to 2016. Seasonal ET changes are mainly driven by climate and rainfall, but GRACE-derived ET shown that the fluctuations of evapotranspiration are also affected by artificial water storage directly, e.g., in the main three water impounding stages (2003, 2006, and 2008), the elevation of the water level caused an abnormal increase in regional ET, but during the water drainage period (spring and autumn), high precipitation did not have a great impact on ET. Our results show that the coverage area of the reservoir area and the short-term fluctuations of the reservoir capacity are the main factors determining the ET in the TGR area.

1. Introduction

Water resources are one of the most important resources for human survival and development. The influence of human factors in the global water cycle cannot be ignored. As the largest hydropower generation project, the Three Gorges Dam (TGD) has received widespread attention at home and abroad since its establishment in 2002. It has brought a number of benefits in flood prevention, power generation, shipping and water resources regulation, but the debate over the ecological, climatic and environmental impacts of the dam have not subsided. Long-term interception and storage of dams will definitely affect the redistribution of the total mass of terrestrial water[1]. The huge artificial lake formed by water storage will cause fluctuations in regional evapotranspiration, and evaporation itself is a component of surface heat balance and water balance, and it is also directly affected by land use and climate change in the water cycle. Quantitative estimation of the evapotranspiration can help us deeply understand the state of water balance in the Three Gorges Reservoir (TGR) area, and it is helpful to analyze the regional terrestrial water cycle process driven by both climate and human factors. Based on the above-mentioned background, in this paper, we take the TGR as the research area, and use GRACE satellite data and hydrological measured data to reconstruct the long-term
changes of terrestrial water reserves. Finally, we estimate the long-term changes in evapotranspiration based on the water balance equation in the basin from 2002 to 2016.

Figure 1. Location of study area. The area outside the black border is the Yangtze River Basin; the area inside the black border is the study area (TGR, Three Gorges Reservoir); the red mark is the Three Gorges Dam (TGD)

2. Algorithm

2.1. Related concept of satellite data

The GRACE data used in this study is Level-2 RL06 version spherical harmonic coefficient solution provided by CSR (Center for Space Research, University of Texas at Austin). We use spherical harmonic coefficients with the order from 2nd to 96th and with a time span from March 2002 to August 2016. The tidal effects and non-tidal atmospheric and oceanic effects are deducted from the data. Due to the insensitivity of the GRACE satellite orbit to the C20 coefficient, there is a large uncertainty in the value of the C20 coefficient. We replaced the C20 coefficient with satellite laser ranging (SLR) coefficients [2,3]; then we used the first-order coefficients (Geocentric) provided by [4,5]; finally, we used the P4M6 decorrelation processing method [6] and the Gaussian filter processing with a correlation radius of 500 km [7], because the model is affected by satellite orbit errors and truncation errors of spherical harmonic coefficients. GIA (Glacial Isostatic Adjustment) is a geodynamic process triggered by the last glacial melting of glaciers, and its impact on monitoring global water quality changes cannot be ignored. In this study, we selected the results of GIA correction given by A [8] to correct the satellite data to subtract the GIA effect.

The surface density change can be expanded in spherical harmonic field as

$$\Delta \sigma (\theta, \lambda) = \frac{a \rho_E}{3} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \tilde{P}_l^m (\cos \theta) \frac{2l+1}{1+k_l} \left[ \Delta C_l^m \cos (m\lambda) + \Delta S_l^m \sin (m\lambda) \right]$$

(1)

where $\rho_E$ is the average density of the Earth ($= 5517$ kg/m$^3$); $k_l$ is load Love number at degree l, a is the average radius of earth at the equator. While the surface mass change is usually regarded as the change of terrestrial water and can be represented in terms of the equivalent water height $\Delta \sigma / \rho_w$, where the $\rho_w$ is the density of water ($= 1000$ kg/m$^3$).

To recover the “leakage” signal, the selected LSM model is synchronized with the satellite data. First, the LSM model is transformed from the spatial domain to the spherical harmonic domain and truncated to the degree 96. A smoothing function of 500 km Gaussian filtering is applied. And then retrieving the LSM model in the spatial domain. By dividing the LSM model grid data before and after the processing, a scale factor grid can be obtained for a certain period of time. Here, least squares fit is performed to the time-dependent scale factor of each grid cell (Fig. 2).
We can multiply the global scale factor grid with the equivalent water height grid to obtain the scaled grid $S$. Here, we need to calculate the average equivalent water height of the study area, thus a basin kernel function should be defined as

$$u(\theta, \lambda) = \begin{cases} 0, & \text{outside the area} \\ 1 \times \cos \theta, & \text{within the area} \end{cases}. \quad (2)$$

The average equivalent water height $H$ of the study area can be expressed as:

$$H = \frac{1}{\Omega} \sum_{i=1}^{n} S(\theta, \lambda) \times u(\theta, \lambda) \quad (3)$$

where $S$ is the equivalent water height, $n$ is the number of grid points, and $\Omega$ is the sum of the cosine values of the latitude of the grid points in the study area.

### 2.2. Principle of the evapotranspiration algorithm

The based on GRACE data, the changes in regional land water storage are obtained. At the basin scale, it can be expressed as the sum of total precipitation, evapotranspiration and net runoff\cite{9}.

Evapotranspiration can be estimated with precipitation data and net runoff data.

$$ET = P - Q - \Delta S \quad (4)$$

where $P$ is the total precipitation, $Q$ is the net runoff, and $\Delta S$ is the change in water storage on land (e.g. the difference between the equivalent water height value of the subsequent cycle and the previous cycle multiplied by the area of study area), $ET$ is evapotranspiration. Since $\Delta S$ is the difference between the average in two periods, formula (4) can be expressed as

$$\begin{bmatrix} S + \cdots + S \\ \frac{1}{2},1 \\ 2, N \end{bmatrix} - \begin{bmatrix} S + \cdots + S \\ \frac{1}{2},1 \\ 2, N \end{bmatrix} = \begin{bmatrix} \sum_{1,1}^{2,1} P + \cdots + \sum_{l,N}^{2, N} P \\ \sum_{1,1}^{2,1} ET + \cdots + \sum_{l,N}^{2, N} ET \\ \sum_{1,1}^{2,1} Q + \cdots + \sum_{l,N}^{2, N} Q \end{bmatrix} \quad (5)$$

where $N$ is the number of days in the observation period. Divide both sides of the formula by $N$, and formula (5) is simplified as

$$\Delta \bar{S} = \frac{1}{N} \sum_{n=1}^{N} \sum_{d=D-n}^{D-n+1} (P_d - ET_d - Q_d) \quad (6)$$

When the two periods are discontinuous and have non-uniform intervals, the formula (6) can be changed to
\[ \Delta S = \sum_{d=D_1}^{D_1+N_1-1} \frac{d - D_1 + 0.5}{N_1} (P_d - ET_d - Q_d) + \sum_{d=D_1+N_1}^{D_2+N_2-1} (P_d - ET_d - Q_d) \]
\[ + \sum_{d=D_2}^{D_2+N_2-1} \frac{D_2 + N_2 - d - 0.5}{N_2} (P_d - ET_d - Q_d) \]  

(7)

where \( N \) is the number of days in the observation period, and \( D \) is the start date of the observation. The effective days of the period corresponding to \( \Delta S \) can be expressed as

\[ \bar{N} = (N_1 + N_2)/2 + \left[ D_2 - (D_1 + N_1) \right] \]  

(8)

The final evapotranspiration is the weighted sum of evapotranspiration for each day in the corresponding period.

2.3. Algorithm instance

Based on the data and methods described above, here we have obtained evapotranspiration estimates for the Three Gorges Reservoir area from 2002 to 2016 (Figure 3). Changes in evapotranspiration values have an obvious annual cycle and are highly correlated with precipitation, and the results also show high anomalous evapotranspiration values in the study area in spring 2003, autumn 2006, and autumn 2008. Although it was at the peak rainfall period, it still showed a significantly higher value compared with the same period of other years. It may be related to the fact that the Three Gorges Dam is in a period of water storage. In contrast, in the summer of 2007, 2008, and 2010, although the precipitation reached its peak, a small trough of evapotranspiration appeared, which may be related to the fact that upstream water level was low, because of the drainage of the Three Gorges Dam at that time. In other years, while the Three Gorges Dam releases water and precipitation increases in summer, evapotranspiration also appears troughs. In the autumn of 2008 and the summer of 2016, when the evapotranspiration value reached its maximum value, it was the storage period of the Three Gorges Dam and the peak of precipitation.

![Figure 3. Estimation of evapotranspiration in the Three Gorges reservoir area](image)

3. Conclusions

Based on the GRACE gravity data released by CSR from 2002 to 2016 and surface hydrological observation data, we estimates the changes in the evapotranspiration of the Three Gorges Reservoir area since the establishment of the Three Gorges Dam, and draws the following conclusions:

1. The rise of the water level in the three water storage stages of the Three Gorges Dam (2003, 2006, and 2008) led to an abnormal increase in regional evapotranspiration, and the period of water drainage in the reservoir area (spring and autumn) caused an abnormal decrease in evapotranspiration. Human factors have driven changes in evapotranspiration in the Three Gorges reservoir area. The
main factors controlling the evapotranspiration in this area are the short-term fluctuations of the flooded area and storage capacity of the reservoir area.

(2) The impacts of the storage and release of water from the Three Gorges Dam on evapotranspiration are mainly reflected in the main and tributaries of the Three Gorges Reservoir area, but the impacts on soil and vegetation in the reservoir area is not obvious.

(3) Changes in evapotranspiration in the Three Gorges Reservoir area caused by human factors are based on the influence of precipitation, which is the main factor affecting the changes in evapotranspiration.

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