Satellite Detection of Spatial Distribution and Temporal Changes of Surface Soil Moisture at Three Gorges Dam Region from 2003 to 2011

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ABSTRACT: Knowledge of the spatial distribution and temporal changes of the land surface parameters at the Three Gorges Dam (TGD) region is essential to understanding the changes of hydrological processes and climate systems possibly brought by TGD. Based on accumulated observations for years from a spaceborne passive microwave radiometer, this study presents and analyzes the spatial and temporal distribution of soil moisture in the TGD region. Major drought and flood events are identified from the satellite-derived soil moisture products. Moreover, the areas around the largest freshwater lakes of China, the Dongting and Poyang Lakes, are frequently subjected to drought events, which might be partially related to the impoundment of TGD since the year 2006. Data analysis further reveals a statistically significant drying trend in May in the middle and lower reaches of the Yangtze River over the years 2003–11. These analyses indicate that water shortage becomes a realistic challenge for the once water abundant Yangtze River region, and more considerations on the

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possible consequences brought by climate changes are needed for the operation of TGD.

KEYWORDS: Soil moisture; Three Gorges Dam; Drought; AMSR-E

1. Introduction

The Three Gorges Dam (TGD) spanning the Yangtze River in Hubei Province, China, is the largest hydroelectric project in the world. The megaproject was built to control Yangtze River floods, generate hydropower, and improve the transportation capacity at the upper reaches of the Yangtze River. Controlling the catastrophic floods downstream is the most important function of TGD since every few decades major flooding of the Yangtze occurs. However, as one of the heaviest manmade hydrological facilities and the world’s largest concrete structure, TGD also raises major concerns about the consequences of the construction of TGD in the context of global changes. Researchers have carried out a number of studies focusing on the TGD’s impacts on a variety of topics, including regional climate, river discharges, aqua and terrestrial ecosystems, sedimentation, pollution, etc. (Guo et al. 2012; Müller et al. 2008; Wu et al. 2012; Xu and Milliman 2009; Xu et al. 2011; Zhao and Shepherd 2012). These studies are very important since the evaluations on the positive and negative impacts of TGD on the earth systems are vital not only for the management of TGD but also for the designing and building similar huge manmade structures such as the ongoing south-to-north water diversion project in China. However, available studies are not enough to help the researchers reach the consensus on the questions whether TGD affects regional climate patterns in a positive or negative way, and it is still under investigation on how to improve the TGD’s ability to mitigate the damages of extreme weather events, such as severe droughts and floods. As a prerequisite to answer these questions, the characteristics of the spatial and temporal distribution patterns of land surface parameters at regional scales instead of local scales need to be evaluated. In this study, we focused on the land surface soil moisture, which is one of the most important parameters for the studies of global and regional water cycle, energy balance, and climate changes. The information on land surface soil moisture at the TGD region observed by satellite over the years 2003–11 is presented and analyzed.

2. Data descriptions

Satellite observations have expanded the conventional “point” measurements from meteorological and hydrological stations to the “surface” measurements. Monitoring soil moisture by satellites is essential for detecting the flood and drought events over large areas and is also important for carrying out the quantitative analysis on the land surface changes for the TGD region. There have been several spaceborne microwave radiometers launched in the past decades that were designed to monitor the terrestrial water cycles. Among them, the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) projects of the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) on board the *Aqua* satellite has been widely used for the retrieval of soil moisture (Kawanishi et al. 2003; Njoku et al. 2003;
Njoku and Chan 2006; Paloscia et al. 2006; Bindlish et al. 2006). As a polar-orbiting satellite, Aqua flies over a given location at a fixed local time (LT), with its descending node 0130 LT and ascending time 1330 LT; this enables AMSR-E to provide consistent long-time data series, which can be used in the data comparisons. The AMSR-E is a conically scanning passive microwave radiometer, sensing horizontally and vertically polarized microwave radiation at 12 channels and six frequencies ranging from 6.9 to 89.0 GHz. Its observations at moderately low frequencies are very sensitive to land water in various forms, such as soil moisture, vegetation water content, and snow, and are little affected by atmosphere conditions. AMSR-E was launched in June 2002 and functioned well until October 2011. During this period, TGD experienced two impounding stages: the initial stage of impoundment with a water level increasing from 135 m on 10 June 2003 to 156 m on 27 October 2006 and the second stage of impoundment from June 2006 to 2010 with the final water level of 175 m on 26 October 2010. Therefore, the standard NASA AMSR-E L3 soil moisture products from 2003 to 2011 are used in this study. The spatial resolution of the products is 25 km. The NASA algorithm uses normalized polarization ratios (PRs) of the AMSR-E channel brightness temperatures to account for the vegetation and roughness effects and to retrieve soil moisture (Njoku and Chan 2006). Validations on the NASA soil moisture products indicate that the root-mean-square error (RMSE) of the products is lower than the 0.06 cm$^3$ cm$^{-3}$ (Jackson et al. 2010). In this study, we are more concerned with the question on how soil moisture changes during the study period, in order to find the possible changes along with the construction and operation of TGD rather than the absolute values of soil moisture. Soil moisture is computed using the deviation of PR at 10.65 GHz from a baseline value in the NASA algorithm; therefore, the inversed soil moisture values are self-consistent and comparable with each other for the same location. The NASA products are adopted to detect the temporal changes of soil moisture. Moreover, the X-band retrievals represent the soil moisture in the 1-cm soil layer, where soil moisture has an immediate response to the atmospheric forcing such as precipitation and evaporation. Therefore, the AMSR-E-derived soil moisture can also be used as an indicator for monitoring drought and flood events.

3. Study area

The selected study area is located between latitudes 23.5° and 37.75°N and longitudes 103.75° and 118.0°E, covering about a 2 million km$^2$ area as shown in Figure 1 with TGD marked by the star symbol approximately in the center. The area includes the upper reach (the section from Yibin to Yichang), the middle reach (the section from Yichang to Hukou County), and part of the lower reaches of the Yangtze River. The middle and lower reaches of the Yangtze River are dominated by a subtropical monsoon climate with a rainy summer and a relatively dry winter. The Huaihe River basin and part of the Yellow River basin are also included. The Yangtze and Yellow Rivers are the two longest rivers of China. The Huaihe River is another major river in China, which is located about midway between the Yellow and Yangtze Rivers. The study area also includes the two largest freshwater lakes of China, the Dongting Lake and Poyang Lake. Both lakes are connected and interact with the Yangtze River.
4. Method and results

When studying the spatial and temporal changes of land surface soil moisture, one needs to consider the seasonal climate patterns of the region and also the possible consequences of the TGD’s seasonal impounding and releasing of water. For the study area, in the dry season from October to March (Guo et al. 2012), significant decrease of precipitation occurs while large impounding by the TGD normally happens in September and October. For the rainy season typically from July to September, the rate of impounding water by the TGD becomes low but also varies frequently to adjust the reservoir storage to control floods. Considering the seasonal behavior of precipitation and impoundment of TGD, the characteristics of the spatial and temporal distribution of surface moisture are studied on a monthly basis. The monthly averaged soil moisture value for each grid is calculated first for the period 2003–11. Then the soil moisture anomaly percentage $x_{ij}$ for each grid can be obtained by

$$x_{ij} = (x_{ij} - \bar{x}_i)/\bar{x}_i,$$

(1)
where $x_{ij}$ is the mean soil moisture for the $i$th month of the $j$th year and $\bar{x}_i$ is the mean soil moisture for the $i$th month during the study period. The values reflect how the surface wetness of the month for a particular year deviates from the average level. The soil moisture anomaly percentage $x_{ij}^\prime$ can be used to monitor the extreme weather events, especially drought and floods. Figure 2 plots the soil moisture anomaly percentage for August from 2003 to 2011, with the red rectangle representing the location of TGD. August, along with June and July, is one of the months that floods are likely to happen. The blue and purple areas in the figure for the year 2003 clearly indicate a very wet condition with soil moisture around 15%–30% higher than normal in the Huaihe basin, which experienced one of the biggest floods since the year 1949 (Liu et al. 2004). The major flood event in the year 2010 in the Yangtze River basin can also be easily identified in the figure. The very wet areas are mainly located in the middle and lower reaches of Yangtze River, especially the areas around the Dongting and Poyang Lakes. During 1998, record flooding of the Yangtze River and adjacent river valleys claimed the lives.

Figure 2. Soil moisture anomaly percentage maps for August of the years 2003–11 with TGD marked by a red rectangle. The maps are organized by increasing year from left to right with the rows being (top) 2003–05, (middle) 2006–08, and (bottom) 2009–11.
of more than 3000 people and caused the total damage from the flooding about U.S. $26 billion (Spignesi 2004). However, the similar flood in the year 2010 caused a much less damage with TGD blocking and releasing the water of the river in a measured way and thus minimizing the impact of flooding downstream. Flooding along the Yangtze River during the rainy season has been a major problem to China and the operation of TGD has helped to control the flood. Except for the symbolic flooding events in August, very dry conditions are also found Figure 2. Since August 2006, the Poyang Lake and Dongting Lake basins underwent severe drought for 3 months, which caused the area of Poyang Lake to shrink from 4000 km² to less than 50 km². As evident in Figure 2, the drought in 2006, the slight drought in 2005, and another severe drought in 2011 were caught by the AMSR-E observations. Normally, there is no major impoundment of TGD in August; however, according to Guo et al. (Guo et al. 2012), the operation of TGD to reduce the flood risks by intentionally lowering the river level results in more lake water flow into the river than the preoperation years of TGD. The additional loss of water storage of the lakes might further aggravate the drought in the Poyang and Dongting Lakes basins.

September is the end of the rainy season for the study area, and major impoundments of TGD start in this month. To study the possible changes brought by the impoundment of TGD, Figure 3 is plotted to analyze the soil moisture conditions in September. In Figure 3, we can see that for the years 2006, 2009, and 2011 the areas surrounding the Dongting and Poyang Lakes are found in drier conditions than the average level while all 3 years before 2006 are shown relatively wetter conditions. Also for 2006, 2009, and 2011, when comparing with the other areas in the middle and lower reaches of Yangtze River, we find that the drought is more severe in the Dongting and Poyang basins. It is noted that the water level of TGD reaches 156 m in October 2006 and finally reaches 175 m in October 2010. The huge impoundment in September and October can reduce the Yangtze River discharge by as much as 30% (Guo et al. 2012). The dam on the upper reach of the river has a negative impact on the water supply downstream, and the low level of the river can cause the additional outflow of water from the two lakes. The lack of precipitation might be the dominant reason of the September drought. However, it is also noted that the lakes play a critical role in modulating the wetness conditions of the wetland surrounding the lakes. The additional loss of water storage of the lakes caused by the impoundment of TGD can result in shrinking wetlands and aggravate the drought. Therefore, the drought around the lake areas in September might be partially attributed to TGD.

When examining all the months, it is found that the driest cases do not happen in September or October. From Figure 4 we can see that, for the middle and lower reaches of Yangtze River, the dry conditions appear in May for the years 2007, 2008, 2009, and 2011. The drought event seems to reach its maximum extent in 2011 as seen in Figure 4. In fact, the drought between January and June 2011 is the worst drought in China for the past 60 years (Qiu 2011), which affected 35 million people. It is unclear if the TGD plays any role in the formation of the drought and further discussions are presented in the next section. The Yangtze River basin is the region generally considered abundant of water; however, the drought shows that water crisis might also be an urgent problem to this region. Mitigating the impacts of the drought events that frequently happened in the spring after 2006 has become
an important task of TGD, along with its primary functions such as controlling flood.

Another issue is related to the argument about how TGD affects regional climate. In this study, for the areas surrounding TGD, which are approximately in the center of all the figures, relatively stable soil moisture conditions are found over the study period. This indicates no significant changes of the monthly-mean precipitation for the vicinity region of TGD are detected in the regional soil moisture mapping from AMSR-E observations. Moreover, the impoundment and release of water by TGD affect the hydrological processes of Yangtze River and the connected lakes. Would the changes of hydrological process link to the regional climate changes? Analysis on the temporal changes of the regional soil moisture in the post-TGD period is a necessary step to answer the question. As seen in Figures 2–4, the middle and lower reaches of the Yangtze River seem to be more likely to be subjected to extreme weather events since the year 2006, when the second impoundment phase of TGD began. To find out if there is a possible temporal trend

Figure 3. Soil moisture anomaly percentage maps for September of the years 2003–11 with TGD marked by a red rectangle. The maps are organized by increasing year from left to right with the rows being (top) 2003–05, (middle) 2006–08, and (bottom) 2009–11.
of soil moisture variations during the two impoundment stages of TGD, we made a simple regression for the monthly-mean soil moisture with the year,

$$y_{ij} = x_{ij}/\bar{x}_i = at_j + b,$$

where $y_{ij}$ is the normalized soil moisture for the $i$th month of the $j$th year; $\bar{x}_i$ is the mean soil moisture for the $i$th month during the study period; and $t_j$ is the time variant in unit year with $t_{2003} = 1$ and $t_{2011} = 9$ for the years 2003 and 2011, respectively. The slope $a$ indicates how the normalized soil moisture changes with year. Plots of $a$ for four selected months are presented in Figure 5, with February representing the dry season, August representing the flood season, May representing the period between the dry and wet seasons, and September representing the beginning of huge impoundment of TGD. It was found in Figure 5 that, for most months, there is no clear trend by soil moisture changes with statistical significance for the Yangtze River basin except for May with the significance level
Figure 5. Yearly changing ratio of the normalized soil moisture for the years 2003–11 with TGD marked by a red rectangle: maps for (top)–(bottom) February, May, August, and September for (left) the original maps and (right) the maps with the areas not statistically significant masked.
set as 0.05. The parts masked in gray are the areas that are not statistically significant. For May, there is a decreasing trend of soil moisture for the middle and lower reaches of the Yangtze River with the soil moisture decreasing by 5%–10% of the mean soil moisture each year. During May, the water level in TGD is lowered to prepare for the possible floods in the coming rain season and more water is discharged from the reservoir to the river. The drying trend seems to be more linked to a decreased precipitation in the spring over these years. There are no direct or simple links between the drying trend and TGD. However, with the statistically significant drying trend found, water shortage in the once water abundant region becomes a realistic challenge and more considerations on drought-relief measurements are needed for the operation of TGD.

5. Discussion

The satellite retrievals help to give us a view of how soil moisture changes at the regional scale in the post-TGD period (2003–11), with a decreasing trend of soil moisture in May and frequent drought events in September and May revealed.

Based on the analysis on the daily meteorological data for 137 stations from 1960 to 2004 and hydrological station data, researchers found that a statistically significant negative trend of precipitation in September over the Yangtze River basin and increasing drought events in May, September, and October (Gemmer et al. 2008). The finding is for the pre-TGD period (1960–2002) and two post-TGD years (2003–04). For the post-TGD period from 2003 to 2011, frequent drought events in May and September are also found in this study and a statistically significant dry trend in May can be detected from the satellite retrievals. Therefore, an increasing trend of drought events has been found in both the pre-TGD period and the post-TGD period. The drought event reached its peak in the early spring of 2011 in the Yangtze River basin as described in the previous section and Figure 4. Based on the study of Sun and Yang (Sun and Yang 2012), the severe drought is likely to be caused by large-scale factors such as the La Niña event in 2010/11 and the North Atlantic Oscillation (NAO). In a separate study, the primary reason of this spring drought is also believed to be the unexpected low precipitation (Feng et al. 2012). These studies along with the findings in this study indicate that large-scale circulation patterns could possibly play an essential role in these drought events and Yangtze River basin seems to be experiencing a period with drier spring and autumn.

Assuming these drought events are mainly due to the natural interannual oscillation of precipitation or global climate changes, it is still interesting to explore if the operation of TGD mitigates or exacerbates the severity of the extreme climate events. It has been well recognized that changes in land use and land cover can influence local and regional climates as detailed in the study by Mahmood et al. (Mahmood et al. 2010). More specifically, for the land-cover changes resulted from the construction of dams, studies have proved that the artificial reservoirs could have mesoscale impact on surrounding climate and precipitation patterns (Hossain 2010; Degu et al. 2011; Degu and Hossain 2012; Zhao and Shepherd 2012). These studies show that the intensity and frequency of rainfall might be affected in the impounded basins. For TGD, studies using high-resolution regional climate models lead to different conclusions. By using the Fifth-generation Pennsylvania State
University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) simulations, Wu et al. (Wu et al. 2006) found TGD had an effect on precipitation at the regional scale (100 km) while other researchers believe TGD is not large enough to influence the regional climate (Wu et al. 2012; Miller et al. 2005). It is noted that these studies on TGD have focused on the effects of the reservoir itself on its vicinity area instead of all the relevant factors in the whole Yangtze River basin. Indeed, the huge artificial structure not only means increased evaporation from the huge standing water and decreased downstream during its impoundment but it also means the changes of the level and the flow speed of the Yangtze River, the changes of the complex interactions between the Yangtze River and the lakes connected to it, and the changes of the wetland surrounding the lakes. The areas surrounding the Poyang and Dongting Lakes, for example, are found more likely to be affected by the drought events than the other areas, especially in the impoundment period of TGD as is evident in Figures 2–4.

6. Conclusions

With the growth of population and economy, a growing number of huge man-made projects are being built to mitigate natural hazards and meet the needs of the increasing demand of water. The TGD is now in full operation and the south-to-north water diversion project is under construction. These large infrastructure projects help people adapt to the global climate changes. Meanwhile, it is still unclear how these concrete structures reshape the environments. With the help of observations for years from satellites, this study 1) identified the flood and drought events frequently happened in the Yangtze River basin from 2003 to 2011; 2) found the drought events frequently happened in the areas around Dongting and Poyang Lakes since the year 2006, where the drought is linked to extreme weather and the severity of the drought might also be related to the loss of lake water storage caused by TGD; 3) detected little changes of soil moisture conditions in the vicinity areas of TGD for the post-TGD period, where, although soil moisture conditions reflect the occurrence of rainfall, it is still needed to carry out further studies based on precipitation measurements from satellites and meteorological stations in order to clarify TGD’s impact on precipitation patterns; and 4) revealed the drier trend in the middle and lower reaches of Yangtze River in May. TGD has played an important role in minimizing the flood risk of the Yangtze River. However, based on the frequent drought events found in the Dongting Lake and Poyang Lake basins and the drier trend found in May for the middle and lower reaches of the Yangtze River, more attentions should be drawn to the drought problem. It needs a good balance between generating electricity by TGD and the water supply of the downstream, especially for the dry spring and autumn. Particularly, the operation procedures of the TGD power stations should be adjusted flexibly to help maintain a healthy lake environment with an earlier and more frequent release of water encouraged in the dry seasons.

As pointed out by Hossain et al. (Hossain et al. 2012), deeper understanding and more considerations on the climate factors are essential in dam design, operations, and water management. Satellite remote sensing enables the mapping of the spatial and temporal distribution of soil moisture for the vicinity area of TGD and also the middle and lower reaches of the Yangtze River. However, the observational study...
alone within the limited study period is not enough to answer the following important questions: In what way does TGD affect the regional climate and hydrology system? What is the role of TGD in the formation of the drought events in the post-TGD period? Does TGD alleviate or exacerbate the regional spring droughts? To clarify the impacts of TGD on the local and regional climate and hydrology systems, a further study based on climate and hydrology models as well as the observations from satellite, meteorological, and hydrological stations is needed with a number of the factors considered, such as land-cover changes triggered by TGD; terrain, river, and lake interactions; and the wetland surrounding the lakes. Moreover, for TGD and the other hydrological facilities on the Yangtze River, further studies on the optimal operation schemes with factors related to local and regional climate changes considered are important particularly for efficient water resource management in dry conditions as well as effective control of flood risks in wet conditions.

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References


