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Damming effect on the Changjiang (Yangtze River) river water cycle based on stable hydrogen and oxygen isotopic records

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ABSTRACT

More than 50,000 dams have been built in the Changjiang (Yangtze River) catchment over the last half century, among which the Three Gorges Dam (TGD) is the largest hydroelectric engineering project in the world. The trapping effect of the TGD on the decline of Changjiang sediment flux has been widely documented, while the damming impact on river water cycle has not received enough attention because of the relative consistence of annual water discharge. In this regard, we present a new isotopic evidence to illustrate the damming effect on the Changjiang river water cycle based on stable hydrogen and oxygen isotopes. A historical comparison of seasonal distribution of stable oxygen isotope in the Changjiang river water indicates that the time lag of river water response to meteoric precipitation has changed from one month in the early 1980s to approximately two months in the past decade. The one-month slowdown of Changjiang river water cycle is probably the result of increasing trapping and water regulation effect by numerous dams in the catchment. This study provides the first quantitative evaluation of this significant damming impact on the Changjiang river water cycle, and the damming effects on ecosystem and biogeochemical process in river and marginal sea, as well as on socioeconomic development in China, have to be carefully considered in the future.

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1. Introduction

The water cycle on earth is one of the most important earth surface processes, which is closely linked to the global energy cycle and biogeochemical cycle. In particular, the water cycle is critical for the maintenance of most lives and ecosystems on the planet. River, which accounts for less than 1% of total water resource, plays a key role in the global water cycle as it carries water, sediment, chemicals, and various nutrients from the continent to the sea. However, the river water cycle is significantly impacted by the growth of population and worldwide hydraulic projects at present (Rosenberg et al., 2000; Vörösmarty et al., 2000; Vörösmarty and Sahagian, 2000; Nilsson et al., 2005; Oki et al., 2013; Haddeland et al., 2014). In this case, the study of river water cycle is of great contribution to the sustainable development of the society and ecosystem.

The Changjiang (Yangtze River) is no doubt the most important river in China and one of the world's busiest waterways linking the leading economic center, Shanghai in the river mouth, to the less-developed hinterland in the large catchment. The Changjiang catchment is also one of the cradles of Chinese culture, and today fosters a population of about 400 millions. Human activities in the Three Gorges area can be dated back to 27,000 years ago (Huang et al., 1995). However, social development within the catchment has been greatly threatened by flood hazards throughout the Chinese history. As such, the residents of the Changjiang catchment have continuously reformed the river through various hydraulic projects, e.g., Dujiangyan, the oldest (250 BC) surviving irrigation system in China. Nowadays, the Changjiang River has once again been the subject of great international concerns (Challman, 2000; Shen and Xie, 2004; Plateau, 2006; Qiu, 2014; Yang et al., 2015) due to the Three Gorges Dam (TGD), which is one of the largest and most powerful hydroelectric engineering projects ever built.

Over the past half-century, more than 50,000 dams have been constructed in the Changjiang River basin, with purpose of flood control, power generation, irrigation, and navigation. These dams range in sizes from those on farmers' fields to more than 100 m high. Till the year of 2000, there exist 15 dams taller than 100 m in height, and more than 20 are scheduled to be constructed by 2015 (Yang et al., 2011). Among these dams, the TGD is of particular interest because it is regarded as the largest construction project in China since the Great Wall. The TGD is located between the upper and middle Changjiang mainstream (Fig. 1) and initialized water impoundment in June 2003. The normal reservoir water level is 175 m, and the total reservoir storage capacity is 39.3 km^3. In dry season from December to next April, the Changjiang river water is retained in the Three Gorges Reservoir

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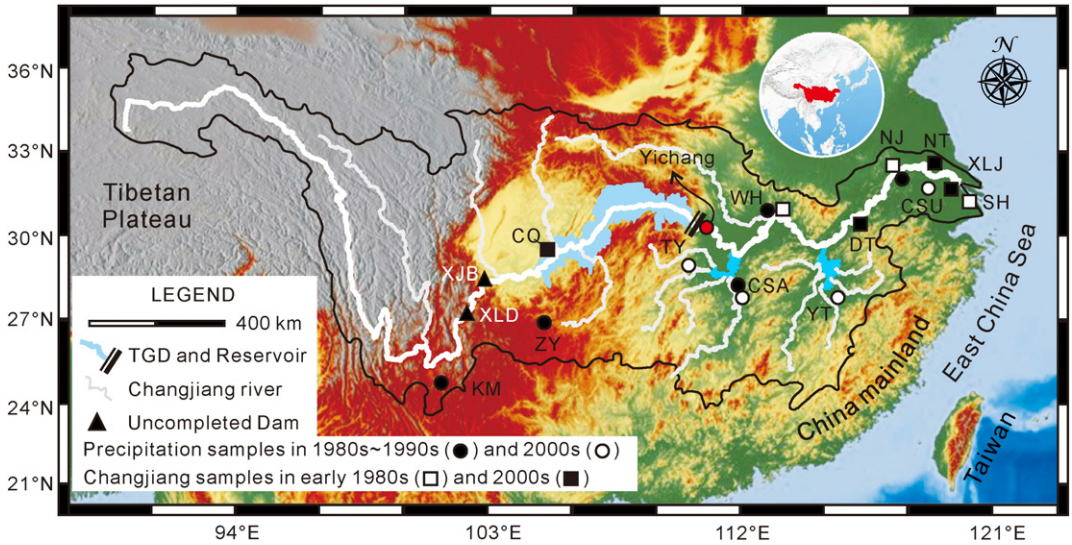

Fig. 1. Map of the Changjiang river basin. The TGD and sampling sites for isotopic measurements are all indicated (see the legend and Table 1 for the details). Abbreviations for sampling site are: CSA-Changsha, CQ-Chongqing, CSU-Changshu, DT-Datong, KM-Kunming, NJ-Nanjing, NT-Nantong, SH-Shanghai, TY-Taoyuan, WH-Wuhan, XLJ-Xuliujing, YT-Yingtan and ZY-Zunyi. XJB and XLD refer to Xiangjiaba Dam and Xiluodu Dam, respectively.

and the water level in the reservoir maintains a relatively high level in order to meet the needs of hydropower plants and water navigation. During the flood season from June to September, the TGD discharges most of the reservoir water to meet the requirement for flood control.

Previous studies reveal that the TGD have caused profound impacts on downstream Changjiang, the Changjiang delta and the East China Sea in terms of hydraulics and sediment dynamics (Yang et al., 2007; Xu and Milliman, 2009; Chen et al., 2010; Nakayama and Shankman, 2013; Yang et al., 2015), water quality (Wu et al., 2003; Nilsson et al., 2005; Plateau, 2006; Müller et al., 2008), and ecosystem (Challman, 2000; Shen and Xie, 2004). A long-term hydraulic observation data from national gauge stations indicates a significant decrease of the Changjiang sediment flux since 1950s (Yang et al., 2006b; Xu and Milliman, 2009), but weak changes in annual water discharge (Yang et al., 2011). However, the seasonal water cycle in the mid-lower Changjiang mainstream (downstream the TGD) has changed apparently since the impoundment of the TGD in 2003, mostly because of the water regulation for hydropower and flood control (Chen et al., 2001; Yang et al., 2010; Gao et al., 2013). For example, the peak water discharge has shifted from July before 2000 to August or September after the TGD operation (Xu and Milliman, 2009; Gao et al., 2013). Nevertheless, compared to the river sediment flux, the damming effect on the Changjiang river water cycle has not received much attention.

The stable hydrogen and oxygen (H and O) isotopes in river water provide diagnostic indications for hydrological processes and water cycling (Gat, 1996; Kendall and Coplen, 2001; Gibson et al., 2002; Good et al., 2015). But, the use of isotopic tracer for river water cycle has been largely limited due to the lack of long-term observation. The first systematic investigation of stable H and O isotopic compositions in the Changjiang was initiated in 2002 by a program of "The isotopic tracing of hydrology processes in the Yangtze River basin" (Lu et al., 2012), which was a cooperative research of "Designing criteria for a network to monitor isotope composition of runoff in large rivers" by GNIR from IAEA. Afterwards, a number of studies focused on the spatial variations of stable H and O isotopic compositions in the Changjiang river water, which found gradual increase of heavy H and O isotopic compositions from the source region to estuary (Li et al., 2010; Li et al., 2011; Ding et al., 2014). However, the seasonal variations of stable H and O isotopic compositions in the Changjiang river water are rarely investigated except for Lu et al. (2012). For example, Müller et al. (2012) indicated that the O isotope in the Changjiang river water is enriched in heavy isotope around May but depleted in September, which largely depends on O isotopic composition in precipitation over the large catchment. In this research, we present a thorough comparison of stable H and O isotopic compositions between Changjiang river water and precipitation in early 1980s and 2000s, aiming to investigate the alteration of Changjiang river water cycle and the potential controls on the stable H and O isotopic basis.

2. Hydrogeological setting

The Changjiang is the longest river in East Asia and the third longest in the world. It originates from the Tibetan Plateau (~5170 m in altitude on average) and flows eastward to the East China Sea. The catchment covers a total area of about 1.8×10^6 km^2 (Fig. 1), and drains the three major topographic reliefs in China, from the upper rocky valley to the lower alluvial river channel and flood plain. Traditionally, the Changjiang river channel is divided into three sections. The upper reaches refers to the section from Yibin to Yichang; the middle reaches starts from Yichang to Hukou, where Poyang Lake meets the river; the lower reaches is from Hukou to the river mouth. The Jinshajiang River as the largest tributary in the Changjiang river system joins the mainstream at Yibin where the "Changjiang" is formally named. Most of the major tributaries are located in the upper Changjiang catchment upstream the Three Gorges region.

Most of the Changjiang River basin is located in the subtropical and temperate climate zone, and subject to subtropical monsoon climate. There are two types of monsoon systems prevailing in the Changjiang catchment, the Siberian northwest winter monsoon and the Asian southeast summer monsoon (or Indian southwest summer monsoon in the upper Changjiang basin) (Qian et al., 2002). The annual average precipitation in the Changjiang catchment is about 1057 mm and the total amount is 1912 km^3 per year. The precipitation in Changjiang catchment is closely related to the monsoon system over east China. The first precipitation period starts from late April to mid-May in the lower catchment. When the South China Sea summer monsoon onsets, the rainy season is formed in the south of the Changjiang River, and migrates northwestward from the lower Changjiang basin in middle June to north China in middle August (Ding and Chan, 2005). Then, the autumn rainy season is formed in eastern China from late August to September. Under the controlling of monsoon climate, the precipitation in the Changjiang catchment is quite complex, and with large spatial and temporal variations. For example, about 70–90% of the total annual precipitation falls from May to September.

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