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

Chao Li [a,b], Shouye Yang [a,c,*], Ergang Lian [a], Chengfan Yang [a], Kai Deng [a], Zhongfang Liu [a]

[a] State Key Laboratory of Marine Geology, Tongji University, Shanghai, 200092, PR China
[b] College of Environmental Science and Engineering, Tongji University, Shanghai 200092, PR China
[c] Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, PR China

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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.

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

* Corresponding author at: State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, PR China.
E-mail address: syyang@tongji.edu.cn (S. Yang).

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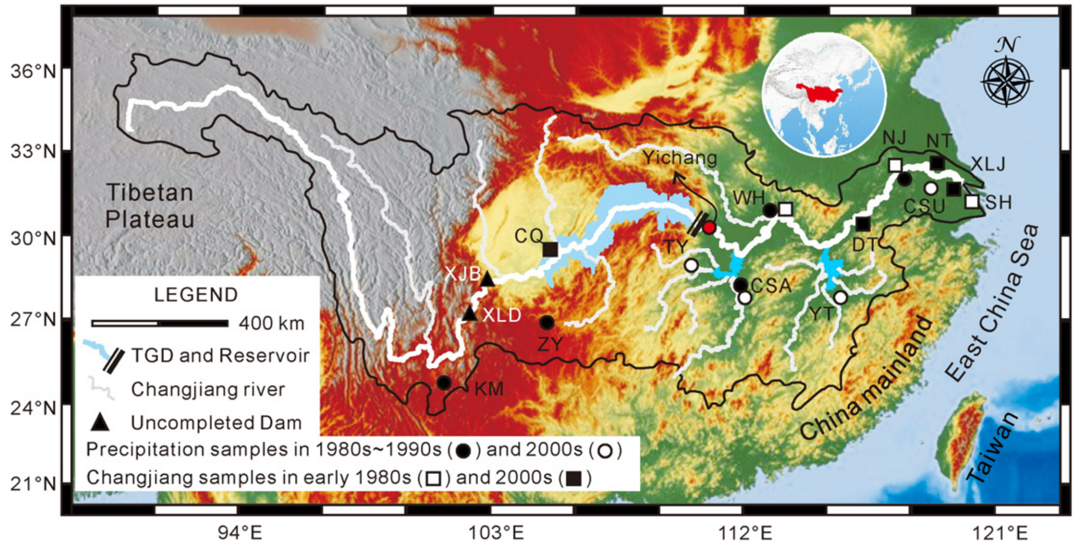

Fig. 1. Map of the Changjiang river basin. The TGD and sampling sites for isotopic measurements are all indicated (see the legend and Table 1 for the details). Abbreviations for sampling site are: CSA-Changsha, CQ-Chongqing, CSU-Changshu, DT-Datong, KM-Kunming, NJ-Nanjing, NT-Nantong, SH-Shanghai, TY-Taoyuan, 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.

3. Materials and methods

A total of 75 river water samples from the lower Changjiang mainstream near Nantong (31.96°N, 120.83°E) were collected once or twice a week with pre-cleaned and sealed plastic bottles from November 2012 to December 2014. All of the water samples were taken at about 50 cm below water surface and sealed in a plastic bottle immediately. The river water sample was measured by the a liquid water isotope analyzer (IWA-45EP from Los Gatos Research, Inc. (LGR), Mountain View, USA) in the State Key Laboratory of Marine Geology at Tongji University. Result is reported as δD and $\delta^{18}O$ in ‰ versus the Vienna Standard Mean Ocean Water standard (V-SMOW). The analytical precision is better than ±0.5‰ for δD value and ±0.1‰ for $\delta^{18}O$ value, respectively.

For the investigation of the damming influence on the Changjiang river water cycle, historical δD and $\delta^{18}O$ records in precipitation and river water are compiled and compared in this study. The historical δD and $\delta^{18}O$ data in precipitation from the Changjiang catchment are mainly from GNIP database system (IAEA), while the precipitation δD and $\delta^{18}O$ data after the year 2000 are from Liu et al. (2010) and Huang (2013). Apart from the Nantong samples measured in this study, historical δD and $\delta^{18}O$ data of the Changjiang river water from Gu et al. (1989) and Lu et al. (2012) are also utilized for a comprehensive investigation between river water and precipitation in multiple sites. Detailed information and isotopic data are given in Table 1 and Appendix Table A. 1.

To make a further investigation of seasonal $\delta^{18}O$ variations in precipitation and the Changjiang river water, a precipitation-weighted monthly average of $\delta^{18}O$ is calculated for each station (Table 2). On this basis, we define a monthly $\delta^{18}O$ anomaly as weighted month-averaged $\delta^{18}O$ value minus the yearly average (Table 3). When the weighted month-average $\delta^{18}O$ is lower than the yearly average, the $\delta^{18}O$ anomaly will be negative and if the weighted month-average $\delta^{18}O$ is higher than the yearly average, the anomaly turns to be positive. The $\delta^{18}O$ anomaly is thus calculated for both precipitations in the Changjiang catchment and the Changjiang river water, before and after TGD construction in 2003. This monthly $\delta^{18}O$ anomaly highlights the seasonal variations of $\delta^{18}O$ compared to the yearly average, and clearly reveals the subtle changes of water cycle in a catchment relative to the absolute isotopic compositions in precipitation and river water.

Table 1
The detailed information of isotopic observation sites and data sources.

Stations	Abbr.	Lon.[a] (°)	Lat. (°)	Alt. (m)	Start	End	N	Data sources
Meteoric precipitation								
Kunming	KM	25.02	102.68	1892	1986	2003	152	*GNIP* (*IAEA*)
Wuhan	WH	30.62	114.13	23	1986	1998	50	*GNIP* (*IAEA*)
Changsha	CSA	28.20	113.07	37	1988	1992	57	*GNIP* (*IAEA*)
Zunyi	ZY	27.70	106.88	844	1986	1992	74	*GNIP* (*IAEA*)
Nanjing	NJ	32.18	118.18	26	1987	1992	58	*GNIP* (*IAEA*)
Changshu	CSU	31.33	120.42	3.1	2005	2006	–[b]	Liu et al. (2010)
Taoyuan	TY	28.93	111.44	106	2005	2010	–	Liu et al. (2010)
Yingtan	YT	28.12	116.56	45	2005	2010	–	Liu et al. (2010)
Changsha	CSA	28.19	112.93	59	2010	2012	482	Huang (2013)
Changjiang river water								
Wuhan	WH	30.55	114.29	15	1982	1983	12	Gu et al. (1989)
Nanjing	NJ	32.11	118.74	1	1982	1983	12	Gu et al. (1989)
Shanghai	SH	31.41	121.50	0	1982	1983	12	Gu et al. (1989)
Chongqing	CQ	29.56	106.59	159	2005	2005	17	Lu et al. (2012)
Datong	DT	30.77	117.64	2	2004	2005	20	Lu et al. (2012)
Xuliujing	XLJ	31.50	121.39	0	2004	2005	24	Lu et al. (2012)
Nantong	NT	31.96	120.90	0	2012	2014	75	This study

[a] Lon. = longitude; Lat. = latitude; Alt = altitude; N = sample number.
[b] "–" data unavailable.

4. Results and discussion

4.1. Dominance of river water stable hydrogen and oxygen isotopes by monsoon-induced precipitation

The seasonal δD and $\delta^{18}O$ isotopic values in the Changjiang river water at Nantong are given in Appendix Table A. 1. The δD value in Nantong river water ranges from −73.3‰ to −38.3‰, with a mean value of −56.4‰. Then $\delta^{18}O$ value varies from −10.6‰ to −6.4‰ with a mean value of −8.5‰. The plot of δD versus $\delta^{18}O$ (Fig. 2) reveals that the Nantong river water samples are highly linearly related, $\delta D = 8.6 \times \delta^{18}O + 16.6$ ($R^2 = 0.95$). Though this regression line of δD and $\delta^{18}O$ is slightly higher in slope and intercept than Global Meteoric Water Line (GMWL) (Craig, 1961), it is in great accordance with Local Meteoric Water Line (LMWL) for representative cities in the Changjiang catchment, e.g. $\delta D = 7.34 \times \delta^{18}O + 2.56$ ($R^2 = 0.98$) at Kunming, $\delta D = 8.47 \times \delta^{18}O + 15.46$ ($R^2 = 0.99$) at Changsha and $\delta D = 8.43 \times \delta^{18}O + 17.46$ ($R^2 = 0.98$) at Nanjing (Zhang and Yao, 1998).

The water on land surface is primarily replenished by precipitation during the global water cycle, thus the stable H and O isotopic values in river water are mainly determined by precipitation (Kendall and Coplen, 2001). Our data indicates that a good correlation exists between δD and $\delta^{18}O$ in the Changjiang river water throughout the year, and the regression line is close to the LMWL and in the range of GMWL (Fig. 2). It confirms that the stable H and O isotopic compositions in the Changjiang river water are primarily determined by precipitation (Lu et al., 2012; Ding et al., 2014). As δD is highly correlated with $\delta^{18}O$ in the Changjiang river water, only $\delta^{18}O$ is referred in the following discussion.

4.2. Seasonal variations of $\delta^{18}O$ in the Changjiang river water and precipitation

The monthly $\delta^{18}O$ anomalies in both precipitation and river water show regular and similar variations within a year, which are positive in the first half of the year (January to May or June) and negative in the second half of the year (June or July to December) (Fig. 3a and b). The Changjiang basin is subject to typical monsoon climate, which causes a distinct variability in annual precipitation and alternation of dry and wet seasons. Generally, the summer monsoon starts from middle May and ends in late November, while the winter monsoon lasts from late November to next middle May in the Changjiang catchment (Qian et al., 2002). The seasonal variations of monthly $\delta^{18}O$ anomaly are in good concert with the seasonal reversal of monsoon circulation.

Within the period of winter monsoon season, cold and dry air masses from the high-latitudinal regions (e.g., Siberia) pass through the Changjiang catchment, result in high $\delta^{18}O$ in the winter precipitation (Araguás-Araguás et al., 1998) and thus positive $\delta^{18}O$ anomaly in our calculation (Fig. 3a). The summer monsoon starts in early April in the source region and arrives in the lower Changjiang catchment in early or middle June, carrying abundant moisture from the western Pacific Ocean (Qian et al., 2002; Ding and Chan, 2005). As a result, the summer precipitation is characterized by lower $\delta^{18}O$ value (Araguás-Araguás et al., 1998) and negative $\delta^{18}O$ anomaly (Fig. 3a). Therefore, the seasonal variations of monthly $\delta^{18}O$ anomaly in precipitation are primarily induced by alternative dominance of different monsoon systems.

The monthly $\delta^{18}O$ anomaly in the Changjiang river water at Nantong displays a similar trend with the variation of $\delta^{18}O$ anomaly in precipitation. However, the $\delta^{18}O$ anomaly of the Changjiang river water shows smaller ranges relative to those in precipitation. This is because the precipitation is transported into the river along diverse flow paths in the unsaturated and saturated zones as tracers migrate through the subsurface toward the stream network (McGuire and McDonnell, 2006). As a result, the H and O isotopic signals in river water are consequently damped (i.e., decrease in standard deviation and amplitude) and lagged

Table 2
Precipitation-weighted monthly averages of $\delta^{18}O$ value in the water samples from the Changjiang catchment.

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\delta^{18}O$ of precipitation (‰)												
(1986–2003)												
NJ[a]	−7.86	−6.14	−7.08	−3.11	−4.74	−10.05	−10.03	−9.02	−7.89	−6.77	−7.56	−8.68
	(1.66[b])	(2.16)	(2.59)	(0.81)	(1.44)	(2.77)	(2.35)	(1.30)	(1.84)	(2.39)	(3.72)	(2.89)
WH	−5.29	−3.57	−5.77	−3.20	−3.25	−7.86	−9.49	−7.40	−9.26	−8.01	−6.64	−4.95
	(1.06)	(1.22)	(1.78)	(1.53)	(0.93)	(2.33)	(3.51)	(2.89)	(4.80)	(3.35)	(2.59)	(2.58)
CSA	−5.38	−4.36	−3.30	−2.57	−2.32	−8.10	−9.47	−9.32	−10.70	−6.70	−6.29	−4.45
	(2.18)	(0.67)	(0.90)	(0.90)	(0.69)	(2.21)	(3.24)	(4.70)	(2.84)	(1.71)	(4.32)	(1.59)
ZY	−3.70	−2.12	−3.89	−4.50	−4.72	−8.15	−11.50	−11.17	−12.11	−8.60	−7.76	−4.40
	(1.30)	(0.48)	(1.29)	(1.76)	(1.23)	(1.70)	(3.61)	(2.64)	(3.53)	(1.86)	(1.71)	(1.46)
KM	−6.13	−3.04	−4.84	−3.18	−6.28	−8.40	−12.35	−13.36	−10.84	−11.07	−9.45	−4.55
	(1.57)	(0.60)	(0.95)	(0.47)	(0.74)	(0.81)	(0.89)	(0.98)	(0.75)	(1.22)	(1.31)	(0.90)
(2005–2012)												
CSA	−6.27	−3.82	−5.00	−3.33	−5.62	−8.86	−9.44	−9.51	−8.73	−9.74	−7.03	−7.16
TY	−4.13	−4.67	−3.93	−3.47	−4.33	−6.53	−10.73	−8.67	−8.87	−6.33	−6.87	−4.33
YT	−3.35	−3.15	−3.62	−4.02	−5.02	−6.96	−8.43	−5.95	−6.22	−6.15	−5.09	−7.76
CSU	−5.04	−5.76	−3.01	−4.55	−5.84	−8.89	−8.71	−7.51	−7.78	−5.31	−6.25	−5.87
$\delta^{18}O$ of Changjiang river water (‰)												
(1982–1983)												
WH	−4.76	−7.44	−4.66	−6.42	−4.75	−4.28	−7.97	−9.36	−8.74	−8.53	−7.36	−6.35
NJ	−5.77	−6.19	−5.54	−4.27	−1.94	−5.04	−6.52	−6.01	−7.28	−8.42	−6.15	−5.46
SH	−5.05	−6.21	−4.53	−3.66	−3.37	−4.96	−5.40	−7.75	−5.75	−7.56	−6.27	−6.07
(2004–2014)												
NT	−8.54	−9.77	−8.25	−7.09	−7.45	−7.30	−7.82	−9.50	−9.49	−9.44	−9.34	−8.25
	(2.47)	—[c]	(1.58)	(1.16)	(0.68)	(0.47)	(1.17)	(1.07)	(0.68)	(1.32)	(0.76)	(1.53)
CQ	−7.47	−6.83	−5.23	−8.00	−4.81	−6.29	−7.24	−9.68	−10.28	—	—	—
DT	−7.73	−6.70	−5.88	−7.14	−6.13	−6.46	−6.88	—	—	−9.47	−8.84	−8.53
XLJ	−8.28	−9.44	−9.23	−9.15	−8.38	−7.51	−9.63	−8.79	−9.85	−10.41	−10.09	−9.81

[a] Details for the sampling sites and data sources are listed in Table 1.
[b] 2σ standard deviation for weighted monthly average of $\delta^{18}O$.
[c] "—" data unavailable.

compared to the input precipitation (Kendall and Coplen, 2001; Rodgers et al., 2005).

4.3. Change of the Changjiang river water cycle as evidenced from $\delta^{18}O$ anomaly

As discussed above, the patterns of $\delta^{18}O$ anomaly in both the precipitation and Changjiang river water are characterized by seasonal switch from positive in the first half year to negative in the second half year. For precipitation, this switch of $\delta^{18}O$ anomaly occurs consistently between May and June from 1980s to the past decade (Fig. 3a), which reflects the arrival of summer monsoon and the onset of the rainy season (Ding and Chan, 2005; Liu et al., 2014). By contrast, the switching time of $\delta^{18}O$ anomaly in the Changjiang river water shifts apparently from between June and July in the early 1980s to between July and August after 2000s (Fig. 3b).

Table 3
Precipitation-weighed monthly anomaly of $\delta^{18}O$ in the water samples from the Changjiang catchment.

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\delta^{18}O$ anomaly of precipitation (‰)												
(1986–2003)												
NJ[a]	−0.45	1.27	0.33	4.30	2.67	−2.64	−2.62	−1.61	−0.48	0.64	−0.15	−1.27
WH	0.94	2.66	0.45	3.03	2.97	−1.63	−3.26	−1.17	−3.04	−1.79	−0.41	1.28
CSA	0.70	1.72	2.78	3.51	3.76	−2.02	−3.39	−3.24	−4.62	−0.62	−0.21	1.63
ZY	3.19	4.77	2.99	2.38	2.16	−1.26	−4.61	−4.28	−5.22	−1.71	−0.88	2.48
KM	1.66	4.75	2.95	4.61	1.51	−0.61	−4.55	−5.57	−3.04	−3.28	−1.66	3.24
(2005–2012)												
CSA	0.77	3.22	2.04	3.71	1.42	−1.81	−2.40	−2.47	−1.68	−2.70	0.02	−0.11
TY	1.94	1.41	2.14	2.61	1.74	−0.46	−4.66	−2.59	−2.79	−0.26	−0.79	1.74
YT	2.13	2.33	1.86	1.46	0.46	−1.48	−2.95	−0.48	−0.75	−0.68	0.39	−2.28
CSU	1.17	0.45	3.20	1.66	0.37	−2.68	−2.50	−1.30	−1.57	0.90	−0.04	0.34
$\delta^{18}O$ anomaly of Changjiang river water (‰)												
(1982–1983)												
WH	1.96	−0.72	2.06	0.30	1.97	2.44	−1.25	−2.64	−2.02	−1.81	−0.64	0.37
NJ	−0.05	−0.47	0.18	1.45	3.78	0.68	−0.80	−0.29	−1.56	−2.70	−0.43	0.26
SH	0.50	−0.66	1.02	1.89	2.18	0.59	0.15	−2.20	−0.20	−2.01	−0.72	−0.52
(2004–2014)												
NT	−0.02	−1.25	0.27	1.43	1.07	1.22	0.70	−0.98	−0.97	−0.92	−0.82	0.27
CQ	−0.16	0.48	2.08	−0.68	2.50	1.03	0.07	−2.36	−2.97	—[b]	—	—
DT	−0.35	0.68	1.50	0.24	1.24	0.92	0.49	—	—	−2.10	−1.46	−1.16
XLJ	0.93	−0.23	−0.01	0.06	0.84	1.71	−0.42	0.42	−0.64	−1.20	−0.88	−0.59

[a] Details for the sampling sites and data sources are listed in Table 1.
[b] "—" data unavailable.

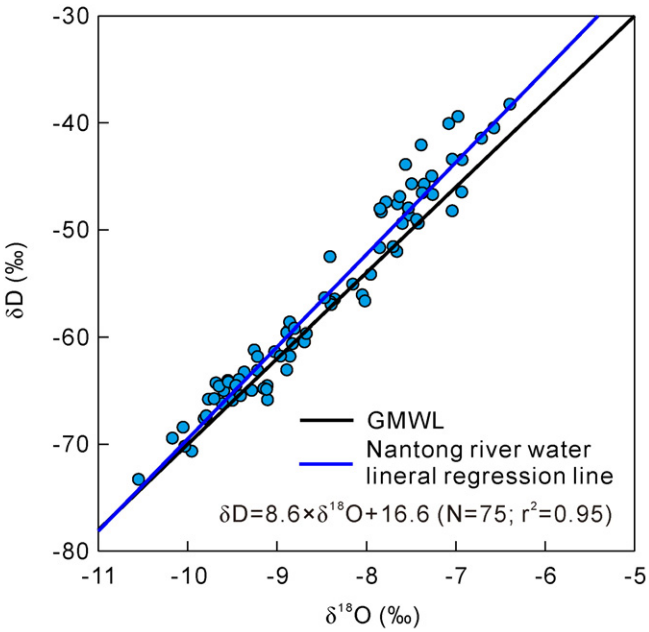

Fig. 2. Relationship between δD and $\delta^{18}O$ in the Changjiang river water at Nantong. GMWL (Craig, 1961) indicates global meteoric water line.

Long-term observations of $\delta^{18}O$ in precipitation from the Changjiang catchment are limited or not updated, e.g. the GNIP data related to the Changjiang catchment are mainly from 1980s to 1990s. Nevertheless, the $\delta^{18}O$ record from GNIP for Kunming station indicates that the mean annual $\delta^{18}O$ in precipitation does not change much from 1986 to 2003 while the annual precipitation amount on basinal scale is also relatively constant since 1950s (Fig. 4) (Yang et al., 2015). In addition, a longer $\delta^{18}O$ record of precipitation from Urumqi in the northwest of Changjiang basin, also shows a constant annual variation from 1986 to 2009 (Liu et al., 2014). Overall, the patterns of $\delta^{18}O$ and the $\delta^{18}O$ anomaly in precipitation in the Changjiang catchment are relatively constant during the last three decades.

Compared to the precipitation, the studies of river stable H and O isotopic compositions are far more inadequate. Long-term isotopic investigation for the Changjiang river water is even rare (Lu et al., 2012; Ding et al., 2014), which largely confines the application of isotopic approach in hydrological processes and river water cycle studies at different spatial and temporal scales. The first investigation of river stable H and O isotopic compositions in the Changjiang river was carried out by Gu et al. (1989) in early 1980s. Yet, in the following 20 years, the river stable isotopic study in the Changjiang river is suspended until 2002 by the program of “The isotopic tracing of hydrology processes in the Yangtze River basin” (Lu et al., 2012). Hence, Gu et al. (1989) provide the valuable and even exclusive background for stable H and O isotopic compositions in the Changjiang river water before massive dam construction started in the late 1990s. Our study indicates that the switching time of $\delta^{18}O$ anomaly in the Changjiang river water is between June and July in the early 1980s, which is about one month lag compared to the $\delta^{18}O$ anomaly switch of precipitation (Fig. 3b).

It is inferred that this time lag between river water and precipitation may be related to the change of temperature, evapotranspiration by soil or vegetation, exchange with groundwater, or catchment retention (McGuire and McDonnell, 2006) of precipitation due to infiltration in aquifer. Previous study indicated that the water residence time in soil moisture ranged up to 2 months (Pidwirny, 2006). However, the switching time of $\delta^{18}O$ anomaly in the Changjiang river water in 2000s is between July and August, which is apparently one month lag compared to that in the early 1980s. This change of $\delta^{18}O$ anomaly variation thus suggests one month slowdown of river water cycle in 2000s compared to early 1980s.

Due to the limited isotopic data, only one year's record of seasonal $\delta^{18}O$ in the river water is available for 1980s. But the data from three independent sampling sites all exhibit similar $\delta^{18}O$ anomaly distributions throughout a year (Fig. 3b). In this regard, the difference of seasonal

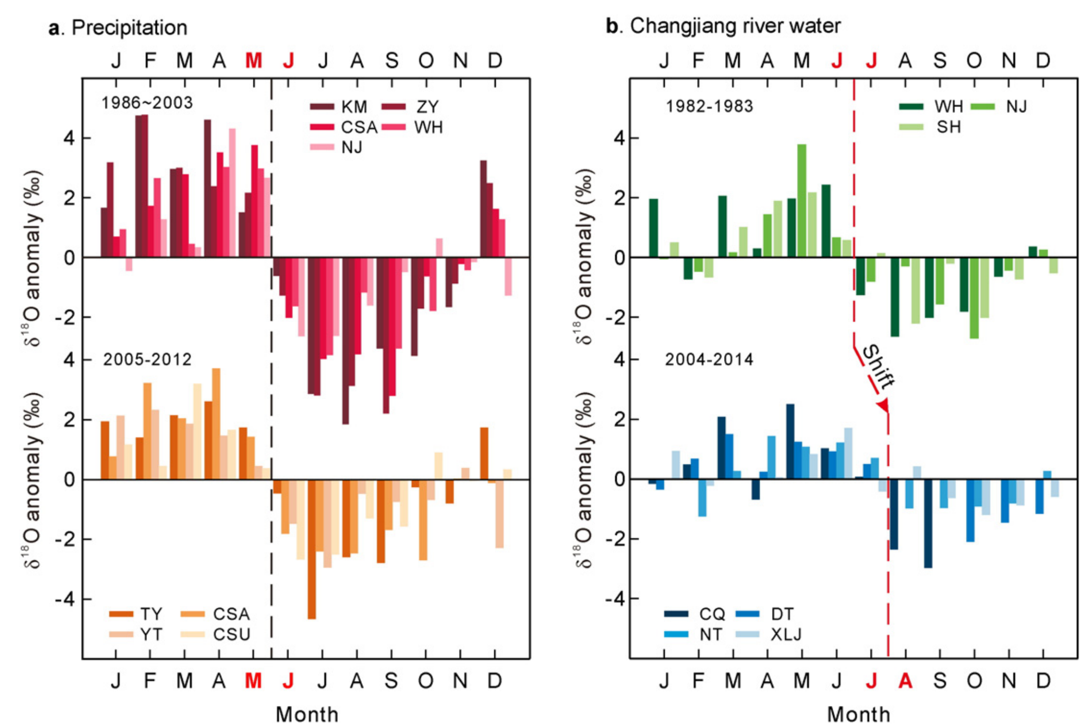

Fig. 3. Monthly $\delta^{18}O$ anomaly in the precipitation (a) and Changjiang river water (b) in 1980s–1990s and after 2003. The monthly $\delta^{18}O$ anomaly is defined as the month-averaged $\delta^{18}O$ minus the yearly average in each station.

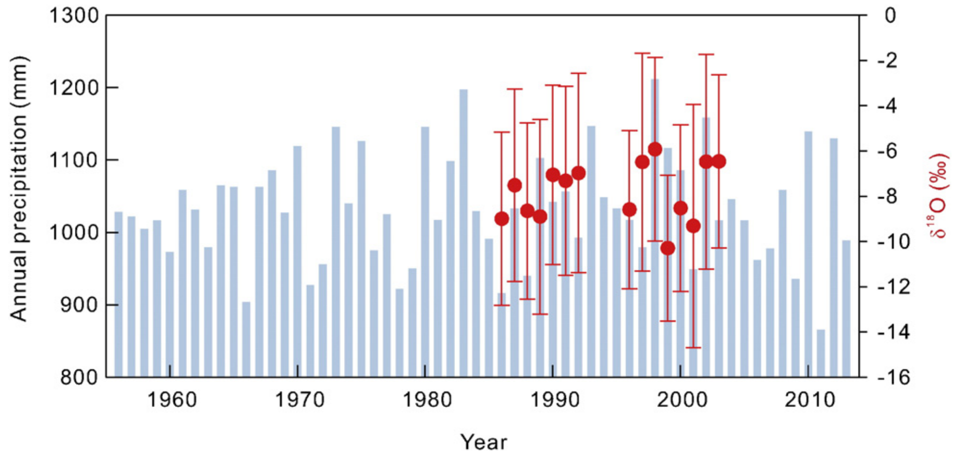

Fig. 4. Basin scale annual precipitation in the Changjiang catchment since 1950s (Reproduced from Yang et al. (2015)) and precipitation $\delta^{18}O$ (in red) at Kunming from GNIP between 1986 and 2003.

$\delta^{18}O$ anomaly between early 1980s and after 2000s is overall remarkable, which implies substantial changes in the river water cycle during the last thirty years.

4.4. Damming effect on the Changjiang river water cycle based on river water $\delta^{18}O$

As discussed in Section 4.1, the seasonal $\delta^{18}O$ variations in the Changjiang river water are mainly determined by local precipitation. However, the precipitation amount and $\delta^{18}O$ in rainwater have remained relatively constant over the past thirty years (Fig. 4). On this basis, the trapping effect of numerous large dams in the Changjiang catchment appears to be the most likely reason for this alteration of river water cycle.

Approximately 50,000 dams have been constructed in the Changjiang catchment over the past several decades (Yang et al., 2011), among which the TGD is the largest in the world. During the past decades, the total storage capacity of the reservoirs in the Changjiang catchment increases exponentially (Fig. 5a), and reaches 141.94 km^3 in 2013, which accounts for 16.4% of total surface water resources (867.45 km^3) in the catchment (Changjiang Water Resources Commission, 2013).

Vörösmarty et al. (1997) proposed a simple estimation of the river water aging in the reservoir in relation to impoundment, which was

$$\Delta\tau_R = \frac{V_R}{Q}.$$

In this equation, V_R is the total effective reservoir volume, and Q is the water discharge from the reservoir. There are over 50,000 dams in the Changjiang catchment. Providing all the reservoirs in the Changjiang catchment are combined as one integrated unit and the total water discharge is represented by the river discharge from Datong gauge station, which is the most seaward gauging station along the river. In this case, the calculated average river water aging in 1980s is 0.26 ± 0.03 month for the entire basin, while it changes to 1.67 ± 0.38 month since 2003 when the TGD first impounded (see Appendix Table A. 2 for details). Thus, the net increase of river water aging induced by construction of reservoirs in the Changjiang catchment between 1980s and after 2003 is roughly 1.41 ± 0.41 month. This estimation may bear large uncertainty because there are over 50,000 dams built in the Changjiang catchment, and the effective reservoir volume for each specific reservoir is difficult to calculate. However, the result of 1.41 ± 0.41 month river water aging is generally consistent with the one-month time lag deduced from monthly $\delta^{18}O$ anomaly (Fig. 3b), which to a great extent verifies our previous inference of the damming effect based on isotopic evidence. A recent study indicates that the reservoir evaporation accounts for 22% of China's total water consumption (Liu et al., 2015). Moreover, a quantitative estimation of human impacts on the Changjiang sediment discharges over the past decades reveals that the dam construction was the dominant factor (~88%) contributing to the decline of sediment flux, followed by the water and soil conservative measures (15 ± 5%) (Dai et al., 2008).

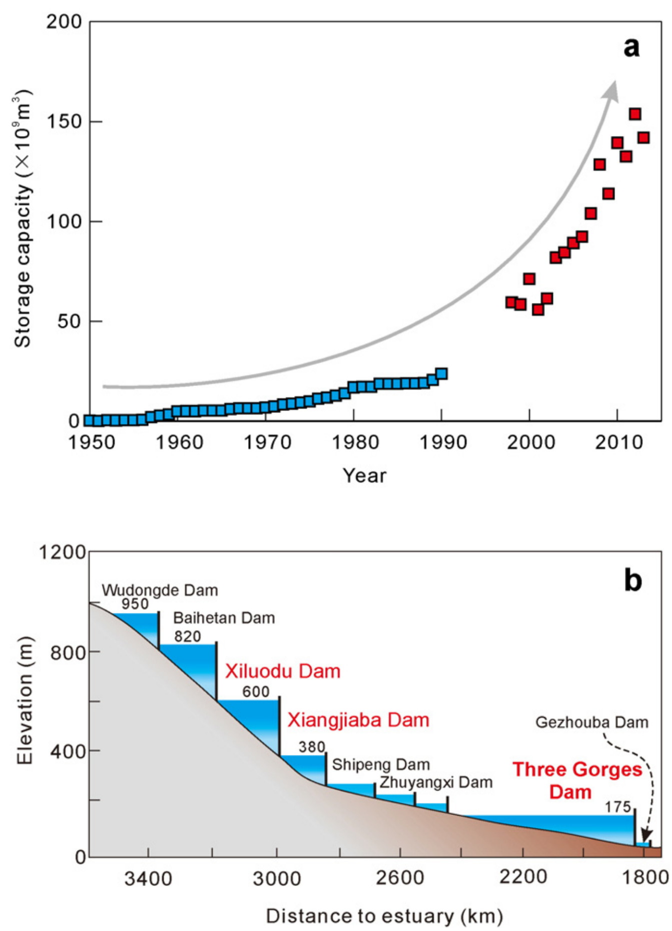

Fig. 5. An increase of total storage capacity of reservoirs in the Changjiang catchment over the last half-century (a) and sketch map showing the dams distribution along the Changjiang upstream (b). Storage capacity of reservoirs data before 1998 are taken from Yang et al. (2006a) and data after 1998 are sourced from the Changjiang Water Resources Commission (2013). Sketch map (b) is reproduced from Calvingao at *https://en.wikipedia.org*, [CC BY-SA 3.0 (*http://creativecommons.org/licenses/by-sa/3.0*)].

It is notable that apart from the damming effect, other environmental factors like evapotranspiration may also exert important influence on the $\delta^{18}O$ in river water (Jasechko et al., 2013; Good et al., 2015). The actual basin evapotranspiration is a complex process that is determined by soil, vegetation and climatic parameters, like air temperature, humidity and wind speed. Some influences are however hard to clarify in this paper because of the limited stable H and O isotopic data from soil and vegetation in the Changjiang catchment, especially in 1980s. Air temperature and humidity in Yichang (Fig. 1) where the TGD is located are compared between 1980s and after 2000 (Fig. 6a and b). The result shows that both air temperature and humidity are quite similar between 1980s and after 2000, without significant change in seasonal variations. It is inferred that the evapotranspiration condition may not change much during the last 30 years. Some modeling work will be much helpful to make a quantitative assessment for the evapotranspiration contribution to river $\delta^{18}O$. Besides, the ion exchange between water and rock may also alter the river water $\delta^{18}O$ (Hoefs, 2009), but this process can be ignored in an open system like surface runoff due to large water/rock ratio (Meunier, 2005).

Compared to the sediment discharge, little attention has been paid to water retention by the TGD because the annual water discharges observed from hydraulic gauge stations have not changed significantly in the past several decades (Yang et al., 2011). Lacking long-term and high-resolution hydrological observations, unfortunately, has often limited our recognition of subtle environmental changes in this large river system. The change of $\delta^{18}O$ anomaly pattern in this study confirms that the seasonal water cycle in the mid-lower Changjiang mainstream has already been altered due to water trapping or retaining effects by the dams (Chen et al., 2001; Yang et al., 2007; Gao et al., 2013). We believe that the available data to date is still insufficient for a robust assessment and full evaluation of the damming impacts on the Changjiang river water cycle. Nevertheless, this study presents a substantial alteration of $\delta^{18}O$ in the Changjiang river water in the past thirty years in relation to the damming effects, and thus the damming impacts on the hydrodynamics and sustainability of ecosystems have to be carefully considered in the future studies. In addition, the stable H and O isotopic approaches may shed new light and provides valuable constraints for tracing imperceptible changes in the water cycle in a large catchment where the natural environment and human activities strongly interact. Compared to other large rivers, e.g. the Mississippi River or Danube River, the stable H and O isotopic study is not comparable in the Changjiang, as quite rare isotopic studies have been carried out in the Changjiang catchment. Overall, this study provides a long term and high resolution data of δD and $\delta^{18}O$ in the Changjiang river water, and is thus an important complement for the stable isotopic database and future studies.

4.5. Dam activities in the Changjiang catchment and the future prospection

Hydraulic engineering has produced global-scale impacts on the terrestrial water cycle (Vörösmarty and Sahagian, 2000). As one of the largest hydroelectric engineering projects in the world, the TGD has long been controversial and received close attention from the public and scientific community as well. Being a power station, the TGD can generate 22,500 MW of electric power at its full operation, as much electricity as 18 nuclear power plants (Kennedy, 1999). According to the National Development and Reform Commission of China, 366 g of coal would have produced 1 kWh of electricity during 2006. In this regard, the TGD can reduce coal consumption by 31 million tons per year, preventing about 100 million tons of greenhouse gas emissions, and millions of tons of dust and other hazardous chemicals (Brown et al., 2008). Except for electricity production, the TGD also plays a significant role in increasing the shipping capacity and reducing the flood risk in the mid-lower Changjiang catchment. These advantages of TGD construction, however, have not been widely recognized. In contrast, concerns and criticisms about the TGD are raised long before the project was launched and have continued till now (Challman, 2000; Wu et al., 2003; Shen and Xie, 2004; Plateau, 2006; Gleick, 2008). One of the strongest and most consistent arguments made by project opponents lies in the vast scale of the environmental and social transformations of the watershed of the Changjiang both upstream and downstream of the dam itself (Gleick, 2008).

At present, two large dams, the Xiangjiaba Dam and the Xiluodu Dam (Fig. 1), are just completed in 2015 in the upper Changjiang valley (Fig. 5b). The Xiangjiaba Dam is located in the Jinshajiang River, the largest tributary of the Changjiang, and approximately 700 km west to the TGD. The total electric generating capacity is designed to be approximately 6400 MW, and the storage capacity is 5.16×10^9 m^3, equal to 1/4 of the TGD. The Xiluodu Dam is also situated in the Jinshajiang River, but is much larger than the Xiangjiaba Dam. Its total electric generating capacity is approximately 12,600 MW and its storage capacity reaches 11.6×10^9 m^3, equivalent to half of the TGD. It will be the second-largest dam in China and the third-largest in the world. Their impacts on the Changjiang river environment are still unknown and await further exploration. However, it is widely speculated that recent frequent earthquakes in the upper Changjiang valley are linked to the filling of these two gigantic reservoirs (Qiu, 2014).

It is difficult, if not impossible, to equitably weigh the pros and cons of the dam construction because of the difficulty of putting monetary values on the complex environmental, social, and cultural impacts of the hydroelectric project. "Blessed dams or damned dams" (Milliman, 1997) is actually a game between human needs and environment sustainability. The controversy over dam construction has lasted for

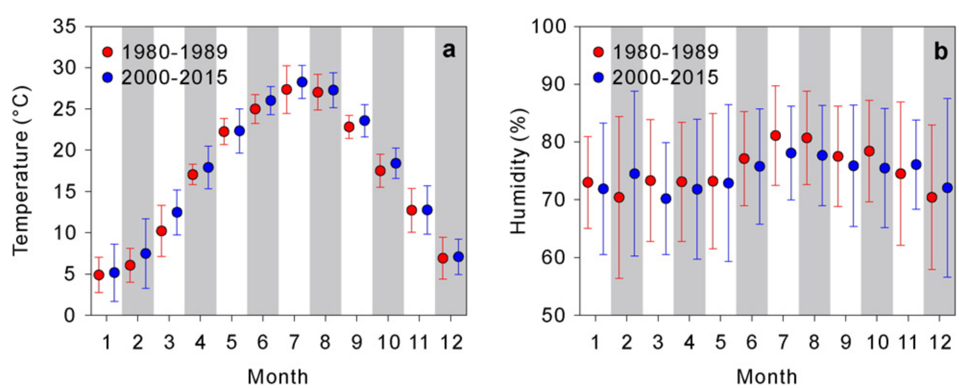

Fig. 6. Seasonal comparisons of air temperature and humidity between 1980s and after 2000 in Yichang (indicated in Fig. 1). Meteorologic data are from National Meteorological Information Center (*http://data.cma.cn/*).

centuries and will not end readily. A long-term plan for sustainable water management is urgently required in China, with a better balancing of economic benefit and environment protection.

5. Conclusions

This paper presents a new perspective and the first isotopic evidences regarding the numerous dams' impact on the Changjiang water cycle. We find that the seasonal isotopic variations in the Changjiang river water are closely related to the isotopic compositions of local precipitation. However, the time lag of the river water response to precipitation has changed from one month in early 1980s to approximately two months after 2000s. It is thus inferred that the one-month lag of this response demonstrates a significant slowdown of the Changjiang river water cycle. We believe that this change is a result of the trapping effect and water regulation of reservoirs, especially by the Three Gorges Dam, which is the largest one among the numerous dams in the large Changjiang catchment. Though the dams' impact on riverine and marginal sea environments is still controversial, two more large hydraulic projects are now under construction in the upper Changjiang valley, which are of the same magnitude as the TGD. How to balance the energy demands required for rapid socioeconomic development with the need for environmental protection presents a severe and urgent social problem for the Chinese government. On the other side, the present research confirms that stable isotopic compositions in river water are sensitive to the alteration of river cycle induced by both natural and anthropogenic activities. Furthermore, this study overall offers a long term and high resolution data of δD and $\delta^{18}O$ in the Changjiang river water, which serves as an indispensable complement for the stable isotopic archives in the Changjiang catchment and provides important database for future studies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gexplo.2016.03.006.

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