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Quantifying the impact of the Three Gorges Dam on the thermal dynamics of the Yangtze River

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Huayang Cai¹, Sebastiano Piccolroaz^{2,3}, Jingzheng Huang¹, Zhiyong Liu⁴ , Feng Liu^{1,5}  and Marco Toffolon³ 

¹ Institute of Estuarine and Coastal Research, School of Marine Sciences, Sun Yat-sen University, Guangzhou 510275, People's Republic of China

² Institute for Marine and Atmospheric research, Department of Physics and Astronomy, Utrecht University, Princetonplein 5, 3584 CC, Utrecht, The Netherlands

³ Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Mesiano 77 Trento, 38123, Italy

⁴ Department/Center of Water Resources and Environment, Sun Yat-sen University, Guangzhou 510275, People's Republic of China

⁵ Author to whom any correspondence should be addressed.

E-mail: liuf53@mail.sysu.edu.cn

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Supplementary material for this article is available [online](#)

Abstract

This study examines the impact of the world's largest dam, the Three Gorges Dam (TGD), on the thermal dynamics of the Yangtze River (China). The analysis uses long-term observations of river water temperature (RWT) in four stations and reconstructs the RWT that would have occurred in absence of the TGD. Relative to pre-TGD conditions, RWT consistently warmed in the region due to air temperature (AT) increase. In addition, the analysis demonstrates that the TGD significantly affected RWT in the downstream reach. At the closest downstream station (Yichang) to the TGD, the annual cycle of RWT experienced a damped response to AT and a marked seasonal alteration: warming during all seasons except for spring and early summer which were characterized by cooling. Both effects were a direct consequence of the larger thermal inertia of the massive water volume stored in the TGD reservoir, causing the downstream reach to be more thermally resilient. The approach used here to quantify the separate contributions of climate and human interventions on RWT can be used to set scientific guidelines for river management and conservation planning strategies.

1. Introduction

River water temperature (RWT) is used as a general predictor of the aquatic ecosystem health since it strongly influences physical, biological and chemical properties of water, such as oxygen solubility, aquatic organisms habitat, and chemical reaction rates (Wu *et al* 2009, Hester and Doyle 2011, Yan *et al* 2015, Woodward *et al* 2016). Hence, understanding the thermal regime of rivers is essential for water quality issues and effective fisheries management. Various studies on RWT have shown that the thermal behavior is strongly linked to both large-scale climate changes (e.g. van Vliet *et al* 2011, Garner *et al* 2014, Rice and Jastram 2015, Chen *et al* 2016) and human-induced perturbations (e.g. dam construction, thermal pollution, deforestation, freshwater withdrawal etc.) on a local scale (e.g. Yang *et al* 2005, Olden and Naiman 2010,

Ding *et al* 2015, Chen *et al* 2016b). In addition, RWT fluctuations may occur across a wide range of time scales (subdaily, daily, weekly, seasonal, annual) depending on the dominant factors (Webb *et al* 2003, Caissie 2006, Webb *et al* 2008, Vanzo *et al* 2016).

It is often assumed that air temperature (AT) is the most important predictor for RWT since it is the dominant driver of the heat fluxes at the air-water interface (e.g. Stefan and Preud'homme 1993, Mohseni and Stefan 1999, Caissie *et al* 2001, Webb *et al* 2003, 2008, Caissie 2006, Sahoo *et al* 2009). However, as pointed out by Arismendi *et al* (2014), Toffolon and Piccolroaz (2015) and Sohrabi *et al* (2017) (just to mention some recent works), the direct statistical link between AT and RWT may be not always exhaustive due to the additional influence from other factors, primarily streamflow. In many cases, purely statistical models based on AT are therefore not adequate to predict

RWT (see e.g. the comparison among different types of models in Piccolroaz *et al* 2016), paving the way for physically based models.

Besides being controlled by a complex interplay among natural heat fluxes, the thermal regime of rivers may be further complicated by the presence of anthropogenic pressures. The construction of large reservoirs highly impacts the hydrological and thermal regime of rivers. Dams may affect downstream RWT dynamics over space and time, including altering of annual river flow patterns (Lowney 2000, Rounds and Wood 2001, Sullivan and Rounds 2004, 2006), changing regional groundwater system (Constantz and Essaid 2007, Risley *et al* 2010), releasing of hypolimnetic water from thermally stratified reservoirs (Preece and Jones 2002, Yang *et al* 2005, Zolezzi *et al* 2011), and the reservoir operations for temperature and flow control downstream of the dam (Lowney 2000). Generally, the thermal effect (cooling or heating) of reservoir regulations is greatest immediately downstream from the dam and dissipates with distance since the river itself has time to exchange heat with its surroundings (Preece and Jones 2002, Toffolon *et al* 2010). The effect is similar to the thermal influence of upstream lakes (Piccolroaz *et al* 2016), but in the case of reservoirs the thermal dynamics are complicated by the sequence of hydraulic operations.

Due to their potential adverse ecological impacts (Belmar *et al* 2013, Chen *et al* 2015, Grill *et al* 2015), the reliable quantification of the effect of dam construction and operations on RWT is a central issue in several studies on water resource management and freshwater ecology (e.g. Cole *et al* 2014, Maheu *et al* 2016, Kedra and Wiejaczka 2017). In this study, we propose a simple yet effective approach to quantify such an effect by using the hybrid semi-empirical model *air2stream* (Toffolon and Piccolroaz 2015, Piccolroaz *et al* 2016) to reproduce the thermal dynamics that a regulated river would have under natural (absence of human interventions, e.g. upstream dam) conditions. The model has the advantage of retaining the limited data requirement of statistical models (i.e. using only air temperature and streamflow as inputs), while preserving the intimate physical structure derived from the governing energy budget. The *air2stream* model can be regarded as a data-driven tool where the model structure and the calibrating parameters are derived from observations (Solomatine *et al* 2008). In this way, if the intrinsic properties of the system are stable, the model parameters have high transferability in time from calibrated conditions to unobserved periods and can be used to explore the functioning of the system under study (see also Patil and Stieglitz 2015). As a similar recent application of the *air2stream* model, we refer the reader to Răman Vinnă *et al* (2017), which predicted RWT of two Swiss rivers under future scenarios including the effect of thermal pollution due to a nuclear power plant. We also note that the companion *air2water* model was successfully tested for

predicting lake surface temperature using only air temperature as a predictor (Piccolroaz *et al* 2013, 2015, Toffolon *et al* 2014, Javaheri *et al* 2016, Piccolroaz 2016, Schmid and Köster 2016), and has been proven to be suitable for climate change studies (Piccolroaz *et al* 2018).

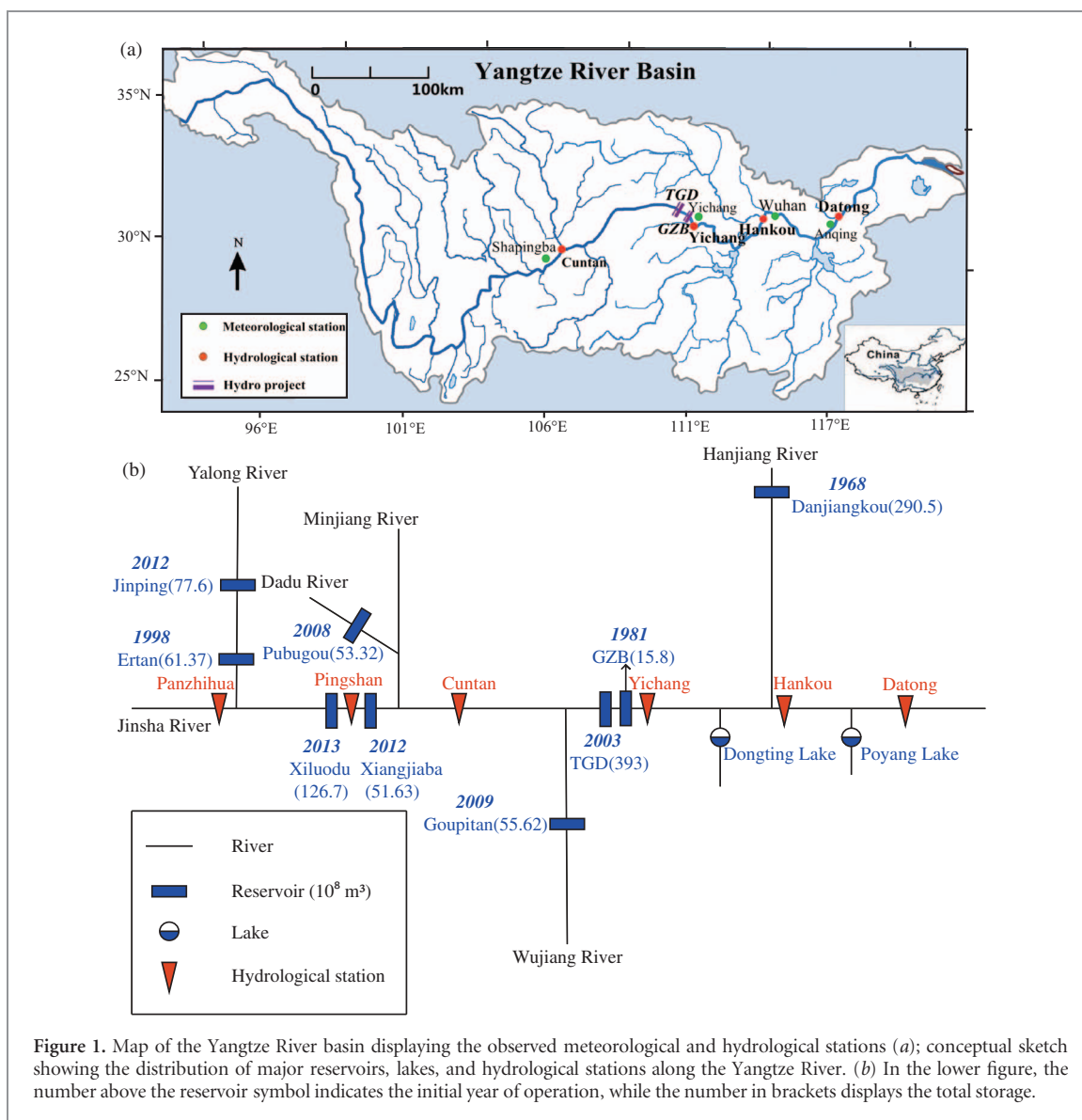
As a significant case study, here we investigated the impact of human interventions on the thermal dynamics of the Yangtze River, China. In order to isolate this effect from the concomitant alteration of environmental conditions, mostly represented by AT changes possibly due to climate change, the *air2stream* model was used to reconstruct the expected natural conditions that the Yangtze River would presently experience in absence of large-scale human interventions. We specifically focused on the ramifications of the construction of the Three Gorges Dam (TGD), which created the world's largest hydroelectric power station.

2. Materials and methods

2.1. Overview of the Yangtze River basin

The Yangtze River ranks as the longest river in Asia and the 4th largest river in the world in terms of water discharge. It delivers an annual water volume of $910 \times 10^9 \text{ m}^3$ into the sea, which contributes about 2.6% of the world's total fresh water delivered to the ocean (Dai and Trenberth 2002). The Yangtze River originates from the Qinghai-Tibet Plateau at an altitude of 4000–5000 m and flows eastward to the East China Sea. It drains a catchment of $1.8 \times 10^6 \text{ km}^2$ and its mainstream is 6300 km long. The Yangtze River is generally divided into three reaches (e.g. Fu *et al* 2003). The upper reach includes the area upstream of Yichang, the Middle Yangtze River extends from Yichang to Datong station, and the lower reach stretches from Datong to the river mouth (see figure 1(a)). The drainage basin is characterized by a subtropical, warm and wet climate and is affected by the Asian monsoon. The Indian summer monsoon and the East Asian summer monsoon influence the upper and mid-lower basins of the Yangtze River, respectively. The average basin-wide precipitation is 1070 mm y^{-1} , and 70%–80% of annual precipitation and over 80% of water discharge concentrate in the wet season from May to October.

More than 50 000 dams have been constructed within the Yangtze River basin since 1950s, ranging in size from small impoundments on farmers' fields to large dams towering over 100 m high (Yang *et al* 2011). Almost all dams are distributed in the Yangtze River tributaries with the exception of TGD and Gezhouba (GZB) located along the mainstream (see figure 1(b)). The GZB dam was constructed 6 km upstream of the Yichang hydrological station and started to operate in earlier 1980s with a height of 47 m, a width of 2595 m, and a total storage of $15.8 \times 10^8 \text{ m}^3$. The TGD, completed in 2003 with a height of 185 m, a width of 2335 m,



and a total storage of $393 \times 10^8 \text{ m}^3$, was constructed 44 km upstream of the Yichang hydrological station. The TGD is operated with a seasonal mode according to its multiple utilization for flood control, irrigation, and power generation (see figure S1 for the operational stage variations at the TGD between 2003 and 2014). The TGD is the world's largest power station in terms of installed power capacity (22 500 MW).

2.2. River gauge data

To understand the impact of human interventions on the downstream RWT, we selected the four main hydrological measurement stations (Cuntan–CT, Yichang–YC, Hankou–HK, and Datong–DT, see figure 1(a)) along the main stream of the Yangtze River. Unfortunately, apart from two other stations (Panzhihua and Pingshan) farther upstream, these are the only stations for which long-term daily thermal records are available. These gauging stations are located in the upper (Cuntan and Yichang

stations located 680 km upstream and 44 km downstream of TGD, respectively), mid-region (Hankou, located 654 km downstream of TGD) and lower (Datong, the most seaward gauging station, 1115 km downstream of TGD) reaches of the river, respectively. Being located upstream of the TGD, the Cuntan station was chosen as a reference station that was not affected by the construction of this dam. It was potentially affected by the construction of other upstream dams, but they are relatively small.

Daily RWT and freshwater discharge (Q) at the four hydrological stations were provided by the Yangtze Water Resources Commission (see <http://xxfb.hydroinfo.gov.cn>). For each station, we also collected the daily AT from the closest meteorological stations (available at <http://data.cma.cn>). Details about the measurements are provided in table S1 in the Supporting Information. In order to quantify the potential influence of the TGD on the downstream river thermal dynamics, we divided the time series into a first pre-TGD period (1975–1987, before the construction

of the dam), and a second post-TGD period (2003–2014, with the operating dam). We did not include the period 1988–2002 since most of the RWT data were not available (see <http://xxfb.hydroinfo.gov.cn>). The period between 2003–2008 coincided with the filling up of the TGD reservoir, and was specifically included in the analysis in order to explore the relation between the water volume stored in the reservoir and the downstream thermal dynamics.

2.3. Reconstruction of river water temperature

The *air2stream* model (Toffolon and Piccolroaz 2015) was used to reconstruct RWT as a function of AT and discharge Q on a daily time scale. The model is set in the form of an ordinary differential equation depending on a number of parameters to be calibrated. The basic assumption is that AT can be used as the main proxy for all processes related to the heat fluxes exchanged at the air-water interface (including short- and long-wave radiation, and latent and sensible heat fluxes; see also Caissie 2006). In addition, Q is introduced in the model to account for the integrated effect of water inflows (from the upstream reach, tributaries, groundwater) and thermal inertia of the river. The net heat flux is then computed in a linear form by using a Taylor series expansion of each heat flux term as a function of AT, Q , and RWT. In this study, the most complete 8 parameter formulation was used. The objective function adopted for identifying the best set of model parameters was the root mean square error (RMSE) between the daily values of simulated and observed RWT, and an evolutionary search optimization technique was used for the calibration. All the details of the model are reported in Text S1 in the supporting information and in Toffolon and Piccolroaz (2015).

The results are presented in a compact form by introducing the climatological reference year, which is defined evaluating for each day of the year the average value of all measurements available over the observation period for that same specific day (29 February of leap year was not considered). To illustrate the advantage of the *air2stream* model over standard tools, we also tested the commonly used nonlinear regression model based on the logistic function (e.g. Mohseni and Stefan 1998), which predicts RWT using AT relying on four calibration parameters. The formulation is again provided in the Supporting Information, where a comparison between the two approaches is illustrated (see figure S2 in the supporting information).

The pre-TGD period was used for calibration. The calibrated model was then run over the post-TGD period to predict the expected RWT if the TGD had not been constructed and there was no other significant human interventions (e.g. land use change, coal-fired plants operation and other industrial facilities impacts etc.), but keeping the discharges actually measured.

The total change in RWT in the post-TGD period relative to the pre-TGD period including both climate change and human interventions is evaluated as:

$$\Delta_{\text{TOT}} = \text{RWT}_{\text{obs, post-TGD}} - \text{RWT}_{\text{obs, pre-TGD}}, \quad (1)$$

which represents the mean RWT difference between observed values for the post-TGD ($\text{RWT}_{\text{obs, post-TGD}}$) period and those for the pre-TGD ($\text{RWT}_{\text{obs, pre-TGD}}$) period. This total change in RWT can be regarded as the combination of two effects:

1. the contribution related to changes in the meteorological forcing (Δ_{CLI} , possibly related to climate change), defined as the difference between RWT values simulated for the post-TGD ($\text{RWT}_{\text{sim, post-TGD}}$) and pre-TGD ($\text{RWT}_{\text{sim, pre-TGD}}$) period

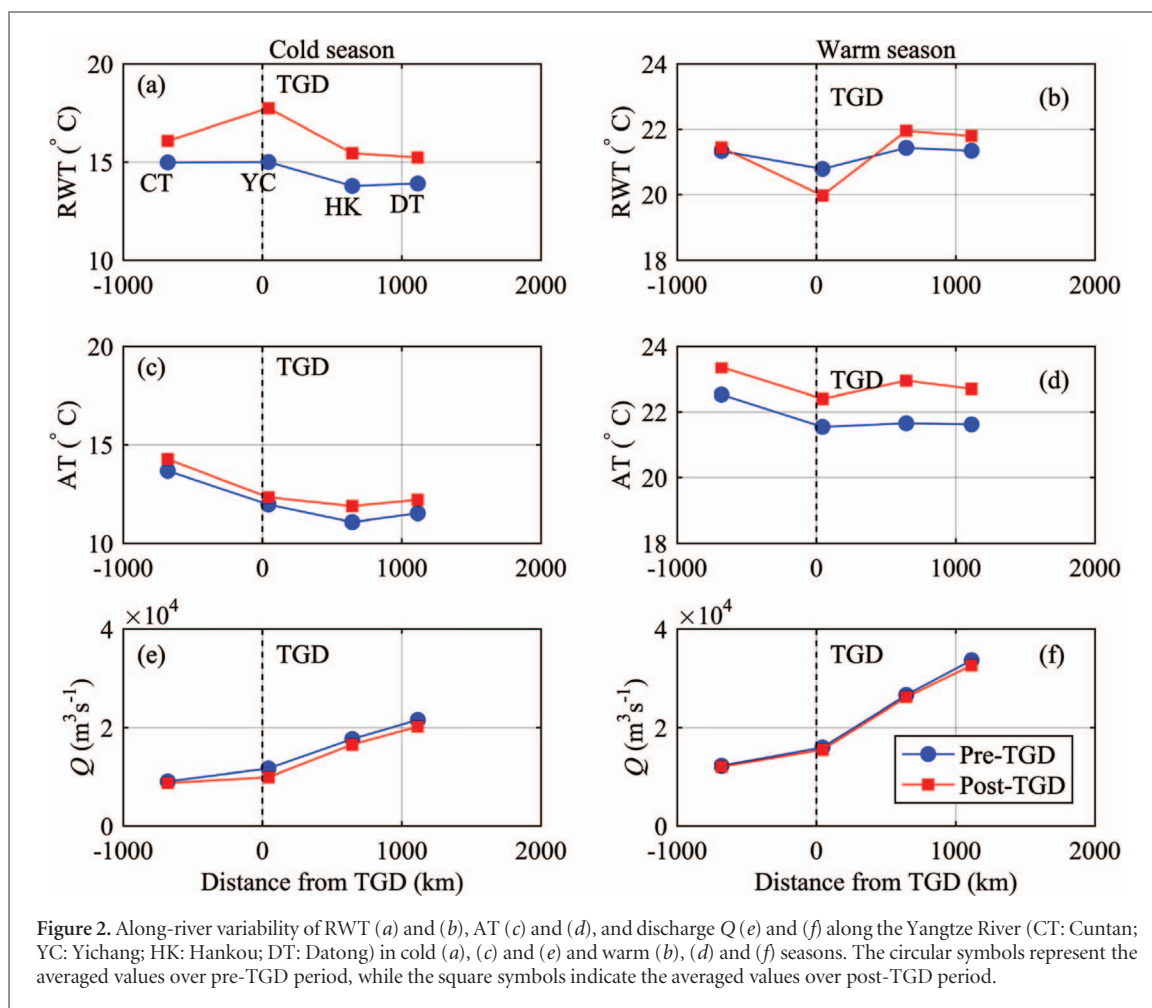
$$\Delta_{\text{CLI}} = \text{RWT}_{\text{sim, post-TGD}} - \text{RWT}_{\text{sim, pre-TGD}}, \quad (2)$$

2. and the contribution ascribable to the anthropogenic interventions (Δ_{ANT}), here assumed primarily attributable to the TGD impact, defined as the difference between observed ($\text{RWT}_{\text{obs, post-TGD}}$) and simulated ($\text{RWT}_{\text{sim, post-TGD}}$) values of RWT for the post-TGD period

$$\Delta_{\text{ANT}} = \text{RWT}_{\text{obs, post-TGD}} - \text{RWT}_{\text{sim, post-TGD}}. \quad (3)$$

Combining the above equations, we obtain that $\Delta_{\text{ANT}} = \Delta_{\text{TOT}} - \Delta_{\text{CLI}} + \varepsilon$, where $\varepsilon = \text{RWT}_{\text{sim, pre-TGD}} - \text{RWT}_{\text{obs, pre-TGD}}$ is the model bias (i.e. mean error) between simulated and observed RWT during the calibration period. In order to assess the performances of the model in estimating RWT differences, Δ_{ANT} should be compared with the bias ε at different time scales (annual and seasonal). The confidence in the model is high if $|\varepsilon| \ll |\Delta_{\text{ANT}}|$.

The quantity Δ_{ANT} can be interpreted as the thermal disturbance due to the overall impacts driven by human interventions. In the stations downstream of TGD, the largest contribution to this difference can be primarily attributed to the TGD impact. In fact, the TGD alone accounts for more than 30% of the total storage capacity of the dams constructed between 1987 and 2014 along the river (Li *et al* 2016). Additionally, the GZB dam (i.e. the only other dam along the mainstream) was constructed during the pre-TGD period (in 1981) and after that no other large dams have been built along the main course of the Yangtze River (Yang *et al* 2007). We also remark that coal-fired and nuclear power plants are mainly located in the North/Southeastern regions, i.e. close to coal resources and along the coast where economies are most active, respectively (Wang and Chen 2010), while the Southwest region of China is more oriented towards hydropower production. For this reason, after the end of the 1990s, only minor coal-fired units



were constructed in the Yangtze River Basin (Liu *et al* 2015, Xie *et al* 2016). Finally, the possible impact of diffused inputs, like those from sewage systems, can be estimated with a simple energy and mass balance (please refer to text S2 in the supplementary material) and is discussed in section 4.

3. Results

3.1. Seasonal and along-river variability

Figure 2 shows the along-river variation of RWT, AT, and discharge Q averaged over the pre-TGD (1975–1987) and post-TGD (2003–2014) periods at the four gauging stations. Considering the pre-TGD period, in both cold (September–February) and warm (March–August) seasons, we observe an abrupt change in RWT between Yichang and Hankou due to the combined influence from both atmospheric effect (i.e. AT) and higher streamflow contribution from tributaries (Mei *et al* 2015). Relatively homogeneous conditions with similar RWT can be identified grouping the upstream (Cuntan and Yichang) and downstream (Hankou and Datong) sites.

Compared to pre-TGD periods, an increasing trend in RWT and AT is visible in both cold and warm seasons for the post-TGD period except for a marked

decrease at Yichang station in the warm season. On average, the observed RWT (Δ_{TOT}) increased by 1.71 °C and 0.06 °C for the cold and warm seasons, respectively. RWT increase was specifically significant at Yichang, with the maximum difference reaching 2.74 °C for the cold season, while a marked decrease by 0.82 °C was observed for the warm season, suggesting a substantial impact of the TGD, which is immediately upstream of this gauging station. Figures 2(c) and (d) show a similar picture for AT, with the largest increase occurred at Hankou. With regard to streamflow, a moderate decrease by 1157 m³s⁻³ (corresponding to 7.7%) can be observed in the cold season, while a slight decrease by 543 m³s⁻³ (corresponding to 2.5%) characterizes the warm season, owing to the operation of TGD.

The change in RWT occurred between pre-TGD and post-TGD periods can also be quantified by comparing the RWT cumulative frequency distribution and histograms based on the observed values for these two periods. The change was greatest immediately downstream of the dam, at the Yichang station (figure 3; for the other stations please refer to figures S3–5 in the supplementary material). There, we observe a narrower range of RWT due to a significant warming of the lowest RWT, thus indicating larger changes in the cold season (see figure 3(b)). Accordingly, the

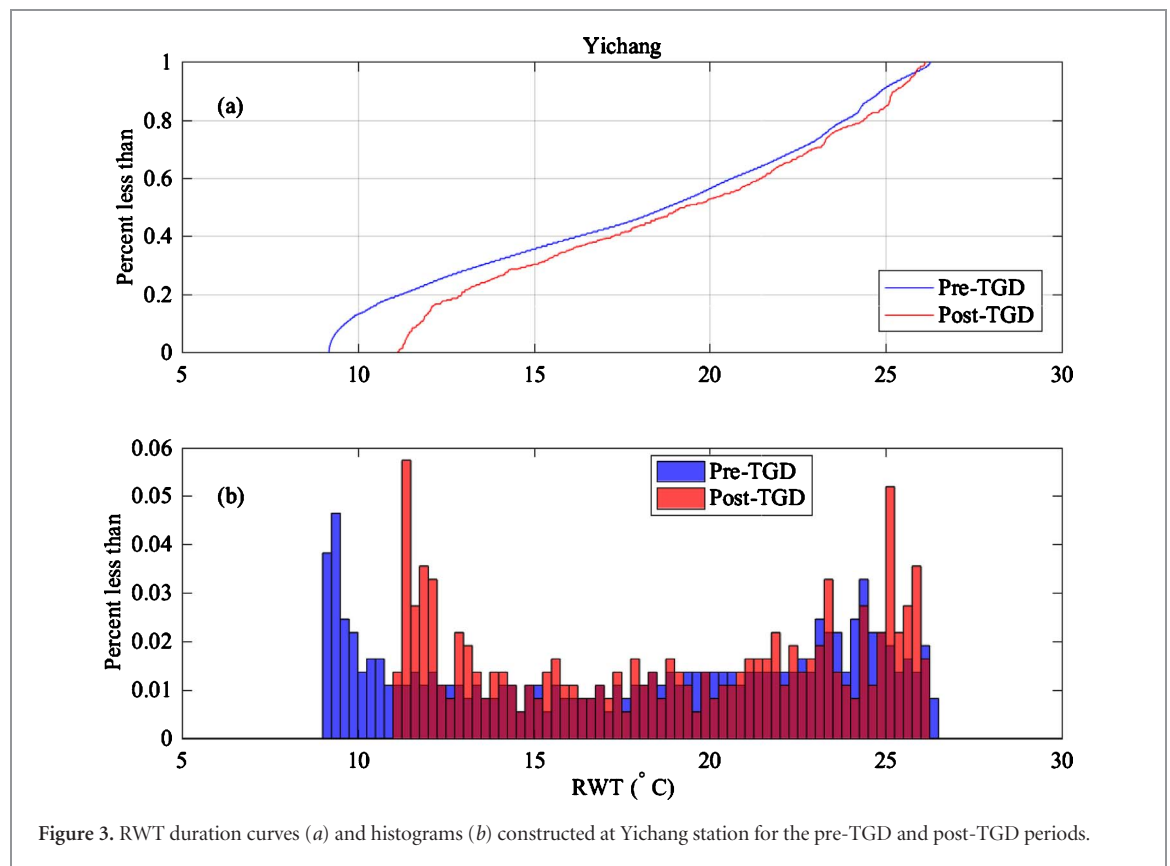


Table 1. Performance of the *air2stream* model (8 parameter version, a2s-8) and the logistic regression applied to the four hydrological stations in the Yangtze River, for the pre-TGD (calibration) and post-TGD periods.

Version	RMSE for RWT (C)							
	Cuntan		Yichang		Hankou		Datong	
	Pre-TGD	Post-TGD	Pre-TGD	Post-TGD	Pre-TGD	Post-TGD	Pre-TGD	Post-TGD
a2s-8	0.59	0.86	0.73	2.45	0.87	1.37	0.67	1.11
Logistic	1.46	1.79	1.79	3.62	2.05	2.78	1.14	2.75

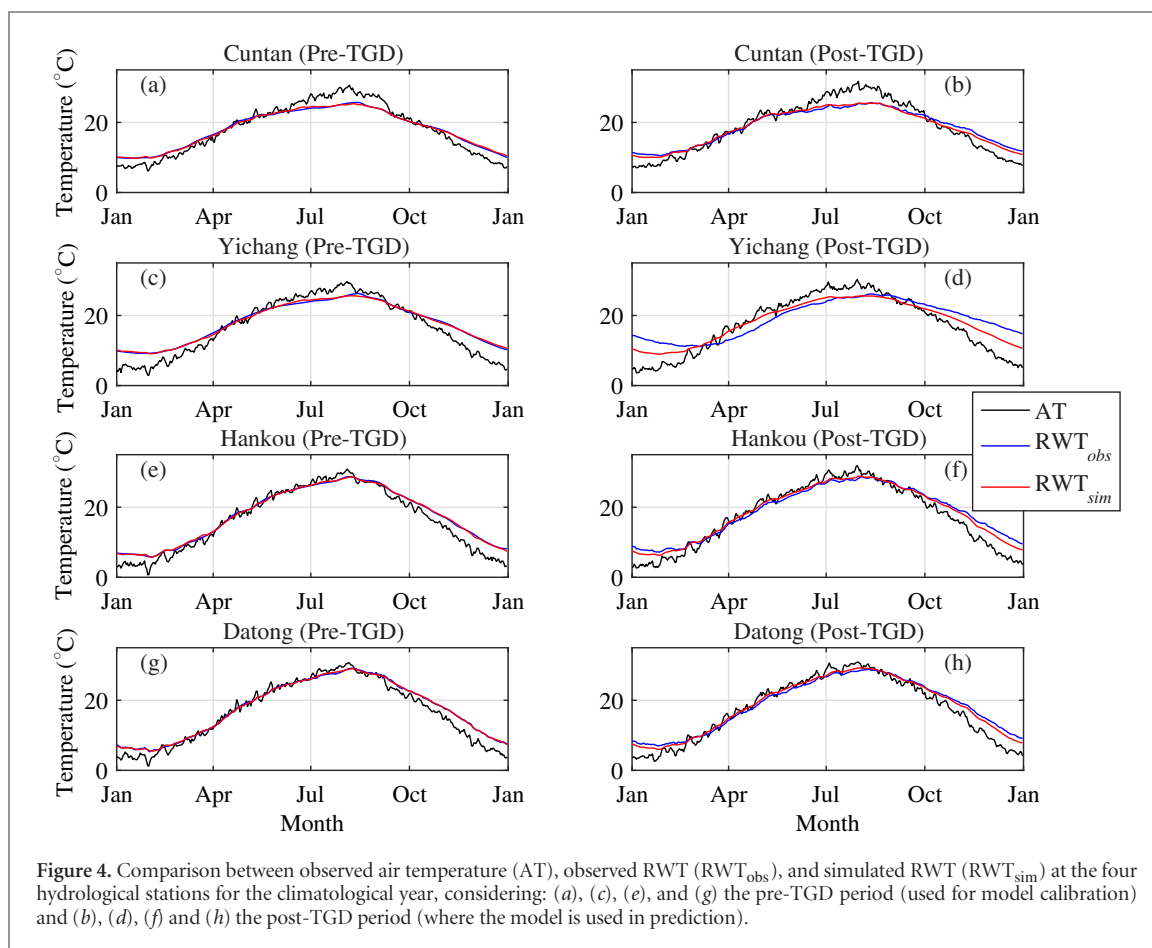
cumulative frequency distribution curve is appreciably steeper in the post-TGD period for RWT values lower than about 16 °C (see figure 3(a)). A significant difference is visible also in the warm season, especially in the upper part of the temperature distribution, although the maximum value is not significantly affected: the two curves are markedly separated for RWT exceeding the 80th–95th percentile (figure 3(a)) with visible warming of RWT during the second analyzed period (figure 3(b)). The differences are minor in the transition seasons (the curves are close for intermediate values of RWT between 16 and 26 °C).

Once verified the existence of significant differences between the pre- and post-TGD periods, the question now arises as to what extent these changes are ascribable to climate change or to human land surface interventions (primarily the TGD construction). This question is addressed in the following sections.

3.2. Model performances

The values of root mean square error (RMSE) for the calibration period (pre-TGD period, 1975–1987, see table 1) indicate that the *air2stream* model is able to

satisfactorily reproduce the thermal dynamics (RMSE ranging from 0.59 °C–0.87 °C in the four stations, at daily resolution), especially if compared with the logistic regression (RMSE from 1.14 °C–2.05 °C). The two models were successively run for the post-TGD period (2003–2014), keeping the same values of the coefficients calibrated before. When compared with the actual observations, the results significantly deteriorate in all stations downstream of the TGD (figure 4 and table 1). This is expected and indicates that the TGD altered the thermal regime of the river. Specifically, the largest RMSE in the prediction is observed at the Yichang station, closely located downstream of the TGD. RMSE increases significantly also for the Hankou and Datong stations, likely due to the additional hydrological impacts from Hanjiang tributary and Dongting and Poyang lakes (see figure 1(b)). However, such an increase was lower relative to the Yichang station due to the much longer distance from upstream reservoirs, which allows the river to slowly adapt to the external conditions and progressively dissipate the effect of these disturbances. The smallest worsening of RMSE is observed at the Cuntan



station, the only station upstream of the TGD. In this case, the RMSE for the post-TGD period remains lower than 1°C , suggesting small modifications of the hydrological and thermal regimes in this part of the Yangtze River. Comparable values of RMSE in the pre- and post-TGD periods in Cuntan also support the robustness of the *air2stream* model when used under different climatic periods at river stations with weak hydrological alterations.

Due to the evident inadequacy of the logistic regression model to properly reproduce the thermal dynamics of the Yangtze River, the following analysis was performed using only the *air2stream* model. In order to quantify also the possible impact of GZB dam on the downstream thermal dynamics (especially at the Yichang station), we divided the pre-TGD period into pre-GZB (1975–1980) and post-GZB (1981–1987) periods. Analogously to the above analysis, we calibrated the *air2stream* model during the pre-GZB period and run it over the post-GZB period. The model results (see the supplemental figure S6 and table S2 available at stacks.iop.org/ERL/13/054016/mmedia) showed that the impact of GZB dam on the downstream thermal dynamics was minor, with averaged RMSE being fully comparable between the two periods.

3.3. Estimating the influence of TGD on RWT

The successful reproduction of natural variation of RWT using the *air2stream* model provides a powerful

tool for understanding the different role of natural (i.e. changes in the meteorological forcing, here represented by AT) and anthropogenic factors influencing the RWT in the post-TGD period. In the following analysis, the values of RWT predicted by the *air2stream* model in the post-TGD period are used to isolate the effects on RWT due solely to changes in AT compared to the pre-TGD period (Δ_{CLI} , see equation 2) on the one hand, and due solely to the presence of large-scale human interventions, here considered as mainly attributable to the TGD construction and operations (Δ_{ANT} , see equation 3) on the other hand. Table 2 shows the annual and seasonal statistics using equations (1)–(3) based on the observed and simulated RWT for the post-TGD period. Also listed is the seasonal and annual bias (ϵ) between simulated and observed RWT during the calibration period, for each river station. We note that the model bias is always smaller than the computed Δ_{ANT} (ϵ/Δ_{ANT} being 13% and 0.2% at seasonal and annual scales, on average), thus suggesting that the effects of model errors on the results of the present analysis are minor.

As a whole, the annual RWT statistics indicate that both climate change and the TGD have increased the mean RWT on average. In particular, results reveal that annual changes of RWT at Yichang are mainly driven by human interventions (Δ_{ANT} accounting for 73% of total difference Δ_{TOT}). Conversely, the RWT differences at Hankou and Datong are mainly

Table 2. Change in RWT in the post-TGD period (2003–2014) relative to the pre-TGD period (1975–1987) attributable to changes in AT (Δ_{CLI}) and to the construction of the TGD (Δ_{ANT}). RWT changes were evaluated using equations (1)–(3) in section 2.3. Also shown is the model mean error ($\epsilon = \frac{1}{n} \sum_{i=1}^n (RWT_{\text{sim},i} - RWT_{\text{obs},i})$, i.e. the bias) between simulated (RWT_{sim}) and observed (RWT_{obs}) daily RWT during the calibration period, where n is the length of the observational time series). All values are in °C.

Station	RWT change	March–May (Spring)	June–August (Summer)	September– November (Autumn)	December– February (Winter)	Annual
Cuntan	Δ_{TOT}	0.13	0.03	1.17	1.08	0.60
	Δ_{CLI}	0.60	0.29	0.38	0.36	0.41
	$\Delta_{\text{ANT}}^{\text{a}}$	–0.27	–0.35	0.80	0.60	0.20
	ϵ	–0.20	0.08	–0.01	0.13	–2.9 E–4
Yichang	Δ_{TOT}	–1.75	0.01	2.30	3.26	0.95
	Δ_{CLI}	0.26	0.20	0.60	0.01	0.27
	Δ_{ANT}	–1.76	–0.30	1.75	3.06	0.69
	ϵ	–0.25	0.11	–0.05	0.20	5.4 E–5
Hankou	Δ_{TOT}	0.67	0.25	1.49	1.66	1.02
	Δ_{CLI}	1.36	0.60	0.76	0.59	0.83
	Δ_{ANT}	–0.69	–0.35	0.66	1.12	0.18
	ϵ	0.002	–0.007	0.08	–0.07	1.6 E–4
Datong	Δ_{TOT}	0.73	0.14	1.16	1.53	0.89
	Δ_{CLI}	1.40	0.59	0.62	0.61	0.81
	Δ_{ANT}	–0.64	– 0.46	0.53	0.92	0.09
	ϵ	–0.02	0.01	0.01	0.01	5.1 E–4

Bold numbers indicate the most significant contribution by each category.

^a Since Cuntan is upstream the TGD, Δ_{ANT} summarizes the effect on RWT due to hydraulic regulations and landscape management upstream of this station, and not the effect of the TGD.

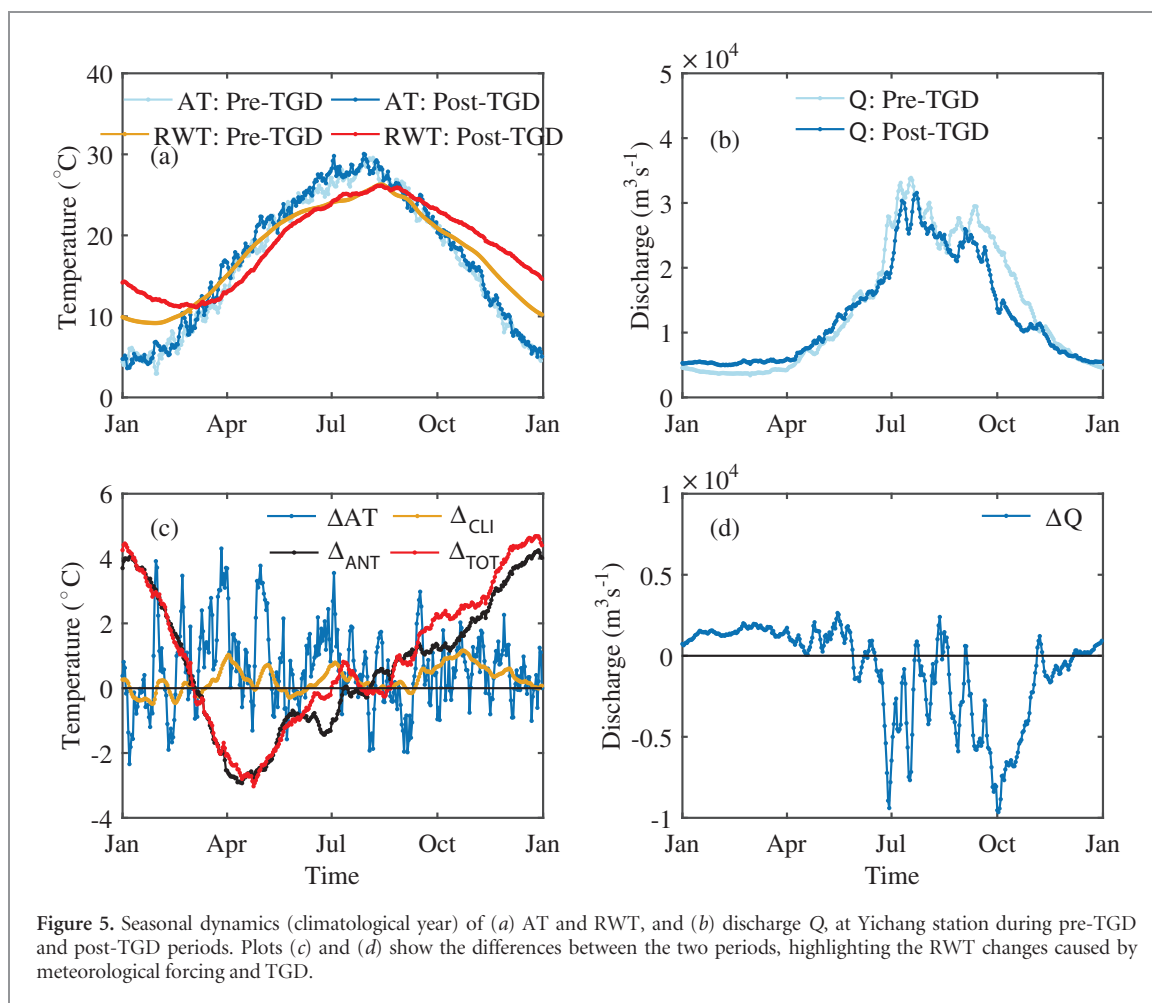
controlled by the change in the meteorological forcing (Δ_{CLI}), suggesting a diminishing effect of the hydropower operations with increasing distance downstream. A moderate effect of hydropower operations is however still visible at the farthest river station (i.e. Datong), which is likely due to the combined effect of the TGD (located more than 1000 km upstream) and the Danjiangkou reservoir (at about 650 km upstream, along the Hanjiang tributary, see figure 1(b)). Although the distance at which the influence is felt might seem unrealistically large, an estimate of the length scale of the thermal adaptation of local disturbances to the external conditions (see text S3 in the supplementary material) suggest that the effect may be felt at distance of thousands of km, mostly because of the very large depth of the Yangtze River (Lai *et al* 2017).

We also remark that Δ_{ANT} at Cuntan should be considered as a generic effect on RWT due to hydraulic regulations and landscape management upstream this station, and not as a direct effect of the TGD, which is located downstream. In fact, the Yangtze River was subject to anthropogenic interventions between the pre- and post-TGD periods also in the upstream region, as evidenced for instance by the significant sediment reduction between 1986 and 2002, mainly ascribable to dam construction and increased soil conservation (Yang *et al* 2006, 2015).

When looking at intra-annual variability of Δ_{ANT} at the Yichang station it is interesting to note that the TGD effect can be divided into two distinct periods. In spring (March to May) and summer (June to August), the presence of the TGD caused monthly mean RWT to decrease by 1.03 °C on average, while

the RWT generally increased during the rest of the year by approximately 2.41 °C. Noticeably, the warming in winter reached 3.06 °C, which corresponds to 94% of the total warming documented by observations (i.e. Δ_{TOT}). The less affected season is summer (from June to August), when RWT experienced a cooling of 0.30 °C. The annual evolution of the thermal effect caused by the TGD on downstream RWT is clearly visible in figure 5(c) (black line). In order to disentangle the underlying mechanisms causing the differential response of RWT during the year, the combined effect of thermal inertia and river flow regulation (figure 5(d)) are analyzed below.

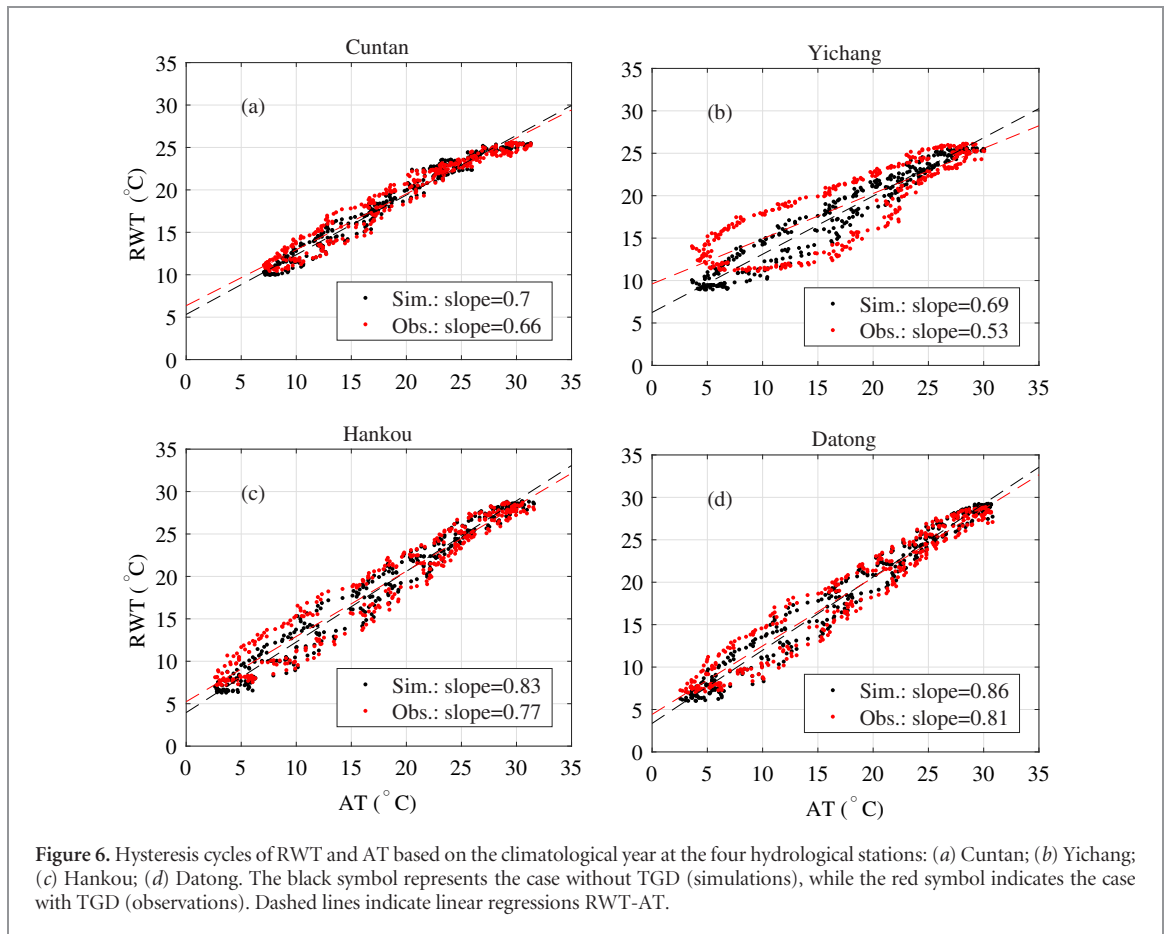
According to the official annual report from China Three Gorges Corporation (see www.ctg.com.cn), water is withdrawn from a mid-depth gate (90–108 m above sea level, see figure S7), at a water depth in the reservoir ranging between 45 and 75 m, depending on the season (see figure S1). According to Long *et al* (2016), despite the large depth of the TGD reservoir, the water column does not stratify, but remains relatively well-mixed throughout the year, likely due to the large water input and mixing effect of the tributaries. The much larger thermal inertia of the water stored in the TGD reservoir, in comparison to that of the Yangtze River during the pre-TGD period, determines a time-lagged response of RWT to AT, similarly to what happens in deep lakes (Toffolon *et al* 2014). This delayed response is further enhanced by the weak thermal stratification of the reservoir, whereby large water volumes always participate to the heat exchanges with the atmosphere (Piccolroaz *et al* 2015).



The streamflow regulation produced a decreased annual peak flow and an increase of annual minimum river flow relative to the pre-TGD levels (figures 5(b) and (d)) due to flow storage for flood control during the wet season (May to October) and flow augmentation for irrigation and municipal uses during the dry season (November to April) (Mei *et al* 2015). As a combined result, the Yangtze River at Yichang experienced a marked warming of RWT in autumn and winter (especially from October to January) because of larger releases of warmer water volumes than before (figure 5(c)) due to the high thermal inertia of the reservoir. For the same reason, the water temperature in the reservoir is colder in spring and early summer (from March to June), due to its slower response to increasing AT. The result is a significant cooling effect with a negative peak in April. In late summer (between July and August), RWT experiences almost neutral conditions because the water temperature in the reservoir crosses the RWT that would establish in the river without TGD. Finally, in autumn, RWT undergoes an increasing warming effect that peaks at the end of December. To summarize, the seasonal cycle of RWT is shifted towards a colder spring, and a warmer autumn and winter pattern (figure 5(a)). Similar pictures displaying contributions of climate change and TGD on the thermal dynamics at the other

hydrological stations can be found in the supporting information (figures S8–S10).

The thermal response of the Yangtze River was also analyzed by means of the hysteresis cycles between RWT and AT. The modifications produced by the construction of the TDG are shown in figure 6 by comparing observed and simulated RWT during the post-TGD period. The hysteresis cycles are wider for the Yichang station due to the operation of the TGD, as a result of the larger thermal inertia of the reservoir, as already commented above. The effect, however, is not only on the breadth of the hysteresis, but also on the slope. According to the thermal classification introduced by Kelleher *et al* (2012) and further developed by Piccolroaz *et al* (2016), the slope of the linear regression between RWT and AT can be used to distinguish two thermal patterns (a threshold ≈ 0.55 was obtained from the analysis of 38 Swiss rivers): thermally reactive (above threshold, strong response of RWT to AT) and thermally resilient (below threshold, damped response). From figure 6, we observe that all stations belong to the first thermal class characterized by steep hysteresis cycles, with the only exception of the Yichang station after the operation of the TGD. In this case, the slope reduces from 0.69 to 0.53, suggesting that the presence of the reservoir exerts a strong influence on the river thermal response,



both widening the RWT-AT hysteresis cycles and shifting the thermal pattern to be more resilient. A slight reduction of the mean slope of the observed hysteresis loop is noted also at the other two stations downstream of the TGD, with variations that become less significant with the distance from the dam. Interestingly, the modification of the RWT-AT hysteretic cycle at the Cuntan station (upstream of the dam) is almost absent.

3.4. Impact of the operation stage at TGD

The operation stage at the TGD (figure S1) may exert significant impact on the downstream RWT through changes in the water volume stored in the reservoir, and hence in its thermal inertia. In June 2003, the TGD started to impound water with the water level rising from 70–139 m by October 2003. The water level followed a seasonal variation between 136 and 143 m until 2006 (initial stage). During the transitional period, from October 2006 to October 2008, the water levels fluctuated seasonally between 145 and 156 m. Subsequently, it rose to 173 m in November 2008 and then to 175 m in October 2010 (standard normal stage). During standard normal stage, the water level in the TGD reservoir is impounded to 175 m for power generation during the winter season, while it is emptied to 145 m for flood control during the summer season (Li *et al* 2016). Generally, water is stored from June to November, corresponding to increasing

flow, for later release from December to March, corresponding to decreasing flow (see figure 5(d)) to maintain electricity generation and water supply during the low flow conditions (Chen *et al* 2016a, Li *et al* 2016).

Figure 7 shows the seasonal variability of RWT at Yichang for different operation stages of the TGD. Also in this case, the difference between observed and simulated RWT confirms the substantial thermal influence of TGD. During the initial stage of the TGD (2003–2005), an effect was produced by the operation of the TGD resulting in modification in the seasonal phases of cooling and heating of RWT (figure 7(a)). The TGD acted as a cold source during March to June, and a warm source during October to January in the next year (see also figure 5(c)). In the following stages, such a behavior was consistently repeated (figures 7(c) and (e)), with an amplification that was a function of the higher water level in the reservoir and that culminated during the standard normal stage (2009–2014). As discussed in the previous section, this is an effect of the large thermal inertia associated with the water volume stored in the reservoir, which delays the seasonal cycle of RWT (Toffolon *et al* 2014). The clear correlation between the operation stage at the TGD and the changes on downstream RWT at Yichang further reinforces the assumption that the overall impact of the human interventions on RWT is primarily ascribable to the TGD.

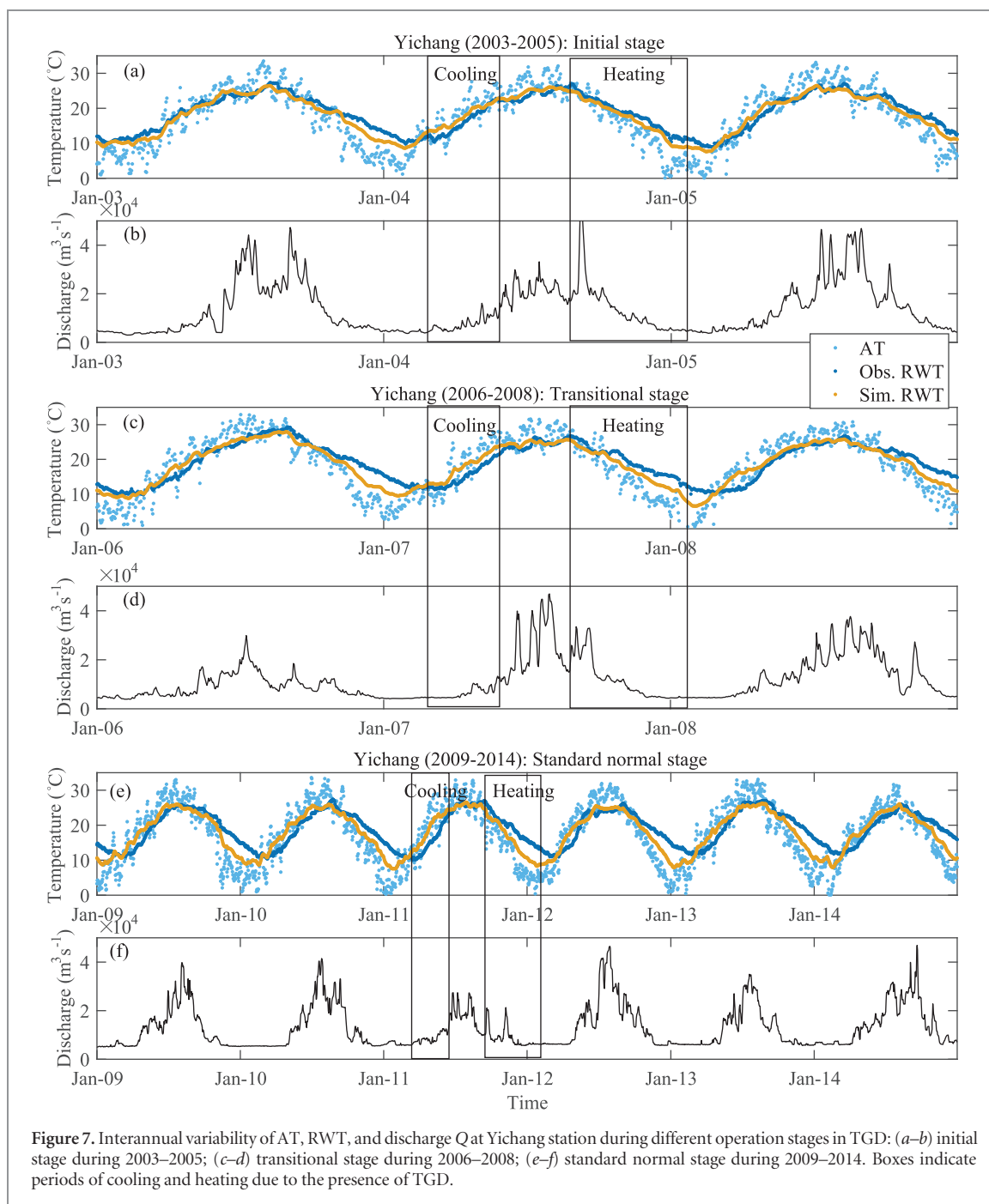


Figure 7. Interannual variability of AT, RWT, and discharge Q at Yichang station during different operation stages in TGD: (a–b) initial stage during 2003–2005; (c–d) transitional stage during 2006–2008; (e–f) standard normal stage during 2009–2014. Boxes indicate periods of cooling and heating due to the presence of TGD.

4. Discussion and conclusions

In this study, we investigated the changes in RWT dynamics of the Yangtze River, specifically exploring and quantifying the separate effects of climate change and human interventions. Observations show a consistent warming of both AT and RWT across the entire Yangtze River. Relative to the pre-TGD condition, the post-TGD mean RWT increased by 1.71 °C and 0.06 °C (averaged over the four stations) in cold and warm seasons, respectively. By means of the *air2stream* model (Toffolon and Piccolroaz 2015), we reconstructed the potential RWT solely due to changes in the meteorological forcing (i.e. AT) and streamflow

Q . In this way we were able to quantify also the alteration that can be attributed to the presence of large-scale human interventions, primarily represented by the TGD.

By comparing the simulated and the observed RWT in the post-TGD period, we found that the thermal effect caused by the TGD was greatest at Yichang station immediately downstream of the dam, where it behaved very differently on a seasonal time scale. In particular, the mean winter RWT (December–February) increased by 3.06 °C, while it considerably decreased by 1.76 °C in spring (March–May). More precisely, the reconstruction of annual variability of RWT caused by the TGD clearly showed that the TGD

acts as a cold source from March to July, and a warm source for the rest of the year, mostly due to the larger thermal inertia of the upstream reservoir compared to previous conditions, and with possible additional effects of streamflow alteration. On the other hand, the impact of meteorological forcing (here represented by AT) was greatest at Hankou station, where the annual mean RWT increased by 0.83 °C. The analysis of the hysteretic patterns of RTW vs AT highlighted that the thermal response of the Yangtze River became more damped (resilient) in the Yichang station, 44 km downstream of the TGD.

We acknowledge that other factors (e.g. land use changes, industrial facilities, sewage, other dams, etc.) may have contributed to the overall human impact on RWT. For example, an estimate of the effect due to sewage discharges (see text S2 in the Supporting Information) indicated a warming impact $\ll 0.1$ °C on average along the Yangtze River. Not only is this contribution small with respect to the whole estimate of Δ_{ANT} , but also the timing is not consistent. In fact, the maximum RWT warming due to wastewater should occur for low flow conditions in winter (December to May), whereas Δ_{ANT} shows a strong cooling in spring (March to May) instead. Further contributions and the modeling uncertainty (e.g. the bias, see table 2) may affect the quantification of RWT attributed to the TGD. However, the strong vocation of the Yangtze River Basin to hydropower instead of other sources of energy (nuclear or coal-fired power plants) and our results suggest that the stronger impact can be primarily attributable to the construction and operation of this dam. This is further demonstrated by the evident correlation between TGD operational stage and RWT changes. Remarkably, interannual analysis of RWT clearly showed that the magnitude of temperature modification (either heating or cooling effects) in Yichang grew with the increase of the TGD operational stage, confirming that the main mechanism is associated with increased water depth, thus thermal inertia, in the reservoir. The assumption of the TGD as the major human intervention affecting RWT in the Yangtze River is further sustained by the fact that the only other dam constructed along the main course of the Yangtze River (i.e. the GZB) has been proven to have a minor role on RWT, despite being closer to the Yichang station than the TGD.

The thermal regime of rivers exerts significant impacts on many aquatic habitat attributes and on the general health of river ecosystems (e.g. Hester and Doyle 2011, O’Gorman *et al* 2012, Woodward *et al* 2016). Due to the increasing demand for the water resources, many rivers have been regulated by dam construction for temporary water storage and withdrawal (Nilsson *et al* 2005). Consequently, the reliable quantification of the potential impact of human interventions on RWT is a necessary prerequisite to define effective river management and conservation planning strategies. In particular, the operation of TGD,

the world’s largest dam, has caused tremendous environmental consequences, such as alternation in water and sediment regimes, downstream riverbed erosion, changes in water quality and fish communities, emission of greenhouse gases to the atmosphere (e.g. Xu *et al* 2013, Wang *et al* 2016, Ban *et al* 2017, Li *et al* 2017). However, the changes in the thermal dynamics of the Yangtze River have been poorly reported, which makes it difficult to assess the potential impact of the TGD on the ecosystem health in the downstream reach of the Yangtze River. In addition, large reservoirs and rivers worldwide have been shown to be important sources of greenhouse gases, water temperature being one of the key controls of the emission rates (Chen *et al* 2009, Yang *et al* 2014, Huang *et al* 2015, McGinnis *et al* 2016, Li *et al* 2017, Marzadri *et al* 2017). In this direction, and taking the Yangtze River as significant case study, our contribution provides an effective and simple method for quantifying the impact of human activities on RWT modification. Such a novel approach will, hopefully, contribute to set scientific guidelines for water resources managers and aquatic ecologists.

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ORCID iDs

Zhiyong Liu  <https://orcid.org/0000-0002-6930-5879>
Feng Liu  <https://orcid.org/0000-0002-5311-3178>
Marco Toffolon  <https://orcid.org/0000-0001-6825-7070>

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