Roles of dam and climate change in thermal regime alteration of a large river

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Abstract
Water temperature in the Yangtze River mainstream has been experiencing significant changes due to the climate change and the operation of a series of world-class large dams, i.e. the Three Gorges Dam (TGD) and upstream cascade dams (CDs). However, quantitative effects of these factors are not fully known, which hinders our understanding on the thermal regime alterations and further prediction in ecosystem response. Here, we will simulate the riverine water temperature (RWT) variations by building a physics-based model, and quantify the respective impacts from TGD, CDs and climate change through a model-based framework. In the framework, both the dam-regulated hydro-thermodynamic processes and the spatial heterogeneity of the meteorological condition in this large river-reservoir system are thoroughly considered. The results show a fluvial warming of 0.31 °C–0.56 °C/10a in recent three decades, mainly attributed to climate change (44%–80% for different reaches). The dam has caused a substantial seasonal thermal lag, e.g. ∼40 d near the TGD in the dry season, and accompanying severe alterations in the monthly RWT. A reduction of 10% in seasonal RWT range is identified, which is attributed to both dam and climate change.

List of abbreviations

| Abbreviation | Description |
|--------------|-------------|
| AT           | Air temperature |
| BHT          | Baihetan Dam |
| CDs          | Cascade dams |
| CL           | Climate change |
| CT           | Cuntan (upper reach station) |
| DT           | Datong (lower reach station) |
| GZB          | Gezhouba Dam |
| HK           | Hankou (middle reach station) |
| NSE          | Nash Sutcliffe efficiency |
| PBIAS        | Percent bias |
| R²           | Coefficient of determination |
| RMSE         | Root mean square error |
| RWT          | Riverine water temperature |
| TGD          | Three Gorges Dam |
| TGR          | Three Gorges Reservoir |
| WDD          | Wudongde Dam |
| XIB          | Xiangjiaba Dam |
| XLD          | Xiluodu Dam |
| YC           | Yichang (upper reach station) |
| ZT           | Zhutuo (upper boundary) |
| ∆i           | Change in RWT caused by ‘i’ |

1. Introduction

In rivers, water temperature is a crucial factor for determining the health and quality of the aquatic ecosystem, as it has a strong influence on the various biochemical processes, such as chemical reaction rate, algal photosynthesis, oxygen solubility and biological activity (e.g. Olden and Naiman 2010, Azadi et al. 2018, Song et al. 2018). In a natural state, the riverine water temperature (RWT) is highly related to the meteorological parameters. Among them, air temperature (AT) is considered to be the most important
driver for the RWT fluctuations (Erickson et al 2000, Yang et al 2006, Dugdale et al 2017, Cai et al 2018, Tao et al 2020). Global atmospheric warming in the recent decades has been considered as one main cause for the RWT increase, and the increasing trend is expected to continue in the future (Punzet et al 2012, van Vliet et al 2013, Rice and Jastram 2014, Chen et al 2016, Jackson et al 2018). In addition, in the past decades, numerous rivers in the world have been or planned to be dammed, which will influence the thermal regime due to water impoundment and flow regulation (Olden and Naiman 2010, He et al 2020). Dam and climate change often combine to cause the RWT alterations, leading to increased complexity in water resources management and water environment protection in river-reservoir systems. In recent years, efforts have been made to quantify the impacts of dam and climate change on the thermal regime (Beek et al 2012, van Vliet et al 2013, Cai et al 2018). Data-dependent models, including regression and neural network models, have been used to reproduce the RWT against meteorological records and discharge at a single station (Erickson et al 2000, Webb et al 2003, Tao et al 2020). This kind of models are simple in form and require less data, thus they are used widely. However, the spatial heterogeneity of meteorological condition is not explicitly considered in those modes, because only local variables are used. In addition, data-dependent models are established based on empirical relationship against past information, so they are limited in their ability to predict the RWT under varying anthropogenic activities and altered watershed environment (Yearsley 2009). Heat-budget model is based on the heat balance to determine the RWT, and is widely applied to predict the RWT in recent years with climate change and anthropogenic disturbances (Beek et al 2012, van Vliet et al 2013, Cheng et al 2020). Information about river depth, width and velocity is required for a heat-budget model, which is usually estimated by fitting empirical relationships with discharge (van Vliet et al 2012). These simplifications are efficient and facilitate the model handling. However, for large river-reservoir systems, the accuracy is limited when complex hydrodynamic processes are simplified, which hindered a proper attribution analysis of RWT alterations. Therefore, in order to obtain more reliable and rational quantitative attribution, it is necessary to consider the full hydrodynamic processes. Thermal regime in the Yangtze River has been found significantly altered in recent decades, which is thought to be related to the operation of a series of world-class dams on its mainstream, e.g. the Three Gorges Dam (TGD), and upstream cascade dams (CDs). However, few efforts have been made to quantify the impacts of dam operation and climate change on the RWT alterations. Cai et al (2018) quantified the impacts of the TGD and climate change on the annual and seasonal mean RWTs in the mid-lower reaches by using the air2stream model. Tao et al (2020) applied a multivariate linear regression model to quantify the RWT alteration caused by the TGD near the dam site. These two studies provide us with a basic quantitative understanding of the TGD impacts and climate change on the RWT in the Yangtze River. In their studies the data-dependent models were used, where the RWT was predicted based on the information from local AT and discharge. However, as one of the largest river in the world, the Yangtze River has strong spatial distributions of topography and meteorological condition, so it is hard for local variables to characterize the climate change across the region. In addition, the impact of dam disturbances on hydro-thermodynamic processes cannot be considered explicitly by these models. Moreover, the impacts of upstream large CDs on the mid-lower reaches have been neglected in those studies. Therefore, the quantitative attribution analysis of the RWT alterations in the Yangtze River requires to be further studied.

Here, a framework has been built up for the investigation and attribution analysis, which is based on the long-term field observation data, a large-scale and full hydro-thermodynamic model, a multivariate statistical regression model and a series of orthogonal experiments. The aims of this study are to produce a more comprehensive picture of the decadal alterations of the RWT in the Yangtze River, to reveal the quantitative contributions of the driving forces, including both climate change and dam operation, and to obtain a better understanding on the mechanism of the thermal regime alterations.

2. Materials and methods

2.1. Study area

The Yangtze River originates from the Qinghai–Tibet Plateau at an altitude of more than 5000 m, and it extends eastward into the East China Sea, along which the spatial distribution of meteorology and geographical features vary significantly, as shown in figure 1. The Yangtze River ranks the third largest river in terms of water discharge (∼960 km³ yr⁻¹), which contributes about 2.6% of the total fresh water delivered to the ocean of the world. The catchment area is approximately 1.8 million km², where more than 450 million people live (Tao et al 2020).

The Yangtze River is one of the heavily dammed fluvial system in the world. Since the 1950s, more than 50 000 dams have been constructed in this catchment (Yang et al 2011). Among them, the TGD is the largest one, and the formed reservoir, i.e. the Three Gorges Reservoir (TGR), extends approximately 640 km from the dam with a capacity being around 40 × 10⁹ m³. Upstream of the reservoir, a series of large-scale CDs have been built or planned since 2000, among which four dams rank in the top
Figure 1. (a) Map of the Yangtze River Catchment. The major hydrological and meteorological stations along the mainstream are shown, with the increase in air temperature (AT) over the study period (1990–2016) being given by scaled symbols. The TGD is located on the outer margin of the Sichuan Basin, where the increase in AT is small compared with those inside the basin. (b) Sketch of the model domain, showing the tributaries, major dams, and hydrological stations. The dashed arrow indicates the site where a multivariate linear regression model is used, and the solid arrow indicates the region where a hydro-thermodynamic model is applied. The abbreviated names in the figure are XLD-Xiluodu Dam, XJB-Xiangjiaba Dam, TGD-Three Gorges Dam, GZB-Gezhouba Dam, ZT-Zhutuo, CT-Cuntan, YC-Yichang, HK-Hankou, DT-Datong. Refer to tables S1–S3 for details of these stations and dams.

15 of the world in terms of the installed capacity, and they are Xiluodu Dam (XLD), Xiangjiaba Dam (XJB), Wudongde Dam (WDD) and Baihetan Dam (BHT). Regarding the RWT alteration in the Yangtze River, this study focuses on the mainstream, i.e. from the location 760 km upstream of the TGD to the estuary mouth. Along the mainstream, there are three inflow tributaries (Jialing, Wu and Han Rivers), two subsidiary lakes (Dongting and Poyang Lake) and three outlets (figure 1(b)).

2.2. Datasets
To investigate the thermal regime in the Yangtze River, a meteorological dataset including AT, relative humidity, hours of sunlight, wind velocity and evaporation, and a hydrological dataset including discharge, water level and water temperature are collected. The meteorological dataset is available from the National Meteorological Information Centre (http://data.cma.cn/en), and the hydrological dataset is based on the Annual Hydrological Report (Volume VI: Changjiang River Basin) published by the Ministry of Water Resources of P. R. China. More details of the hydrological stations and meteorological stations are listed in tables S1 and S2, respectively.

2.3. Framework of attribution analysis
In the Yangtze River the RWT has been changed due to multiple factors, including the climate change, the TGD, the upstream CDs, and etc. Thus, the total change in the RWT ($\Delta_{TOT}$) can be written as follows:

$$\Delta_{TOT} = \Delta_{CL} + \Delta_{TGD} + \Delta_{CDs} + \varepsilon \quad (1)$$
$\Delta_{TOT} = \Delta_{TGD} + \Delta_{CDs} + \Delta_{CL} + \varepsilon$

where $\Delta_{CL}$, $\Delta_{TGD}$, $\Delta_{CDs}$ and $\varepsilon$ are the components caused by the climate change, TGD, upstream CDs and other factors, respectively. In this study, a framework is proposed to quantify the impact of each driving factor, as shown in figure 2. In this framework, coupled hydro- and thermodynamic models and a regression model are built to simulate the RWT under a series of scenarios for attribution analysis. The root mean square error (RMSE), the coefficient of determination ($R^2$), the Nash Sutcliffe efficiency (NSE) and percent bias (PBIAS) are used to thoroughly evaluate the model performance (Moriasi et al. 2015). For both the pre- and post-TGD periods, the RMSE ranges are from 0.41 to 0.68 °C along the mainstream; the $R^2$ is larger than 0.99 for all stations; the NSE is larger than 0.98; and the PBIAS is between ±1.10%. An excellent performance of the physics-based model is obtained, and readers can find the supporting text 1–3 for detailed information.

The total change in the RWT ($\Delta_{TOT}$) is calculated as the difference between the observed RWTs during the pre-TGD period (1990–2002, $RWT_{o,pre}$) and post-TGD period (2009–2016, $RWT_{o,post}$), which is written as follows:

$$\Delta_{TOT} = RWT_{o,post} - RWT_{o,pre}$$  \hspace{1cm} (2)

in which the first subscript indicates observed (‘o’) or modeled (‘m’), and the second subscript indicates the period, either pre- or post-TGD period. The impact of the TGD is identified through the difference between the model-simulated RWTs in actual scenario (RWT$_{m,post}$) and in the absence of the TGD (RWT$_{m,post,noTGD}$) during post-TGD period, as follows:

$$\Delta_{TGD} = RWT_{m,post} - RWT_{m,post,noTGD}.$$  \hspace{1cm} (3)

Similarly, the impact of CDs is identified through the modeled RWTs in an actual scenario (RWT$_{m,post}$) and in the absence of the upstream CDs (RWT$_{m,post,noCDs}$) during the post-TGD period, as follows:

$$\Delta_{CDs} = RWT_{m,post} - RWT_{m,post,noCDs}.$$  \hspace{1cm} (4)

To quantify the impact of climate change using the numerical model, the anthropogenic interferences should be removed. In the model, the main anthropogenic interferences are dams, including CDs and TGD. Therefore, scenarios in the absence of dams are carried out to obtain the RWT change dominated by the climate change, which is labeled with the subscript ‘CL’ hereafter. Therefore, the impact of the climate change can be quantified as the difference between the modeled RWTs during the post-TGD period (RWT$_{m,post,CL}$) and pre-TGD period (RWT$_{m,pre,CL}$), as follows:

$$\Delta_{CL} = RWT_{m,post,CL} - RWT_{m,pre,CL}.$$  \hspace{1cm} (5)

Based on the present framework, an attribution analysis is conducted at four main hydrological stations along the mainstream, and the contribution of each factor regarding the phenomena of fluvial warming, reduction in seasonal RWT range and seasonal thermal lag in the Yangtze River is obtained (tables S8–S10).
3. Results

3.1. Fluvial warming
A significant fluvial warming is identified through the annual mean RWT in recent decades (figures 3(a) and S1). Along the Yangtze River, the hydrological stations CT and YC are representative for the upper reach, HK for the middle reach, and DT for the lower reach. The bulk increases in the annual RWT over the study period from 1990 to 2016 are approximately 0.80 °C, 1.02 °C, 1.45 °C and 1.32 °C at the above four key hydrologic stations, i.e. CT, YC, HK and DT, respectively, with the rates of change being 0.31 °C–0.56 °C/10a (figure 3(a)). We find that both the climate change and dam operation play positive roles in the fluvial warming, while the former is the dominant driver. A main manifestation of the climate change is the increasing annual AT, which has an increase by up to 1.25 °C along the mainstream over the study period (figure 1 and table S2). The increasing AT has caused a higher RWT through the heat exchange process at the air–water interface. As a result, the climate change contributes approximately 70%–80% to the fluvial warming in the middle (HK) and lower (DT) reaches of the Yangtze River, while 44%–52% in the upper reach (CT and YC), as shown in figure 3(b). The positive contribution of the dam is mainly related to the enhanced thermal inertia due to the massive water impounded in the reservoir in the dry season (Cai et al 2018, He et al 2020). From a quantitative point of view, in the middle and lower reaches dams just play a minor role, and the impact of both the TGD and upstream CDs is not significant. Even at the near-dam station YC, the contribution rate of the TGD is just 25%, while at other stations far from the dam site the percentage is generally less than 10%. The role of CDs shows a declining trend in the downstream direction, with the percentage from about 16% at CT Station to less than 5% downstream of TGD.

As one of the largest rivers in the world, the Yangtze Catchment has a large-scale variation in geographical and meteorological condition (Piao et al 2010, figures S4–S6). Although the AT and RWT both show a warming trend, the increase in AT is spatially inconsistent with the increase in RWT (figure S3). The annual mean AT increase is ~0.87 °C in the Sichuan Basin where the TGR is located, but at the outer margin of the basin, where the dam is situated, the AT increase is relatively small, ~0.11 °C. This meteorological heterogeneity is highly related to the geographical features of the basin, canyons and downstream plains. Meteorological condition in both Sichuan Basin and dam site will affect the thermal regime near the TGD. Therefore, the spatial distribution of meteorological condition should be considered in the attribution analysis in order to obtain an accurate understanding on the agents of RWT alterations. Otherwise, the contributions could be improperly estimated in a large catchment if only local meteorological information at a single hydrological station is used and the far-field meteorological effect is neglected. This is the main reason why the contribution of climate change to the warming of the Yangtze River has been substantially underestimated in previous studies, in which only the near-dam AT was used to investigate the RWT alteration near the TGD (Cai et al 2018, Tao et al 2020). In addition, the dam-regulated flow has obviously influenced the RWT-AT relationship (figure S7), which significantly reduces the reliability of the attribution analysis results by using simplified heat-budget and regression models based on the relationship between the RWT and local AT. In this study the effects of the spatial heterogeneity of the meteorological condition along the mainstream and the TGR interference on the hydrodynamic and thermodynamic processes have been considered explicitly by the physics-based model, which help us to obtain more appropriate attribution result for RWT alterations.

3.2. Reduction in seasonal RWT range
In annual cycles the seasonal RWT variation is a basic feature in most rivers. We find that the RWT variation range in the Yangtze River has shrunk significantly over the past decades. Figure 4(a) shows the scaled RWT by min–max normalization, which indicates the distinct reduction in the seasonal RWT range: the annual minimum RWT has a substantial increase, while the maximum value changes little. As a result, the RWT variation range has decreased by 1.48 °C (10%), 2.68 °C (17%), 1.21 °C (6%) and 1.74 °C (8%) at CT, YC, HK, DT Stations, respectively (figure 4(b)), with a mean rate of change being ~0.68 °C/10a. Attribution analysis reveals that dams always contribute positively to the reduction in the RWT range along the river, with the contribution proportion varying between 30–88%. In contrast, the contribution of climate change is location-dependent, i.e. it is positive in the upper and middle reaches, while negative in the lower reach.

Dam-induced reduction in seasonal RWT range is mainly related to the alteration of the hydrodynamic processes, including the seasonal regulated water volume of the reservoir and redistributed discharge in annual cycle downstream of the dam. In the dry season, when the RWT is relatively low, reservoirs operate at a high water level for power generation and waterway navigation. The massive water stored in the TGR leads to a large thermal inertia, which hinders the natural cooling process caused by the lower AT. As a result, the annual minimum RWT in the dry season has a significant increase, which then contributes to the reduction in the RWT range, as shown in figure 4(a). On the contrary, in flood season, the reservoir is kept at a low water level for flood control,
which results in a limited capacity and thus small impact on the seasonal RWT range.

For the downstream reach of a dam, it is usually taken for granted that the impact of reservoir on RWT should dissipate downstream-ward, owing to the recovering effect of air–water heat exchange. However, we find that at HK station, ~700 km downstream of the dam, the TGR has reduced the seasonal RWT range by 0.91 °C, even more than that at the near-dam station YC (0.69 °C). The paradox can be interpreted by the combined effect of the dam-regulated replenished discharge in the dry season encountering with the special climatic feature. Due to the geographical features of this region, the AT in the Sichuan Basin is much warmer than that in the downstream plain (figure S6). The downstream-ward decreasing trend in the AT from Sichuan Basin to the downstream plain in dry season leads to a similar trend in the RWT through heat exchange (figure S2). However, during the post-TGR period, the replenished discharge in the dry season increases the water depth and shortens the water transport timescale downstream of the dam (Sun et al 2021), which weakens the cooling effect caused by the downstream-ward colder air and reduces the duration of the cooling process. As a result, the downstream-ward decreasing trend in the RWT is retarded, which leads to an additional increase in the downstream RWT in the dry season. This additional increase will further contribute to reduce the seasonal RWT range and this is considered as the reason why TGR-induced reduction in RWT range at HK is more than that at YC.

3.3. Seasonal thermal lag

Monthly RWT values have changed significantly over the last decades, especially near the TGD, see insets of figure 5. At the near-dam YC Station, a warming temperature period is identified from September to next February, with an increase of ~4 °C in January and
December. In contrast, the RWT from March to June is characterized by cooling, with a decrease of $\sim 3.5^\circ$C in April. As for the two warmest months, i.e. July and August, there is little change in RWT. These changes are closely related to the seasonal thermal lag effect, which is mainly caused by the retention ability of the TGR (Cai et al. 2018, Sun et al. 2019). In the dry season, the hydraulic residence time of the riverine water is $\sim 70$ d according to the ratio of the TGR capacity, $\sim 40$ km$^3$, to outflow discharge, $\sim 6000$ m$^3$ s$^{-1}$, while before the TGD operation the corresponding transport timescale in the same reach is just $\sim 10$ d. Thus, the resident time is prolonged by $\sim 60$ d. The annual minimum RWT lag time is $\sim 40$ d at the YC Station near the TGD, as shown in figure 5, which is shorter than the two months’ water resident time. The reason is that the air–water heat exchange has relieved the thermal lag to a certain extent. In the flood season, the thermal lag is not significant due to the limited increase in the water resident time ($\sim 10$ d) with the low water level and large discharge. At the upstream ZT and CT Stations, the mean lag time of the minimum RWT is about $\sim 7$ d, and the lag-induced RWT alteration is up to $\sim 1^\circ$C (insets of figure 5), which is dominated by the upstream CDs (table S10). At the middle (HK) and lower (DT) stations, there is almost no negative value for the RWT alteration due to the superimposition of the severe fluvial warming.

Although it is known that dams have certain impacts on the rivers worldwide, the influenced thermal landscape is not clear so far, especially for large rivers (Grill et al. 2019). The results in this study show that the TGD plays an important role in the thermal lag over a considerably long distance along the Yangtze River. The largest impact occurs near the dam, and the impact extends in both upstream and downstream directions. In the upstream direction, the effect does not diminish completely until the CT Station, $\sim 550$ km from the dam. In the downstream direction, the effect of the TGD can extend beyond the HK Station, $\sim 800$ km from the dam. It demonstrates that the potential influence of a large dam on the thermal regime can be as long as a thousand kilometres, and the impact attenuates gradually away from the dam site, which may provide a useful reference for future investigation on dam impacts in world’s large rivers.

4. Discussion and conclusions

In this study, the RWT alterations in the Yangtze River are systematically investigated, and in particular, the impacts of the TGR, upstream CDs and climate change are distinguished. The results indicate that the fluvial warming in the current decades is mainly caused by the climate change, while the seasonal thermal lag has been dominated by the dam operation. Reduction in seasonal RWT range is identified, which is attributed to both the climate change and dam operation. This research has refined the understanding of driving factors of RWT alterations in the Yangtze River by integrating a physics-based model and a multiple linear regression model into the attribution analysis framework. It is revealed that the impact of climate change has been underestimated in
previous studies due to neglecting the meteorological heterogeneity over the catchment (Cai et al. 2018, Tao et al. 2020), which indicates that the reliance relationships should be used with caution in such large river-reservoir systems. More than one dam is usually constructed on a large river, and their cumulative effects on the downstream RWT and ecosystem have attracted extensive attention (Petesse and Perere 2012, Cheng et al. 2015, Yu et al. 2019). This study elaborates the dominance of CDs in the thermal lag upstream of the TGR, and finds that the impact of CDs is rather weak downstream of the TGR, which is in general agreement with the finding of He et al. (2020). That is, the upstream CDs and TGR have no obvious cumulative effect on the RWT in the mid- and lower Yangtze River, which provides a reference for understanding the thermal regime alterations caused by a series of dams, not just an individual dam.

The results of this study also offer insights for riverine ecosystems. In a warming aquatic surrounding, the net primary production of a riverine ecosystem may decrease, which has been found from the temperature sensitivity analyses at both the cellular level and the ecosystem level (Song et al. 2018). Therefore, the riverine systems would become more heterotrophic with the increasing RWT. With Song’s estimation, a 1 °C increase in the RWT could lead to a ~23.6% decline in net productivity. A similar loss is expected in the Yangtze River, with an increase in the average annual RWT of ~1.15 °C, and more attention should be paid to the possible increase in the net carbon emission associated with the change in the net productivity. Regarding the thermal lag, the seasonal RWT variation in the mainstream tends to induce temperature differences between the mainstream and tributaries, and contribute to density stratification in tributaries. The density stratification has been proved to be a vital trigger for algal blooms in the tributaries since the impoundment of reservoirs (Long et al. 2016, 2019, Chuo et al. 2019, Li et al. 2020), and breaking thermal stratification is expected to be a potential measure to reduce the probability of algal blooms (Yang et al. 2018). Therefore, climate change and dam play different but vital roles in alternating riverine ecosystems. The combined impacts from the future climate change and dams under construction deserve more attention.

Aquatic animals, especially ectotherms, are significantly affected by the changing RWT. As a well-known example, the Chinese sturgeon is one kind of critically endangered fish, whose spawning period highly depends on the RWT, generally within a range of 18 °C–20 °C. The thermal lag, together with the dam block induced effects (Huang and Wang 2018), have led to a severe decline or even extinction of the wild population. The increasing RWT downstream of the dams also has potential impacts on macroinvertebrate community. Increased fish species richness, and reduction in brown trout, brook trout and slimy sculpin population densities have been observed (Lessard and Hayes 2003). Attribution analysis in this study indicates that dams have obviously altered the RWT process mainly due to the thermal lag, which is one basic ecological condition for aquatic animal normal life cycles. Meanwhile, the climate change could affect aquatic animals through an overall fluvial warming. Therefore, the impact of the RWT alterations on the ecosystem should be attributed to the combined effect of dams and climate change.

Data availability statement

The meteorological datasets are openly available from National Meteorological Information Centre (http://data.cma.cn/en), and the hydrological data sets are openly available from the Annual Hydrological Report (Volume VI: Changjiang River Basin) published by Ministry of Water Resources of P. R. China.

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