Heat budget contribute rate in the Three Gorges Reservoir tributary bay between mainstream and tributary using stable isotope analysis
Yao Cheng, Yuchun Wang, Huaidong Zhou, Mingming Hu, Rong Jiang, Yufei Bao and Chenghua Dang

ABSTRACT
Understanding the interaction processes between the mainstream and its tributaries and detailing the rates of contribution of water and heat from two different water bodies in the tributary bay are essential for water management in the Three Gorges Reservoir (TGR). The stable isotope ratios of hydrogen ($\delta^D$) and oxygen ($\delta^{18}O$) were applied to explore the interactions between the TGR mainstream and the tributary, Zhuyi River. A heat budget of the TGR tributary bay was constructed for the year 2014 using data for water temperature, meteorological data and water mixing ratio. The results showed that approximately 91% of the water in the tributary bay was from the TGR mainstream. And the heat budget reveals that the tributary bay net heat flux is dominated by the mainstream advective heat, and the average contribution rate is 87% during the whole year, while the tributary advective heat and atmosphere make a minor contribution to the tributary bay heat budget.

Key words | heat budget, stable isotope, Three Gorges Reservoir, tributary

INTRODUCTION
The Earth is experiencing significant changes in response to anthropogenic activities. We have entered the Anthropocene (Crutzen 2002; Zalasiewicz et al. 2010), a new epoch where our impacts combined with natural variations are leading to dangerous global environmental changes. Research on surface waters is critical to determine the influence of human activities on the Earth.

Humans have extensively altered river systems through impoundments. General impacts of dams include changes in the net water balance (Charles 1997), regulation of the flow regime (Batalla et al. 2004; McClelland et al. 2004), modification of water levels (Lu & Siew 2006; Wang et al. 2013), disruption of downstream sediment transport (Topping et al. 2000; Walling & Fang 2003; Willis & Griggs 2003), changes in channel morphology (Xu 1996; Bondar & Blendea 1997; Brandt 2000; Villanueva 2003), and alterations in stream ecology (Power et al. 1996; Koel & Sparks 2002). While the impacts of dams on river hydrology have...
received much attention, relatively little is known about the heat budget contribution rate between mainstream and tributaries in large reservoirs. Moreover, most previous studies focused on the downstream impacts of dams without considering the impacts on reservoir tributaries.

The thermal regimes of rivers are of major importance for freshwater ecosystems and human water use. Both heat budget and water temperature directly affect water quality (Haag & Westrich 2002; Ozaki et al. 2003; Ducharme 2007), and the growth rate and distribution of freshwater organisms (Eaton & Scheller 1996; Ebersole et al. 2001; Mohseni et al. 2003). A primary focus of physical limnology is understanding the thermal structure and heat budget of lakes and reservoirs over a wide range of temporal and spatial scales. Heat content quantifies the relative amount of thermal energy within the water column, and its time derivative is used to quantify the rate of change occurring within the water column.

The advective heat associated with inflows and outflows was often considered a minor source of heat or not measured and thus neglected in heat budget calculations (Keijman 1974; Colomer et al. 1996; Rouse et al. 2003; Binyamin et al. 2006; Momii & Ito 2008), although Tanny et al. (2011) noted its possible significance. While many lake heat budgets show that the input and output of heat energy are dominated by surface heat fluxes, including radiation fluxes, latent heat flux, and sensible heat flux (Myrup et al. 1979; Lewis 1985; Livingstone & Imboden 1989; Oswald & Rouse 2004), this may not be so for reservoir tributary bays. In such areas, advective heat transport may be equal to or greater than surface heat flux in the heat budget.

The construction of the Three Gorges Dam (TGD), which impounds the Yangtze River to provide drinking and irrigation water, electrical energy, flood control, infrastructure, and economic benefits, is one of the most intense anthropogenic impacts on surface water in China. Approximately 40 rivers are impounded by the Three Gorges Reservoir (TGR). The total area of these bays accounts for 1/3 of the whole surface area of the TGR. The impacts of the TGR on the ecosystem and environment have been widely discussed (Stone 2008). Density currents are major hydrologic component of the TGR tributary bays (Liu et al. 2012; Mao et al. 2013), where there are inflows and outflows from the Yangtze River to the tributary bay. These indicate there are continuous water and heat exchanges between the Yangtze River and the tributary. It is difficult to calculate the water and heat flux between the Yangtze River and the tributary, as the density currents are influenced by many factors, such as water depths, flow and temperature difference between the mainstream and the tributary. Thus a quantitative evaluation of the impact of the mainstream and tributary on the heat budget is a tough task.

The stable isotopic composition of H2O can provide useful information for tracing the source of water in rivers according to the distinct isotopic signatures of the different water sources (Kabeya et al. 2008). Studies of many river systems around the world have used stable isotope tracers to investigate hydrologic processes (Gibson & Prowse 2002). These stable isotope tracers have been demonstrated to be valid tools for clarifying the complex interactions among different sources (Yurtsever & Araguas 1993; Clark & Fritz 1997; Kendall & Caldwell 1998).

This paper analyzes the vertical distribution of temperature in the Zhuyi Bay (ZB), which is one of the TGR tributary bays, the stable isotope characteristic and the heat budget relationship between TGR mainstream and the tributary. A heat budget of a TGR tributary bay is constructed using data for water temperature, meteorological data and water mixing ratio. The mainstream, tributary inflow and atmospheric contributions to the tributary bay heat budget can be calculated quantitatively.

**STUDY AREA**

As the third longest river in the world and the longest river in Asia, the Yangtze River, extending from the Tibetan Plateau to eastern China, spans a total length of 6,300 km and drains an area of 1,800,000 km² (Chen et al. 2001). Its annual flow is 951.3 km³. The Yangtze River drainage is divided by Yichang and Hukou into upper, middle and lower reaches (Xu et al. 2006; Zheng 2013).

The TGD, located at the end of the upper Yangtze River, is 185 m high. Construction began in 1998 and was completed in 2003. The TGR is currently the largest man-made reservoir in the world with a capacity of 39.3 billion m³ over a length of 663 km (Nilsson et al. 2005; Yang et al. 2013).
Before the TGD was built, the water level of the Yangtze River at Yichang was approximately 70 m. The TGR completed filling to full capacity in 2008, and its water level is approximately 175 m in winter and 145 m in summer. The water level decreases from 175 m to 145 m in the spring and increases from 145 m to 175 m in autumn.

The Zhuyi River is a tributary in the middle reach of the TGR on the left bank (Figure 1). It is 156 km upstream from the TGD. It has a watershed area of 149 km², length of 29 km and annual average discharge 0.07 km³. After impoundment of the TGR, a 6.5 km long bay was formed, with a depth at upstream site ZY03 being from 0 to 30 m as a consequence of TGR regulation. Hereafter this area is called Zhuyi Bay in this paper.

**DATA AND METHODS**

To determine the spatiotemporal variations in water temperature, monthly observations were conducted in 2014 at 5 sites in Zhuyi Bay (Figure 1). ZY01 is 0.5 km distance from the confluence, ZY02 is 3.3 km, ZY03 is 5.5 km and ZY04 is 7.5 km. ZY04 represents the natural river, which is not influenced by the regulation of TGR. YR01 is located at the Yangtze River, 1 km upstream of the confluence. Every station is in the stream central line.

A boat with two to three persons and a set of Multi-Parameter Water Quality Sondes (Fondriest Environmental YSI EXO2) were used to collect monthly water temperatures. Measurements began at approximately 10:00 am on the 25th of each month, starting with station YR01 and ending with station ZY04, lasting approximately 30 minutes at each station. Water samples were taken from moving river water with a water sampler. Multiple depths (surface, 5 m, 10 m, 20 m, and to the bottom) were sampled. Water samples were collected in airtight glass bottles (20 mL), the caps were then sealed with paraffin film. The water samples were preserved in a refrigerator (4 °C) and promptly analyzed. Meteorological data were obtained from the Weather Underground website (WU website). Due to the shallow water depth of ZY03 in June, July and August, there is no temperature and isotopic observation data in these months at the station.

**Heat budget model**

The total heat budget for a body of water includes heat exchanged with the atmosphere, heat transported by inflows/outflows, heat generated from chemical/biological reactions, heat exchanged between the water and the reservoir bottom, and heat generated from current friction. The latter three are negligible in most applications (Ji 2008). Thus, a simple heat budget model can be expressed as Equation (1):

$$\Delta Q_{Hc} = Q_{Ha} + Q_{Ht}$$  \hspace{1cm} (1)

where $\Delta Q_{Hc}$ is the heat content change of the water (J m⁻²), $Q_{Ha}$ is the heat exchange with the atmosphere, and $Q_{Ht}$ is the advective heat transported by currents.

**Heat content**

The heat content is calculated by Equation (2):

$$Q_{Hc} = C_w \int_{-H}^{0} \rho_T (T)(273 + T_z) \, dz$$  \hspace{1cm} (2)

$$\rho_T = 999.842594 + 6.793952 \times 10^{-2}T - 9.095290 \times 10^{-3}T^2$$
$$+ 1.001685 \times 10^{-4}T^3 - 1.120083 \times 10^{-6}T^4$$
$$+ 6.536332 \times 10^{-9}T^5$$  \hspace{1cm} (3)
where $QH_c$ is the heat content of the water relative to the temperature of maximum density ($J \cdot m^{-2}$), $\rho_f(T)$ is the density of water ($kg \cdot m^{-3}$) at temperature $T$ (Gill 1982), $C_w$ is the heat capacity of water (taken to be a constant of 4,180 $J \cdot kg^{-1} \cdot K^{-1}$), $T_z$ is the measured temperature at depth $Z$ ($^\circ$C), and $H$ is the water depth (m). As most rivers and lakes have a different width, heat content is usually calculated in a 1 m$^2$ water column. In this way different rivers and lakes may be compared (Kalff 2002; Gronewold et al. 2015).

### Heat exchanges with the atmosphere

Heat exchanges with the atmosphere can be expressed as Equation (4):

$$QH_a = \int_0^t F_H(a)(t) \, dt$$

where $F_H(a)(t)$ is the surface net heat flux, and $t$ is time in seconds.

The surface net heat flux is calculated as shown in Equation (5):

$$F_H = F_{Hs} + F_{HL} + F_{Ha} + F_{He}$$

where $F_{Hs}$ is the shortwave solar radiation flux, $F_{HL}$ is the net longwave radiation flux from the atmosphere and the body of water, $F_{He}$ is the latent heat flux due to evaporation and $F_{Ha}$ is the sensible heat flux due to conduction.

The shortwave solar radiation flux is derived from NOAA’s Net Shortwave Radiation Flux (Kalnay et al. 1996).

Equation (6) by TVA (1972) is used to calculate the long-wave radiation flux:

$$F_{HL} = \varepsilon \sigma (T + 273.15)^4 + 0.97 \left[ 9.57 \times 10^{-6} \sigma (1 + 0.17C^2)(T_a + 273.15) \right]$$

where $F_{HL}$ is longwave radiation ($kJ \cdot m^{-2} \cdot h^{-1}$), $\varepsilon$ is the emissivity of the body of water (0.97), $\sigma$ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}$), $T$ is water temperature ($^\circ$C), $T_a$ is atmospheric temperature ($^\circ$C), and $C$ is the cloud fraction (0 = cloudless, 1 = full cloud coverage).

The latent heat of evaporation is calculated using Equation (7) (Bolton 1980):

$$F_{He} = f(w)(e_s - e_a)$$

$$e_a = e_s \times \frac{R_h}{100}$$

$$e_s = 6.112e^{(17.67T_a/(T_a + 243.5))}$$

$$f(w) = 6.9 + 0.345w^2$$

where $F_{He}$ is the evaporation heat flux ($W \cdot m^{-2}$), $f(w)$ is the wind speed function ($W \cdot m^{-2} \cdot mb^{-1}$), $w$ is wind speed ($m \cdot s^{-1}$), $e_s$ is the saturated vapor pressure at water surface temperature (mb), and $e_a$ is the actual vapor pressure in the overlying air, typically 10 m above the water (in mb).

Using the Bowen ratio (Bowen 1926), the sensible heat flux can be calculated as Equation (11):

$$F_{Ha} = C_B \frac{P_a}{P_0} f(w)(T - T_a)$$

where $C_B$ is the Bowen coefficient (0.62 mb $\cdot$ $^\circ$C$^{-1}$), $P_a$ is atmospheric pressure (mb), and $P_0$ is reference atmospheric pressure at sea level (1,013 mb).

The study area is small, only about 30 km$^2$, and the 5 sampling sites are all in the stream central line; shading by the local mountains and ridges have little influences, so all sites experience the same amount of solar insolation. Daily meteorological data was used to calculate the heat budget.

### Advection heat

The heat transported by inflows/outsflows is expressed as Equation (12):

$$QH_i = \Delta QH_c - QH_a = QH_{c}^{t+1} - QH_{c}^{t} - QH_a$$

where $QH_{c}^{t}$ is the heat content at time $t$.

### Measurement of stable hydrogen and oxygen isotopes

The hydrogen and oxygen isotopic compositions of the water samples were determined using a liquid water isotope...
analyzer (LWIA, DLT-100, Los Gatos Research, Inc., Mountain View, CA). In nature, stable isotope composition changes are small, and $\delta$ values are generally used to represent the value of the isotopic composition of an element. The $\delta$ value is the ratio of stable isotopes in a sample relative to a standard sample isotope ratio multiplied by a factor of 1,000.

The oxygen and hydrogen isotopic compositions can be expressed as follows, respectively:

$$\delta^{18}O(‰) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1,000 \quad (13)$$

$$\delta D(‰) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1,000 \quad (14)$$

where $R_{\text{sample}}$ is the stable isotope ratio ($^{18}$O/$^{16}$O or D/H) of the sample, and $R_{\text{standard}}$ is the stable isotope ratio of Vienna Standard Mean Ocean Water (VSMOW, 0‰); in VSMOW, D/H and $^{18}$O/$^{16}$O were $1.5576 \times 10^{-4}$ and $2.0052 \times 10^{-3}$, respectively (Hayes 1985). All of the stable isotope ratio results were expressed as parts per thousand deviations from VSMOW with analytical precisions of ±0.15‰ (δD) and ±0.02‰ δ$^{18}$O.

**Calculation of mixing ratio**

The mixing ratio $x$ in this study refers to the percentage of the discharge from the TGR mainstream in the ZB. This ratio is calculated according to (Clark & Fritz 1997; Kabeya et al. 2008):

$$\begin{align*}
   x\delta D_M + (1-x)\delta D_T = \delta D \\
x\delta^{18}O_M + (1-x)\delta^{18}O_T = \delta^{18}O
\end{align*} \quad (15)$$

where, $\delta D$, $\delta D_M$ and $\delta D_T$ are the hydrogen isotopes in ZB, the mainstream of the TGR (YR01) and the Zhuyi River (ZY04), respectively; $\delta^{18}O$, $\delta^{18}O_M$ and $\delta^{18}O_T$ are the oxygen isotopes in ZB, the mainstream of the TGR (YR01) and the Zhuyi River (ZY04). We analyzed all of the sampling sections.

**Calculation of heat budget contribution rate**

According to the advective heat and mainstream mixing ratio, mainstream and tributary advective heat can be expressed as follows, respectively:

$$Q_{H_m} = Q_H x \bar{x} \quad (16)$$

$$Q_{H_t} = Q_H (1 - \bar{x}) \quad (17)$$

where, $Q_{H_m}$ is mainstream advective heat, $Q_{H_t}$ is tributary advective heat, and $\bar{x}$ is the vertical average mixing ratio. The heat budget contribution rates can be expressed as follows:

$$PQ_{H_m} = \frac{|Q_{H_m}|}{|Q_H| + |Q_{H_t}|} \times 100 \quad (18)$$

$$PQ_{H_t} = \frac{|Q_{H_t}|}{|Q_H| + |Q_{H_t}|} \times 100 \quad (19)$$

RESULT

**Water temperature in ZB**

Water temperature showed not only strong seasonal variation but also a seasonal pattern of stratification. The temperature structure varies greatly across seasons (Figure 2). The surface layer temperatures range from 12.3 to 28.6 ºC. The water is warmed in summer (June, July and August) and cooled in winter (January, February and December). Upstream (ZY03) temperatures are lower than those downstream (ZY01) in winter and are higher than those downstream in summer. The bottom layer temperatures range from 12.2 to 24 ºC, and the bottom layer water is also warmed in summer and cooled in winter. There is not much difference in monthly bottom layer temperatures at three stations (ZY01, ZY02 and ZY03). Water temperatures in the ZB strongly stratify during the warmest part of the year (from May to October); however, there is mixing during the remainder of the year.

**Heat content**

The monthly tributary heat content shows clear temporal and spatial variation (Figure 3). The heat content spatially
increases from upstream to downstream. Heat content at the upstream station (ZY03) ranges from $7.9 \times 10^9$ to $36.5 \times 10^9$ J m$^{-2}$, the midstream station (ZY02) ranges from $25.6 \times 10^9$ to $61.1 \times 10^9$ J m$^{-2}$, and the downstream station (ZY01) ranges from $37.9 \times 10^9$ to $73.4 \times 10^9$ J m$^{-2}$. The heat content in the ZB is lowest in spring and highest in autumn. The surface net heat fluxes are shown in Appendix Figure 1 (available with the online version of this paper).

Stable isotopic characteristics of the mainstream and the tributary

Coupled with the seasonal variation in the isotopic characteristics of precipitation (Dansgaard 1964), the natural compositions of hydrogen and oxygen isotopes in different water sources provide non-artificial signatures for water sources. The $\delta D$ and $\delta^{18}O$ values of the TGR mainstream
(YR01) ranged from −80.65‰ to −57.25‰ and from −11.40‰ to −8.29‰, respectively (Figure 4). However, the δD and δ18O values of the ZB (ZY01, ZY02 and ZY03) ranged from −84.05‰ to −54.39‰ and from −11.70‰ to −8.08‰, respectively. The δD and δ18O values of the waters in the Zhuyi River (ZY04) ranged from −49.55‰ to −46.12‰ and from −7.61‰ to −7.19‰, respectively.

A significant difference in both the δD and δ18O values (p < 0.05) between the TGR mainstream and the Zhuyi River was found (Table 1). Thus, both δD and δ18O values can be used as water mass indicators of both the TGR mainstream and the ZB.

The mainstream and ZB stable isotopic compositions are near to the Local Meteoric Water line (LMWL), which was calculated using data from the Global Network of Isotopes in Precipitation (GNIP) for stations in China (Lin 2015). The results indicate that the Yangtze River mainstream and the ZB have the same composition with precipitation being the major source of water for them, while precipitation is not the main source for the tributary. The tributary inflow water is different form LMWL indicating that the tributary water experienced intense evaporation or came from groundwater.

**DISCUSSION**

**Heat budget**

The heat budget balances for three sampling sites are shown in Figure 5. The heat exchange with the atmosphere varies greatly in time. There are minor differences between heat exchanged with the atmosphere at all three sampling sites. Advective heat also varies greatly in time; at the upstream station (ZY03) it ranges from −14.6 × 10⁹ to 8.1 × 10⁹ J m⁻², while at downstream station (ZY01) it ranges from −14.2 × 10⁹ to 15.6 × 10⁹ J m⁻². Advective heat at the confluence of the mainstream and tributary are almost the same as the ZB upstream.

Air temperature, water temperature and depth variation all influenced the heat budget. Both water and air temperature changed coincidentally with shortwave radiation (Figures 5(a) and 6(a)). Due to the higher heat capacity of water, it takes a longer time to heat and cool than air. Zhuyi River and Yangtze River water temperature variation could change ZB water temperature distribution; river temperature monthly variation changed inconsistently with advective heat (Figure 6(b)). Water depth variation changed coincidentally with advective heat (Figure 6(c)). These indicated that both Zhuyi River and Yangtze River temperature variation had only a small influence on advective heat, while depth variation due to the TGR regulation greatly influenced advective heat.

**Mixing ratios**

In this study, the average stable isotopic values of the TGR mainstream (YR01) and the tributary River (ZY04) were used to analyze the rates of contribution of the two types of water to the tributary bay. Equation (15) was used to analyze the mixing ratios of all of the sections in the tributary bay. The vertical distributions of mixing ratios in the tributary bay were obtained by cubic spline interpolation.

**Table 1 | Stable isotopic characteristics of samples**

<table>
<thead>
<tr>
<th>Sample sites</th>
<th>Sample numbers</th>
<th>Regression equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainstream (YR01)</td>
<td>120</td>
<td>δD = 7.52δ18O + 5.05</td>
<td>0.93</td>
</tr>
<tr>
<td>Tributary (ZY04)</td>
<td>12</td>
<td>δD = 6.44δ18O - 0.40</td>
<td>0.43</td>
</tr>
<tr>
<td>ZB (ZY01, ZY02 and</td>
<td>177</td>
<td>δD = 7.81δ18O + 8.06</td>
<td>0.95</td>
</tr>
<tr>
<td>ZY03)</td>
<td></td>
<td></td>
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</tbody>
</table>
and are presented in Figure 7. The Yangtze River water parcels invade into the tributary bay due to the density difference between the mainstream and the tributary. The supplement of water from the mainstream is calculated when TGR is filling according to the water balance equation and tributary bathymetric map. The tributary inflow and mainstream supplement are $80 \times 10^6$ m$^3$ and $94 \times 10^6$ m$^3$ respectively in 2014, which are almost 1:1. The isotope data also provide a clear illustration of how tributary inflow behaves at different times of year. In April, tributary inflows have entered the bottom of ZB (Figure 7(d)). And from May to July, tributary waters enter ZB as overflows during spring and summer warming periods (Figure 7(e)–7(g)). The mixing ratio in the ZB ranged from 55% to 99%, and the average value was 91% during the whole year. The invasion of flow is greater than the tributary inflow, so ZB is dominated by Yangtze River water parcels. The Yangtze River parcels mix ratio increases significantly, suggesting that the baroclinic flow is dominant in the tributary bay rather than barotropic flow.
Heat budget contribution rate

The heat budget was influenced by wind induced evaporation. The annual average wind speed is lower than 1 m s\(^{-1}\) and evaporation takes up less than 2% of the ZB volume. The heat exchange between the water and the sediment is only a few W m\(^{-2}\). It is about 1/10 to 1/100 of the net heat fluxes, so it is negligible in most applications. So both wind effect and heat exchange between the water and the sediment are neglected in this study. If there is no temperature difference between the mainstream and the tributary, the density currents would disappear, and ZB would fill with tributary water. The heat content may be dominated by tributary inflow. In fact due to the density currents, ZB is dominated by mainstream water according to the isotope analysis. The heat is contained in water entering or leaving the bay as a result of seasonal TGR filling or drawdown, and in this way both water parcels from the tributary and mainstream influenced water heat content.

Regulation of the TGR and local climate both influence heat budget. Heat exchange with the atmosphere, mainstream and tributary advective heat are shown in Figure 8(a1)–8(a3), and the proportions of heat budget are shown in Figure 8(b1)–8(b3).

In the downstream of the ZB, mainstream advective heat ranges from \(-13.2 \times 10^9\) to \(15.4 \times 10^9\) J m\(^{-2}\), its proportion ranges from 79% to 98%, tributary advective heat ranges from \(-1.1 \times 10^9\) to \(0.8 \times 10^9\) J m\(^{-2}\), and its proportion ranges from 1% to 16%. In the ZB midstream, mainstream advective heat is a bit lower than downstream, ranging from \(-11.2 \times 10^9\) to \(15.2 \times 10^9\) J m\(^{-2}\), but tributary advective heat ranges from \(-3.1 \times 10^9\) to \(1.1 \times 10^9\) J m\(^{-2}\), and its proportion ranges from 1% to 25%. This is mainly because ZY02 is closer to the tributary, and mainstream influence is smaller than ZY01.

In the whole year, mainstream advective heat is the key factor. The average contribution rate of mainstream advective heat is 87% during the whole year, while the tributary advective heat is 10%, which is a minor contribution to the ZB heat budget. Even in the summer (from June to August), when solar radiation is strongest in the year, heat exchange with the atmosphere is the not key factor of the heat budget.

Previous studies have shown the ecology pattern of the tributary bay varies with time and space (Liu et al. 2012; Mao et al. 2015). The phytoplankton are different in the
different area of the tributary and algal blooms occurred in different months at the middle stream of the tributary bay. These may also be related to the heat budget contribution rate and heat budget is also helpful to recognize the physical mechanism of the ecology pattern.

CONCLUSIONS

The regulation of the TGR changes the tributary water depth. The temperature difference between the Zhuyi River and Yangtze River creates continuous density currents in the tributary. Our measurements show that advective heat is an important component of the overall heat budget and cannot be neglected. Mainstream advective heat is the key factor. The tributary advective heat and heat exchange with the atmosphere make a minor contribution to the ZB heat budget. The Zhuyi River flows into the mainstream, and is one of the heat sources of the Yangtze River. Both the Zhuyi River and the Yangtze River flow into ZB, the Zhuyi River and Yangtze River exchange heat in ZB.

Both regional and local factors influence the heat budget in the TGR tributaries. The heat exchanges with the atmosphere and tributary advective heat are a local influence, where heat exchanges with the atmosphere and tributary advective heat range from 1% to 6% and 1% to 25% of the heat budget, respectively. The mainstream advective heat are regional influences from the regulation of the TGR, ranging from 70% to 98%. In summary, the regulation of the TGR and mainstream temperature plays an important role on the tributary bay heat budget, and the average contribute rate is 87% during the whole year.

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