Spatial and seasonal variability of CO₂ flux at the air-water interface of the Three Gorges Reservoir

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Received 09 January 2013; revised 07 March 2013; accepted 01 April 2013

Abstract

Diffusive carbon dioxide (CO₂) emissions from the water surface of the Three Gorges Reservoir, currently the largest hydroelectric reservoir in the world, were measured using floating static chambers over the course of a yearlong survey. The results showed that the average annual CO₂ flux was (163.3 ± 117.4) mg CO₂/(m²·hr) at the reservoir surface, which was larger than the CO₂ flux in most boreal and temperate reservoirs but lower than that in tropical reservoirs. Significant spatial variations in CO₂ flux were observed at four measured sites, with the largest flux measured at Wushan (221.9 mg CO₂/(m²·hr)) and the smallest flux measured at Zigui (88.6 mg CO₂/(m²·hr)); these differences were probably related to the average water velocities at different sites. Seasonal variations in CO₂ flux were also observed at four sites, starting to increase in January, continuously rising until peaking in the summer (June–August) and gradually decreasing thereafter. Seasonal variations in CO₂ flux could reflect seasonal dynamics in pH, water velocity, and temperature. Since the spatial and temporal variations in CO₂ flux were significant and dependent on multiple physical, chemical, and hydrological factors, it is suggested that long-term measurements should be made on a large spatial scale to assess the climatic influence of hydropower in China, as well as the rest of the world.

Key words: CO₂ emission; spatial variation; seasonal variation; water velocity; temperature; pH

DOI: 10.1016/S1001-0742(12)60291-5

Introduction

Carbon dioxide (CO₂) is the foremost anthropogenic greenhouse gas (GHG) in terms of its radiative forcing contribution to global warming, and has contributed about 70% of the enhanced greenhouse effect (Houghton, 2005). Hydropower has been regarded as green energy for a long time (Chen et al., 2011), but this viewpoint was tarnished in the last two decades (Demarty and Bastien, 2011), because a large amount of CO₂ would be generated when rivers were dammed to create the reservoirs for hydroelectricity (St Louis et al., 2000; Fearnside, 2011). It was estimated that 48 Tg C-CO₂ was emitted from hydroelectric reservoirs every year, which accounted for 9% of the total natural lake emissions (Barros et al., 2011). The average CO₂ emission flux in hydroelectric reservoirs is 21.6% of that in soil respiration (Bond-Lamberty and

Thomson, 2010). Thus it is necessary to investigate CO₂ emission from hydroelectric reservoirs.

Spatial heterogeneity in CO₂ flux was found for large reservoirs due to differences in the pre-flood landscapes (Teodoru et al., 2011). Neglecting the spatial variability in CO₂ emission from reservoirs may lead to more than 25% error in estimation for tropical reservoirs (Roland et al., 2010). Moreover, CO₂ emission was also found to be variable depending on the season of the year due to the variations in temperature (Xing et al., 2005; Wang et al., 2011; Diem et al., 2012). CO₂ emission from reservoir surfaces was often reported to be influenced by temperature. Respiration and primary production in the water column were strongly influenced by temperature, but the former was always reported to have a stronger response, thus resulting in a net increase in CO₂ production under warmer conditions (Mendonça et al., 2012). In addition, CO₂ flux was also reported to be influenced by pH (Soumis

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et al., 2004; Tremblay et al., 2005; Therrien et al., 2005), chlorophyll-*a* (Zhao et al., 2011), rainfall (Abril et al., 2005), and dissolved organic carbon (Tadonlk et al., 2005). Therefore, the spatiotemporal variations in CO₂ flux and their potential influencing factors need special attention in CO₂ emission from reservoirs.

The Three Gorges Reservoir (TGR), which was impounded in 2003, has a length of 660 km and an area of 1084 km² when the water level reach 175 m. The water level fluctuates between 145–175 m throughout the year, and the water falls 80–110 m when passed through the turbines in the Three Gorges Dam (TGD), producing 8.47×10^{10} kWh of electricity in 2010, making the TGR the largest hydroelectric producer in the world (Yang et al., 2012a). Greenhouse gas (such as CH₄) emission from the TGR has aroused wide debate because of the remarkable spatial-temporal variations in CH₄ emission (Chen et al., 2009, 2011; Lu et al., 2011; Yang et al., 2013; Zhao et al., 2013). CO₂, another important greenhouse gas, should also be monitored from the TGR surface in consideration of spatial and temporal heterogeneity. The objectives of this article were to analyze temporal and spatial variations in CO₂ flux and to determine the environmental factors that influence CO₂ flux at the TGR.

1 Materials and methods

1.1 Site description

The TGR region is located in a subtropical monsoon climate zone, with an average annual temperature of 16.3–18.2°C and annual precipitation of 987–1326 mm, and the relative humidity is about 70% (Guo et al., 2007). The annual average water inflow from the upstream rivers was 12,800 m³/sec in 2010, with the maximum of 69,000 m³/sec on July 19 and the minimum of 3500 m³/sec on February 21 (Yang et al., 2012b). Although the water inflow is remarkably larger in the flood season than in the non-flood season, the water level in TGR is controlled at 145 m artificially during the flood season (June–August) to discharge the flood water and sediments. After the flood season (in October), the reservoir begins to store clear water to a water level of 175 m (Lu et al., 2011; Yang et al., 2012a). The water quality during the non-flood season is grade III and is grade IV during the flood season, according to the surface water environment quality standard of the People's Republic of China (Yang et al., 2012b).

The study was conducted at four sites along the mainstream of the TGR (Fig. 1). Three sampling sites upstream of the TGD were selected, i.e., Yunyang (30°56'N, 108°39'E), Wushan (31°03'N, 109°51'E), and Zigui (30°51'N, 110°58'E), which are about 240 km, 120 km, and 2 km upstream from the TGD, respectively. Another sampling site was located at Sandouping (30°49'N, 110°03'E), which is 5 km downstream from the TGD.

At the four sites with different distances from the dam,

Fig. 1 Locations of the sampling sites in the Three Gorges Reservoir.

three sampling points were selected at different water depths on each site. To show the seasonal variation, CO₂ emissions from all the sampling points were measured from 9:00 to 11:00 in the morning once or twice per month, depending on weather, from January to December of 2010. The previous studies (Xing et al., 2005; Iqbal et al., 2009) and the preliminary experiments in the sites (data not shown) all support the hypothesis that the CO₂ flux at 9:00 to 11:00 am could represent the daily mean CO₂ flux.

At the four transects perpendicular to the bank, we selected five locations from the littoral zone to the pelagic zone for water depths of 5, 10, 20, 50, and 100 m at Sandouping, Zigui, Wushan, and Yunyang. However, measurement was not made at 100 m at Sandouping because the maximum water depth was less than 70 m. We selected June to July 2010 (summer) and January 2011 (winter) as the dates for comparing CO₂ fluxes at different water depths in different seasons.

1.2 Measurement of CO₂ flux

CO₂ flux was measured at the air-water interface of the TGR using floating static chambers (Kemenes et al., 2011). The chamber (65 cm in length × 45 cm in width × 40 cm in height) consisted of a plastic box without a cover that was wrapped in light-reflecting and heatproof films to prevent temperature variation inside the chamber. In addition, plastic foam was fixed onto the opposite sides of the chamber. Each chamber was inverted and immersed into the water, and the height of the headspace in the closed chamber was about 30 cm. A silicone tube (with outer and inner diameters of 0.6 and 0.4 cm, respectively) was inserted into the upper side of the chamber to collect gas samples and another silicone tube was inserted into the chamber in order to keep the air pressure balanced between the inside and outside of the chamber (Lu et al., 2011). Three floating chambers were simultaneously deployed at the water surface of each sampling point by attaching them to a stationary boat during the measurement process.

The gases in the headspace of the closed chamber were collected into air-sampling bags (0.5 L; Hedetech, Dalian, China) five times every 10 min over a 40-min period. CO₂ concentrations in the air-sampling bags were analyzed us-

ing a CO₂ analyzer (LI-840 CO₂/H₂O Analyzer; LI-COR Co., Lincoln, USA) to determine the CO₂ concentration. CO₂ flux (F , mg CO₂/(m²·hr)) was determined using Eq. (1). Only samples with r^2 values larger than 0.95 were considered.

$$F = \rho \times dc/dt \times 273.15 / (273.15 + T) \times H \quad (1)$$

where, ρ (kg/m³) is the density of CO₂ under standard temperature and pressure (1.96 kg/m³); dc/dt is the rate of concentration change in the chamber; H (m) is the height from the top of the inversed chamber to the water surface (0.3 m in this study); 273.15 is the absolute temperature at 0°C and; T (°C) is the air temperature inside the chamber.

1.3 Measurement of environmental variables

Air and water temperatures were measured using alcohol thermometers. The water depth at each measurement point was determined using a sounding rope. Water velocities, pH, and turbidity were measured *in situ* using a velocity meter (LS1206B; Midwest Group, Beijing, China), pH meter (HI 8424; Microcomputer HANNA, Rome, Italy), and turbidity meter (HI93703, Microcomputer HANNA, Rome, Italy), respectively. These environmental variables were simultaneously measured when the gas samples were collected.

1.4 Statistical analysis

The normal distribution of CO₂ flux was tested using the Kolmogorov-Smirnov Test. Because the variation in CO₂ flux was skewed to the right, the data were first normalized by natural logarithmic transformation so that the data would follow a normal distribution, and then the spatial differences in CO₂ flux at the four sites and different water depths were tested using one-way analysis of variance (ANOVA) in combination with the Tukey test. In addition, CO₂ flux was linearly regressed in terms of pH, air temperature, air-water temperature difference, and water velocity. The multiple regression method was used to find out the key environmental variables that influenced CO₂ emission. The data were analyzed with the SPSS 16.0 statistical package.

2 Results

2.1 Spatial variation in CO₂ flux

In 2010, the annual average CO₂ flux at the TGR was (163.3 ± 117.4) mg CO₂/(m²·hr) (range: 18.4–893.5 mg CO₂/(m²·hr)). Significant spatial variations in CO₂ flux were found between the four measured sites in the TGR (last column in **Table 1**). The maximum average CO₂ flux was found at Wushan (221.9 ± 130.3 mg CO₂/(m²·hr)), and the lowest average CO₂ flux was found at Zigui (88.6 ± 52.5 mg CO₂/(m²·hr)). There was no significant difference between the CO₂ flux measured at Sandouping and Yunyang (189.2 ± 129.1 mg CO₂/(m²·hr) and 156.3 ± 88.6 mg CO₂/(m²·hr), respectively). The average CO₂ flux of the 3 sites in the upstream of TGD is (148.5 ± 110.8) mg CO₂/(m²·hr), which was 78% of the CO₂ flux in the river downstream.

Although CO₂ flux increased with increasing water depth during the summer and winter, there was no significant difference between CO₂ flux at the different water depths, except at 50 m at Wushan in July 2010, 100 m at Zigui in June 2010, and 50 m at Sandouping in June 2010 and January 2011 (**Fig. 2**). However, at the same water depth of the same site, CO₂ flux was significantly higher in June or July 2010 compared with that measured in January 2011, except at 100 m at Yunyang.

2.2 Seasonal variation in CO₂ flux

Obvious variations in seasonal CO₂ flux were found at Yunyang, Wushan, Zigui, and Sandouping, with significantly higher CO₂ flux measured in the summer and lower CO₂ flux measured in the winter (**Table 1**). CO₂ flux began to increase from 47.2–186.1 mg CO₂/(m²·hr) in January 2010, reaching its maximum level (166.8–439.1 mg CO₂/(m²·hr)) in the summer (June–August) and declined thereafter (**Fig. 3**). Among the four sites, seasonal CO₂ variation was the smallest at Zigui, being in the range of 38.6–166.8 mg CO₂/(m²·hr). However, differences between the maximum and minimum CO₂ fluxes all exceeded 300 mg CO₂/(m²·hr) at the other three sites.

Table 1 Average CO₂ flux at different sites in four seasons

Site	CO ₂ flux (mg CO ₂ /(m ² ·hr))				Average
	Spring (Mar–May)	Summer (Jun–Aug)	Autumn (Sep–Nov)	Winter (Dec–Feb)	
Upstream					
Yunyang	117.9 ± 58.1 a	279.3 ± 97.1 b	125.1 ± 38.7 a	123.5 ± 35.8 a	156.3 ± 88.6 B
Wushan	229.0 ± 86.6 b	313.0 ± 161.4 c	166.7 ± 85.2 ab	124.0 ± 78.0 a	221.9 ± 130.3 C
Zigui	87.2 ± 47.7 b	129.8 ± 58.6 c	65.5 ± 26.6 ab	59.9 ± 33.1 a	88.6 ± 52.5 A
Downstream					
Sandouping	191.9 ± 123.1 b	339.1 ± 125.8 c	186.7 ± 97.6 b	77.7 ± 35.2 a	189.2 ± 129.1 B

Data are expressed as mean ± SD.

Different lower-case letters within a row indicate significant differences ($p < 0.05$), and different upper-case letters in the last column indicate significant differences ($p < 0.05$).

Fig. 2 CO₂ flux at different water depths in the summer (June or July, 2010) and the winter (January, 2011) at Yungang, Wushan, Zigui, and Sandouping. Different upper case letters indicate a significant level of difference ($p < 0.05$) in CO₂ flux in June to July 2010, and different lower case letters indicate a significant level of difference ($p < 0.05$) in January 2011.

2.3 Environmental factors influencing CO₂ flux

A significant negative correlation was found between CO₂ flux and pH ($p < 0.001$) (Fig. 4a). Meanwhile, CO₂ flux was positively correlated with water velocity, air-water temperature difference, and air temperature ($p < 0.001$; Fig. 4 b, c, d). The results of the linear multiple regression analysis show that CH₄ emission (F ; mg CO₂/(m²·hr)) is significantly related to water velocity (V ; m/sec), turbidity (Turb; NTU), air-water temperature difference (ΔT ; °C), and water depth (D ; m), as shown by Eq. (2) ($r^2 = 0.50$, $df=299$, $p < 0.001$).

$$F = 68.24 + 342.57V + 0.37\text{Turb} + 4.00\Delta T + 0.35D \quad (2)$$

3 Discussion

3.1 Spatial variation in CO₂ flux

Spatial variation in CO₂ flux is commonplace in reservoirs. In the TGR, the spatial variation in CO₂ flux was probably related to the water velocities at different locations. The average annual water velocity measured at Wushan (21.3 cm/sec) was considerably higher than that measured at Zigui (5 cm/sec) and Yunyang (12.6 cm/sec). In addition,

CO₂ flux increased with increasing water depth at a perpendicular transect to the bank (Fig. 2), and the high CO₂ flux measured at deep water areas was probably due to the high water velocities in such areas.

The average CO₂ flux at Sandouping, 5 km downstream from the TGD, was more than twice as large as that measured at Zigui, 2 km upstream of the TGD. Besides the difference in water velocity between the two places, the dissolved CO₂ in the hypolimnion at Zigui probably contributed significantly to the high CO₂ flux at Sandouping because of the disturbance by turbines. Rivers downstream of dams have been considered as contributing a significant fraction of the CO₂ emission from hydroelectric systems (Guérin et al., 2006; Kemenes et al., 2011). CO₂ emissions downstream from hydroelectric dams were often reported to be significantly larger than that upstream from hydroelectric dams (Roland et al., 2010; Wang et al., 2011).

3.2 Temporal variation in CO₂ flux

Seasonal variation in CO₂ flux in the TGR could be explained by the variation in water velocity, temperature, and pH. Firstly, the inlet water flow to the TGR drastically increased starting in June, causing floods during summer. The water velocity was faster in the flood season (June–September) than the non-flood season, which contributed

Fig. 3 Seasonal variations in CO₂ flux at Yunyang, Wushan, Zigui, and Sandouping in 2010.

greatly to CO₂ flux (Borges et al., 2004; Ferrón et al., 2007). Moreover, high air and water temperatures and a high air-water temperature difference in the summer stimulated CO₂ production and transport. Furthermore, the pH was significantly lower in the summer than in the winter ($p < 0.05$) because large amounts of acid rain in the summer neutralized alkaline water (Larssen et al., 2006). CO₂ flux was negatively correlated with pH (**Fig. 4a**); therefore, the low pH of the water was conducive to CO₂ emission in the summer.

CO₂ emission flux in the TGR peaked in the summer (**Fig. 3**), which was different from the seasonal variations in CO₂ flux reported in natural lakes and other reservoirs in China. CO₂ was absorbed from the atmosphere in the spring and summer via photosynthesis by algal blooms but emitted in large amounts in the winter, such as in Lake Donghu (Xing et al., 2005) and the four cascade reservoirs on the Maotiao River in southwest China (Wang et al., 2011). However, algal blooms hardly occurred in the summer because of high water velocity in the mainstream of the TGR then (Xin et al., 2011). Negative CO₂ flux was often reported in other reservoirs in the world, such as the Três Marias Reservoir in Brazil (dos Santos et al., 2006), Petit Saut Reservoir in French Guiana (Abril et al., 2005), and F. D. Roosevelt, Dworshak, Wallula, and New Melones Reservoirs in the western United States (Soumis

et al., 2004). These negative fluxes were possibly related to high phytoplankton activity.

3.3 Environmental variables influencing CO₂ flux

Temperature was critical to CO₂ emission because it regulated microbial activities and influenced the decomposition of organic carbon. In this study, CO₂ flux was 2–3 times higher in the summer than in the winter (**Table 1**), which was probably related to the differences in water temperature. The results of controlled experiments showed that CO₂ production could increase by 3–5 times during periods of high water temperature (20–22°C) compared with periods of low water temperature (4–5°C) (Thérien et al., 2005). The air-water temperature difference reflected the thermal difference at the air-water interface. An increased air-water temperature difference promoted CO₂ emission from the reservoir surface under evaporative conditions due to the destabilization of the water surface (Guérin et al., 2007). For example, CO₂ flux was 4% higher under evaporative conditions in the Pacific Ocean (Ward et al., 2004). In contrast, CO₂ fluxes were reduced by 30% under condensing conditions (Liss et al., 1981).

CO₂ flux was negatively correlated with pH in this study (**Fig. 4a**), which was in agreement with other studies (Gui, 2007; Peng et al., 2012). CO₂ flux decreased as pH increased, and atmospheric CO₂ was even absorbed

Fig. 4 Relationships between CO₂ flux and pH (a), water velocity (b), air-water temperature difference (c), and air temperature (d) at TGR.

at high pH values because high pH favored the formation of bicarbonate and led to the undersaturation of dissolved CO₂ in the water (Tremblay et al., 2005). The critical pH value for CO₂ absorption was 8.0–8.5 in boreal and temperate reservoirs (Soumis et al., 2004; Therrien et al., 2005; Tremblay et al., 2005). However, most of the CO₂ flux was positive in the study, probably because most of the pH values in the TGR ranged from 7.2 to 8.4, which did not surpass the abovementioned critical range.

Water velocity, as a source of turbulence at the water surface, had an effect on the gas-transfer rate at the air-water interface (Ferrón et al., 2007). Water velocity had significant spatial and temporal variations at the TGR, with high values in summer at Wushan, and low values in other seasons and sites, which were almost coincident with the spatiotemporal variations in CO₂ flux (**Table 1**). Water velocity was probably a crucial factor that drove the variations in CO₂ emission from the TGR, and a well-correlated relationship between water velocity and CO₂ flux also supported the assumption (**Fig. 4b**). Water velocity also influenced gas emissions from the water surface in the shallow bay of Cádiz, Spain (Ferrón et al., 2007). In addition, Borges et al. (2004) proposed an empirical equation that parameterized the cumulative effects of water velocity on gas exchange at the air-water interface.

A wide variation in the intensity of the emissions was noted, indicating the influence of many other different

factors: flooded organic carbon, allochthonous carbon, primary productivity, and dissolved oxygen (St Louis et al., 2000; Barros et al., 2011; Wang et al., 2011; Kemenes et al., 2011). However, the relationships between CO₂ flux and these factors were not found in our study because every reservoir had its specific characteristics. In the TGR, most of the biomass was cleared before flooding, and water quality was homogeneous after water storage. In addition, no macrophytes or phytoplankton were distributed in the water surface of the mainstream.

3.4 Carbon budget at the TGR

The average diffusive CO₂ flux at the air-water interface of the TGR was (163.3 ± 117.4) mg CO₂/(m²·hr) (3919 ± 2818 mg CO₂/(m²·day)) in 2010, which was higher than the fluxes measured at boreal and temperate reservoirs (except the Sainte-Marguerite Reservoir in eastern Québec, Canada) but lower than the fluxes of most of the tropical reservoirs listed in **Table 2**.

To obtain the total CO₂ emission from the TGR surface, the CO₂ emissions from the mainstream and the tributaries were estimated separately. Our experiment was conducted on the mainstream, and the diffusive CO₂ flux was 3919 mg CO₂/(m²·day). Considering the area of 528 km² in the mainstream, the total diffusive CO₂ emission from the mainstream was estimated to be 0.21 Tg C/yr. Xiangxi River and Pengxi River are two representative tributaries in

Table 2 CO₂ flux in the boreal, temperate, and tropical reservoirs

Location	Reservoir	Age (yr)	CO ₂ flux (mg CO ₂ /(m ² ·day))		Reference
			Mean	Range	
Boreal					
Finland	Lokka	27	1520	−768~6120	Huttunen et al., 2002
	Porttipahta	25	1536	1296~3456	Huttunen et al., 2002
Poland	Solina	41		−914~648	Gruca-Rokosz et al., 2010
	Rzeszow	36		2042~7150	Gruca-Rokosz et al., 2010
	Wilcza Wola	21		3893~4161	Gruca-Rokosz et al., 2010
Switzer- land	5 old reservoirs	42–85	970	132~2516	Diem et al., 2012
Canada	La Grande-2	18–20	1500	200~6000	Duchemin et al., 1995
	Laforge-1	2	2250	380~6700	Duchemin et al., 1995
	Old Québec reservoirs	>10	1600	980~4400	Tremblay et al., 2004
	Sainte-Marguerite	2–4	4400	400~8400	Tremblay et al., 2004
	Old Manitoba reservoirs	35–73	3350	2000~5560	Tremblay et al., 2004
	Grand Rapids		624	−347~7260	Demarty et al., 2009
	Jenpeg		316	−926~2126	Demarty et al., 2009
	Kettle		514	−723~5646	Demarty et al., 2009
	McArthur Falls		367	−1057~3556	Demarty et al., 2009
	Eastmain-1	1–4	2426	−4~19676	Demarty et al., 2009
	Rivière-des-Prairies		665	−234~9380	Demarty et al., 2009
	Robert-Bourassa	28	661	45~6509	Demarty et al., 2009
Temperate					
USA	F. D. Roosevelt	59	−462	−852~251	Soumis et al., 2004
	Dworshak	28	−1195	−2278~−720	Soumis et al., 2004
	Wallula	47	−349	−1629~1060	Soumis et al., 2004
	Shasta	57	1247	351~2150	Soumis et al., 2004
	Oroville	33	1026	266~2430	Soumis et al., 2004
	New Melones	22	−1186	−3415~−275	Soumis et al., 2004
China	Xiangxi River (a tributary of TGR)	7	1836	−2400~5053	Zhao et al., 2011
	Hongfeng	50	660	−396~3080	Wang et al., 2011
	Baihua	48	1012	−352~3388	Wang et al., 2011
	Hongyan	37	1056	−264~3916	Wang et al., 2011
	Xiuwen	48	2077	−352~3828	Wang et al., 2011
	TGR	7	3919	442~21444	This study
Tropical					
Brazil	Miranda	1–2	4388	16~61182	dos Santos et al., 2006
	Três Marias	36–37	1114	33~10060	dos Santos et al., 2006
	Barra Bonita	35–36	3986	83~33424	dos Santos et al., 2006
	Xingó	4–5	6139	29~89203	dos Santos et al., 2006
	Samuel	4	7447	2200~24283	dos Santos et al., 2006
	Tucuruí	8	8475	457~142723	dos Santos et al., 2006
	Balbina	18	13845	1258~31273	Kemenes et al., 2011
French Guiana	Petit Saut	10	5764	−440~15840	Abril et al., 2005
Laos	Nam Ngum	38	−704	−932.8~−118.8	Chanudet et al., 2011
	Nam Leuk	10	136.4	−466.4~1680.8	Chanudet et al., 2011

Different lower-case letters within a row indicate significant differences ($p < 0.05$), and different upper-case letters in the last column indicate significant differences ($p < 0.05$).

the TGR, and the average diffusive CO₂ fluxes were 1836 mg CO₂/(m²·day) and 2196 mg CO₂/(m²·day) in 2010, respectively (Zhao et al., 2011; Guo et al., 2011). The total diffusive CO₂ emission was estimated to be 0.10–0.12 Tg C/yr from the tributaries, considering the total area of 556 km² in all the tributaries. Therefore, the total diffusive CO₂ emission was estimated to be 0.31–0.33 Tg C/yr from the TGR surface. If adding in the diffusive CH₄ emission from the surface of the TGR (2.46 Gg CH₄/yr; Chen et al., 2011), the total diffusive emissions of C-CO₂ and C-CH₄ were 0.36–0.38 Tg C/yr from the reservoir surface (CO₂ equivalent) (Table 3).

The diffusive CO₂ flux at the surface was the dominant fraction in a hydroelectric system, which accounted for

99% of the total CO₂ emission from the reservoir surface (Rosa et al., 2003; Abril et al., 2005; Kemenes et al., 2011). The frequency of bubble occurrence was 5% in our experiment. We considered the bubble occurrence when CH₄ concentration increased abruptly in the chamber (Yang et al., 2012a, 2013). However, CO₂ concentration did not increase obviously in the chambers when bubbles were trapped in the chambers, indicating that bubbles had little contribution to CO₂ emission from the TGR surface. Thus CO₂ bubbling flux was ignored in the estimation.

No measurement was conducted on degassing of CO₂ and CH₄ at the turbine outflow at the TGR, which was the major uncertainty in the estimation for the entire reservoir. Based on the available literature, degassing flux at the

Table 3 CO₂ budget of the TGR in 2010

	Carbon fluxes ^b (Tg C/yr)
Carbon input	
Allochthonous carbon from the upstream river	+10.08 ^c
Water pollution sources	+1.98 ^d
Carbon output	
Carbon export to the downstream river	−10.06 ^e
Diffusive emission from reservoir surface (C-CO ₂ equivalent) ^a	−0.36~−0.38 ^f
Diffusive emission from downstream river (C-CO ₂ equivalent)	−0.0093 ^g
Degassing at the turbine outflow (C-CO ₂ equivalent)	−0.006~−0.135 ^h
Total carbon budget	+1.48~1.62

^a CO₂ equivalent is calculated as the data for CO₂ plus the CH₄ data multiplied by 25 according to IPCC (2007); ^b positive values indicate carbon input to the TGR, while the negative values indicate carbon output from the TGR; ^c calculated from the inlet flow of the TGR and the concentration of total carbon at Cuntan (entrance to the TGR) every month (unpublished data); ^d cited from (Li and Huang, 2005, 2006). Water pollution sources included point source pollution (household sewage, industrial sewage), non-point source pollution (agriculture pollution, municipal waste and industrial waste pollution, ship-flowing pollution); ^e calculated from the outlet flow of the TGR and the concentration of total carbon at Sandouping (outlet of the TGR) every month (unpublished data); ^f total CO₂ emission was estimated to be 0.31~0.33 Tg C/yr from the TGR surface in this study, and the total CH₄ emission was estimated to be 0.00185 Tg C/yr (Chen et al., 2011); ^g estimated from CO₂ flux and CH₄ flux at Sandouping and the area of river downstream (19 km²). The total CO₂ emission was estimated to be 0.0086 Tg C/yr and the total CH₄ emission was estimated to be 0.000029 Tg C/yr (Yang et al., 2013); ^h estimated by the proportions (CO₂: 1.6%–7%, CH₄: 1.5%–70%) of degassing at the turbine outflow account for the total from the available literature.

turbines accounted for about 1.6%–7% of the total CO₂ emission and 1.5%–70% of the total CH₄ emission in a hydroelectric system (Soumis et al., 2004; Abril et al., 2005; Fearnside, 2005; Chanudet et al., 2011; Kemenes et al., 2011). Referring to these two proportions, the degassing emission at the turbine outflow of the TGR was estimated to be 0.006–0.135 Tg C/yr. In addition, an emission of 0.0093 Tg C/yr from the river downstream of the TGR was estimated based on the data at Sandouping (Table 3).

The exchange of CO₂ across the air-water interface is an important term in the carbon budget of aquatic ecosystems. About 0.38–0.52 Tg C/yr of carbon would be released from the TGR system based on the above analysis, including reservoir surface emission, degassing emission at the turbine outflow, and emission from the river downstream of the TGR. As a net carbon source to the atmosphere, the TGR must be supported by some carbon input. These inputs consisted of allochthonous carbon from the upstream rivers, water pollution sources in the TGR region, and photosynthesis of the phytoplankton in the reservoir surface. The carbon input from the upstream rivers was estimated to be 10.08 Tg C/yr, which was almost balanced by carbon output to the downstream river (10.06 Tg C/yr) (Table 3). Moreover, large amounts of point source pollution and non-point source pollution were

dumped into the TGR every year, which was estimated to be 1.98 Tg C/yr (Li and Huang, 2005, 2006). Judging from the above analysis, the TGR is a carbon sink (1.48–1.62 Tg C/yr). This carbon loss might be buried in the sediments. The TGR is located in the mainstream of the Yangtze River, which intercepted 60% of the inflow sediments (about 3 × 10⁸ tons) from the upstream rivers every year. Most of the pollution could adhere to the sediments and deposit into the bottom of the TGR (Zhou et al., 2006). CO₂ and CH₄ emissions from the TGR surface are mainly derived from the input of all types of pollution by human beings. Thus, it is necessary to control the water pollution sources in the TGR region.

4 Conclusions

Based on our findings, the annual total emissions of C-CO₂ and C-CH₄ from the surface of the TGR were 0.38–0.52 Tg C/yr (1.39–1.91 Tg CO₂/yr). The CO₂ emission density is 16.41–22.55 g/kWh when taking account of the fact that 8.47 × 10¹⁰ kWh of electricity were produced by the TGR in 2010. The CO₂ emission density of the hydropower generated by the TGR is much less than that of the electric power currently generated by most power plants in China (807 g/kWh) (Lu et al., 2010). If the goal of generating in total 1.216 × 10¹² kWh of electricity is fulfilled in 2020 (Zhou and Qian, 2011), 19.95–27.42 Tg CO₂ will be emitted from hydroelectric reservoirs every year, which will be 0.22%–0.30% of the CO₂ emission from fossil fuel combustion (9051 Tg) in 2020 (Tang, 2009).

In this study, a significant spatial variation in CO₂ flux was found in the TGR, which was attributed to differences in water velocities at the various sites and water depths under investigation. Seasonal variation indicated that the CO₂ flux was higher in the summer than in the other seasons, which was mainly influenced by the seasonal changes in temperature, pH, and water velocity. Other factors, such as local human activities and waves caused by the wind or passing steamships, also influenced CO₂ emission from the TGR. More investigations need to be carried out to design coupled hydrological and biogeochemical process models that can better estimate CO₂ emissions from reservoirs.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 50809067, 41303065), the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA05060102, XDA05050602), the Project of Zhejiang Key Scientific and Technological Innovation Team (No. 2010R50039) and the Project of Zhejiang Scientific and Technological Plan (No. 2011F20025).

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