Spatial and Temporal patterns of Greenhouse Gas Emissions from Three Gorges Reservoir of China

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Abstract

Anthropogenic activity has led to significant emissions of greenhouse gas (GHG) that is thought to play important roles in global climate changes. It remains unclear about the kinetics of GHG emissions including carbon dioxide (CO_2), methane (CH_4) and nitrous Oxide (N_2O) from the Three Gorges Reservoir (TGR) of China, the second largest dam on Earth. Here we report monthly measurements for one year of the fluxes of these gases at multiple sites within the TGR, Yangtze River, China, and from several major tributaries, and immediately downstream of the dam. The tributary areas have lower CO_2 fluxes than the main storage; CH_4 fluxes to the atmosphere after passage through the turbines are negligible. Overall, TGR showed significantly lower CH_4 emission rates than most new reservoirs in temperate and tropical regions. We attribute this to the well-oxygenated deep water and high water velocities which produce oxic mainstem conditions inimical to CH_4 emission. TGR's CO_2 fluxes were lower than most tropical reservoirs and higher than most temperate systems. This is due to the high load of metabolizable soil carbon delivered through erosion to the Yangtze River. Compared to fossil fuelled power plants of equivalent power output TGR is a very small GHG emitter, annual CO_2-equivalent emissions are approximately 1.7% of a coal-fired generating plant of comparable power output.

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1. Introduction

Three Gorges Reservoir was established on the Yangtze river as the largest dam in China. It could reach 175 meters above sea level (a.s.l) at total capacity of water storage with, while the lowest storage holds 145 meters a.s.l to buffer the waterflood mostly occurring in June every year. ~~At full storage level (FSL = 175 m a.s.l.) it is 660 km long(the area would be more helpful for readers to understand how big the reservoir it, it can be expressed as square meters), decreasing to 556 km at planned lowest storage level of 145m a.s.l in June each year, ready to receive flood waters.~~ The dam of the Three Gorges Reservori indeed has the largest power capacity installed by far and generates electricity power only next to Itaipu in Brazil. However, TGR it has attracted tremendous attentions for environmental concerns such as greenhouse gas (GHG) emissions including carbon dioxide (CO_2), methane (CH_4) and nitrous Oxide (N_2O), although it plays an important role in flood control and navigation on the Yangtze river in addition to hydroelectric benefit. In fact, it has been much debated about the impact of TGR on ecosystem function and sustainability since the start of TGR construction (Giles, 2006; Stone, 2008; Qiu, 2009; Fu et al., 2010).

It has for long been recognized that the metabolism of allochthonous and autochthonous organic matter in reservoirs contributes to global GHG emission (Louis et al., 2000), whereas the accurate budget appears under much debate. For instance, the results from Brazilian hydro-reservoirs suggested that GHG emissions could be equivalent to or even exceed those of fossil-fuelled power stations of the same power capacity (reference). There are also observations showing low GHG emissions from reservoirs (Fearnside, 2002), despite being heavily disputed (DosSantos et al., 2006). The increasing line of evidences

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indicates that GHG emission kinetics might be dam-dependent (Tremblay et al., 2005). It seems plausible that TGR might produce GHG in a way different from those well-studied boreal (Tremblay et al., 2005; Duchemin et al., 1995; Soumis et al., 2004) and tropical reservoirs (DosSantos et al., 2006; Guerin et al., 2006, 2008; Rosa et al., 2004) due to its unique physiochemical characteristics such as physical configuration and organic matter turnover. For example, TGR occupies a steep-sided gorge rather than a relatively shallow basin characteristic of the boreal and tropical reservoirs. The amount of organic matter which is the main precursor for GHG generation through microbial metabolisms is low. This is arguably ascribed to the fact that 1.2 million habitants in the small and narrow riverine floodplain were relocated and much of the vegetation and organic materials removed before the zone was flooded (Zhang et al., 2011). This situation is distinctly different from the Brazilian reservoirs where organic matter-rich rainforests were inundated. In addition, the majority of allochthonous organic C input is primarily particulate organic carbon (POC) of eroded soil origin for TGR about 2.5 M tonnes C per year (Wu et al., 2007). In stark contrast, surface plant biomass boosts initial CO_2 emissions in boreal reservoirs, whereas it is driven by sediment and pelagic respiration in the long term (Teodoru et al., 2011).

Despite its ecological and environmental significance, GHG emissions remains poorly understood in TGR. There are no emission rates of N_2O and CO_2 from TGR determined by far, while a better understanding of CH_4 emission patterns is required toward an accurate of CH_4 emission budget. Chen et al. (2009) reported relatively high emissions of CH_4 from stands of predominant *Scirpus triqueter* (14.9 ± 10.9 mg m^{-2} h^{-1}) growing in temporary

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marshes formed in the drawdown zones of a tributary connected to the mainstem of TGR, leading to an estimated emission rate of 3.3 mg CH_4 m^{-2} h^{-1} from the main body of the TGR. It implies that the riparian zones constituted an important 'hotspot' being responsible for 20% of the total CH4 budget in TGR regions? "(about 20% of total emissions from 10 % of the area, this sentence is not clear). This budget appears to be drastically overestimated by a factor of ~30 in the main stem of TGR (Liu et al., 2011) The authors mentioned that no details were provided by the same group (Liu et al., 2011). The same rational is applied to this study. i.e., if Liu and co-authors would have read this paper, could they extract your data and re-evaluate your conclusion. In doing so, I guess the authors need to make a more specific description about sampling and data analysis, It further highlights the importance of precise GHG emission patterns for a predictive understanding of GHG budget across temporal and spatial scales, Recent studies indeed have demonstrated that specific reservoir characteristics play a key role in high emission of GHG, but not well represented in the mathematic models (Sobek et al., 2012; DelSontro et al., 2011). The process-based model will be of great help for decision making for future construction of hydro-power reservoirs.

Therefore, in this study we aimed to determine the GHG seasonal emission patterns from TGR, and to develop a process-based model trying to approach the GHG emission budget.

2. Materials and Methods

2.1 Site description (please note that the headings of all sections must be numbered, and more importantly, three levels of sectioning are allowed e.g, 2, 2.1, 2.1.1

The hydroelectric dam The Three Gorges Dam (**Figure 1**) (If the term of Three Gorge Dam is not used often in the text, it may be better rephrased. This may facilitate the readability

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by avoiding the possible confusion between TGR and TGD) is located on the mainstem of the Yangtze River right upstream of Yichang city of Hubei Province. The Yangtze river is the largest and longest river in China with 6,300 kilometers long, and the third-longest in the world. Its source lies to the The source of the Yangtze River lies to the west of Geladandong Mountain, the principal peak of the Tanggula Mountain chain in the Qinghai-Tibetan Plateau, southwest of China. The river flows from west to east through 11 provinces of Qinghai, Tibet, Sichuan, Yunnan, Sichuan, Hubei, Hunan, Jiangxi, Anhui and Jiangsu as well as the city of Shanghai, finally emptying into the East China Sea. TGR is a typical valley-type reservoir with steep slopes on both sides of river channel, covering a total catchment area of 1.1 million km^2. Up to 74% of the TGR catchment is dominated by hilly regions, while only 4.3% expands in the river valley and 21.7% hilly area (please correct this point. I am not sure about the difference between hilly area and mountainous areas.). Annual average flow at Cuntan station?, the upstream end of the dam when full, is 11,100 cumecs. The area of the catchment directly between Cuntan and the dam is 58,000 km^2 (right upstream from the dam, it is said that 1.1 million km2. I guess this 58000 is more appropriate to be used and the 1.1 million km2 phrase could be removed?) and generates an additional annual average discharge to the Yangtze of 2,800 cumecs. TGR at the total capacity covers a total surface area of 1,084 km^2 including 782 km^2 of mainstem and 302 km^2 of tributary). Average depth of the reservoir is about 70 m and maximum depth of the dam is about 170 m. The climate of the reservoir region is subtropical monsoon with an annual mean temperature of 18 °C. The river flow peak occurs generally in late summer coinciding with heavy rainfalls in the TGR catchment. The local annual rainfall is about 1,100 mm and occurs mainly from May to September.

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Since the end of 2008, TGR has been in full operational mode. It retains water from late September until early November, and high water levels were maintained up to late April in the following year. As the rainy season approaches, water level is drawn down gradually to 145m, in preparation for flood retention and mitigation. The interplay between water inflows and outflows for power generation, flood control, river navigation, and planned scouring of the bed sediment produces marked variations in the water residence times. These can be as short as 6 days at maximum design flows during the flood season and exceed 30 days in early summer when the dam is drawn down to its minimum level (145m). The modeled water velocity in the upper mainstem (310 to 660 km from Dam~~ wall, is it necessary to use the term of ‘ Dam wall”~~) remains above 2 m s^{-1} irrespective of the dam level. In the 310 km stretch closest to the dam wall the modeled velocity is predicted to be about 0.5 m s^{-1}.

3. Greenhouse gases Measurements

3.1 Field Sites

Fluxes of CO_2, CH_4, and N_2O through the surface of the TGR reservoir were measured monthly from January to December of 2010 at four primary sampling regions (**Figure 1**). Zigui (ZG: just upstream of the dam wall, water depth 170m at FSL), Badong (BD: 75 km upstream and depth 110m at FSL) and Wanzhou (WZ: 282 km upstream and depth 80m at FSL) are longitudinally distributed along the mainstem. GHG determination was also performed at Xiangxi (XX), one of the biggest tributaries (Xiangxi River) in the TGR catchment. The water storage of TGR results in a significant decline of the water velocity in the Xiangxi River, making it a lake-like region prone to algal blooms (Ye et al., 2006,

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2007). At each site 4-5 independent flux measurements were made each month to take into account the variability of gas emissions. All sampling sites were away from the central shipping channel to avoid the unexpected disturbance (please confirm this point), and the water depth at all sites exceeded 30 m.

In addition, GHG fluxes were measured at four other regions in the further upstream (Zhutuo: ZT, Cuntan: CT, Longxi: LX, Qingxi: QX) and in two major tributaries (Xiaojiang: XJ and Daning: DN) which were inundated by the reservoir (**Figure 1**). These regions represent distinctly different environmental conditions that may further affect GHG emission kinetics. For example, the ZT sit is free from the reservoir influence (is my understanding right. Or please explain what is above the reservoir influence.). The CT site is in the interfluvial zone, formed as the reservoir water level is lowered from FSL to 145 m a.s.l., preparatory for the onset of the summer floods. All these sites were sampled monthly from June 2010 to May 2011.

Hydro-power reservoir GHG emission by degassing downstream of the turbines (is this from the dam?) was also measured at two stations of Xiling Bridge (XLB) and Huanglingmiao (HLM). The extent of degassing depends on the precise conditions under which the water leaves the turbines. For instance in Petit Saut there is a hydraulic shute where the water is deflected into the air (Guerin et al., 2006). As for TGR the water exits the turbines underwater and there is limited scope for immediate degassing. Two supplementary stations (Xiling Bridge: XLB and Huanglingmiao: HLM) below the dam These two stations were established specifically below the dam to quantify the degassing component of the GHG emissions. Surface CO_2 and CH_4 fluxes were determined at XLB in

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the turbulent dam tailrace 4.9 km downstream of the dam wall, and at HLM, 7 km downstream, in the tail waters of Gezhouba dam (about 38 km downstream) and at the edge of the less turbulent shipping channel.

3.2 Flux measurements

At each site CO_2, CH_4 and N_2O fluxes at the air-water interface were directly measured using floating static chambers, usually with two replicate chambers deployed at each sampling site. The chamber is a close-ended stainless steel cylinder, 60 cm in height and 30 cm in diameter, equipped with a dry battery driven fan and a small lateral vent sealed by silicon septum. The fans were turned on before the chambers were deployed, three air samples from each chamber were manually collected with 100 ml syringes at 0, 10, 20 min intervals (subsequently increased to 4 samples/30 minute interval) after the deployment and stored in 500 ml air-tight gas sampling bags. Please specify (1) how deep the chamber was merged during GHG determination; (2) the time when GHG was determined, for example, early morning or ???; (3) How to fix the chamber out there, and (4) small boat is used for sample collection?

Gas samples were transported to the laboratory and were analyzed at the Institute of Atmospheric Physics, Chinese Academy of Sciences. GHG concentrations were determined by a HP-4890D Gas Chromatograph (Agilent Corp.) according to the method as previously described (Xing, 2005). The standards were run before and after each set of samples to ensure the reproducibility of measurements ~~and to evaluate the precision of measurements~~ (this phrase could be deleted if not mentioned in the text). The detection limit of the gas chromatograph is 0.1 ppm (I have serious doubt on this because N2O is generally at ppb or

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lower level. Please specify the detection limit for methane, carbon dioxide and nitrous oxide, respectively) and the minimum detectable flux is 0.1 mg m^{-2} d^{-1}, with analytical error on duplicate standard samples of less than 1%. Gas flux was calculated from a linear regression with gas concentration change within chamber versus time (IHA, 2010):

$$\mathrm{Flux}[\mathrm{mg}\cdot\mathrm{m}^{-2}\cdot\mathrm{d}^{-1}] = \frac{Slope[ppm\cdot s^{-1}]\times F_1\times F_2\times ChambleVolume[m^3]}{ChamberSurface[m^2]} \tag{1}$$

Where slope is the value from linear regression of the gas concentration change within the chamber versus time, F_1 is a conversion factor from ppm to mg m^{-3} for standard temperature and pressure for gas in air and F_2 is a conversion factor of seconds into days. Only the sites where the gas concentration change had a linear regression coefficient over 0.8 were included in the calculation.

3.3 Water environment sampling

While collecting air samples, the temperature inside the chamber, air temperature, and water temperature were measured with a JM624 portable digital thermometer equipped with 6 m length probes. Water conductivity, and Dissolved Oxygen (DO) were measured in-situ (depth = 0.5 m) with a DDB-3 (Leici Instrument, Shanghai, China) and a JPB-607 DO meter (Leici Instrument, Shanghai, China) respectively, transparency was determined using Secchi disk. Water samples at 0.5 m depth were collected for laboratory analysis of chlorophyll a, turbidity, total phosphorous (TP), total nitrogen (TN) and total organic carbon (TOC). The analysis of the water samples were performed by the Institute of Hydrobiology, Chinese Academy of Sciences (Yang et al., 2011).

Water column physic-chemical data was provided by the Bureau of Hydrology, Changjiang Water Resources Commission. Vertical profiles of water temperature and DO concentrations were measured monthly in front of the dam from July 2008 to June 2009 (what is the point to make these measurements?). Water temperature was measured at 2 m intervals from top to the bottom of the reservoir, using the reversing thermometer method (according to National Standard: water quality – determination of water temperature – thermometer or reversing thermometer method, GB 13195-91), while DO concentrations were sampled at the surface (0.5 m), bottom (how deep it is) and middle layer(how deep it is) using Winkler titration method (according to National standard: Water quality – determination of dissolved oxygen – Iodometric method, GB 7489-87).

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3.4 Data analysis and GHG budget modelling

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Mean CO_2, CH_4 and N_2O fluxes were calculated by averaging the available replicate samplings in each region. The results were used to compare the fluxes between different regions directly (please specify how you make data analysis, for example, two-way ANOVA and so on). Furthermore, to calculate the total GHG emissions from the TGR, we divided the water surface into 25 subregions, representing 11 of mainstream and 15 of tributary regions and administrative boundaries(administrative regions can be deleted?). Water surface areas of each subregion at 135, 145, 156 and 175 m a.s.l (is this right?) were extracted using a 10 m resolution digital precision elevation map (DEM). Linear relationships between water level (I imagine this is altitude or above sea level?) and surface water area for each subregion were then established using a regression analysis and the surface area at different water level was calculated. Subregions (the number has to be

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specified) without measured flux were interpolated using the values of the two nearest regions.

ArcGIS 9.3 was used to manipulate the DEM while other analysis was performed by the EXCEL 2007 software. GHG emissions from the TGR were calculated by multiplying the total averaged CO_2 fluxes from the sampling regions each month by the surface water area, CH_4 emissions were added up to the total emission by multiply its Global Warming Potential (GWP) value of 25. Equivalent CO_2 emission per unit hydroelectricity power??? generating capacity was further calculated by dividing by the power generation of the TGR (is there any coherent relationship between hydroelectricity power and GHG emission. I imagine that hydroelectricity generation is occurring only by the turbines that are installed within the dam. The reservoir is such a big waterbody and I could not imagine why GHG emission in Wanzhou of Chongqing is related to the dam in Yichang.). Meanwhile, CO_2 and CH_4 emissions were related to water quality variables by Pearson correlation analysis, which was performed with SPSS 16.0 software.

4. Results

4.1 Spatial and temporal variation of CO_2 fluxes

The results (**Figure 2**) show that the surface waters at mainstem stations (WZ, BD, and ZG), are sources of CO_2 to the atmosphere all year round with the CO_2 fluxes higher in warm season (**Figure 5**) Figure 3 must appear in the text before Figure 4 and Figure 5.. This is the period with high flow also. The fluxes at the 3 primary mainstem stations were consistently high (WZ, 126±110mmol m^{-2} d^{-1}; BD, 126±80; and ZG, 104±87mmol m^{-2} d^{-1}). The annual average CO_2 fluxes at the upstream regions varied (WZ, BD and ZG are located

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upstream?). The fluxes are less at upstream ZT (88±57mmol m^{-2} d^{-1}) and comparable to those at the 3 mainstem stations at QX (127±57mmol m^{-2} d^{-1}), CT (170±97mmol m^{-2} d^{-1}) and LX (175±150mmol m^{-2} d^{-1}). Overall the CO_2 fluxes at mainstem regions are higher during the rainy season. This finding suggests that CO_2 production is due to the oxidation of incoming particulate organic carbon from the catchment, primarily soil organic carbon (Wu et al., 2007). Relative to ZT (the representative upstream riverine site free of impact by the full reservoir waters), average mainstream CO_2 fluxes have increased by 56%.

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The tributary region at XX shows markedly contrasting behavior (**Figure 5**). The CO_2 flux was negative (i.e. from the atmosphere into the water) during the summer, due to photosynthetic uptake by phytoplankton, and is consistent with the very high Chlorophyll a concentrations, and a higher transparency compared to other regions. Because of the photosynthetic uptake there the Xiangxi River has the lowest average annual CO_2 flux (25±54mmol m^{-2} d^{-1}). The CO_2 fluxes at the tributary regions were less than all the mainstem regions (XJ 79±52mmol m^{-2} d^{-1}; DN 25±30mmol m^{-2} d^{-1}), 50.6% less than the reference sit of ZT. All the tributary regions have a large standard error (F**igure 2**) reflecting a substantial seasonal variation of CO_2 due to drawdown by photosynthesis during the summer season with still shallower waters favoring pelagic phytoplankton, and submerged and emergent vegetation growth leading to low CO_2 fluxes. This stock of organic matter is subsequently submerged and oxidized during the high water stage leading to high CO_2 fluxes post-TGR reaching its full operational level.

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The annual average CO_2 fluxes from the downstream station closer to the dam wall (XLB: 81±80mmol m^{-2} d^{-1}) is less (though not statistically significant) than that at ZG immediately upstream of the dam wall, suggesting that about 22% of CO_2 degassed due to the turbulence induced after the power house. However, significantly high emission rates of 212±136 mmol m^{-2} d^{-1} was observed at HLM station, which is only 2 km downward from the dam. This implies that the degassing effect is likely constrained within a limited waterbodies before the dam.

4.2 Spatial and temporal variation of CH_4 and N_2O fluxes

The four primary regions (ZG, BD, WZ, and XX) act, at times, as both sources and weak sinks of CH_4 (Figure 5). The annual average flux at XX was 0.41 ± 0.96mmol m^{-2} d^{-1}, higher (though not statistically significant) than other three regions excluding the peak value of 3.12mmol m^{-2} d^{-1} in June in WZ. This high emission rate might result from the unexpected rain events (if it is called sudden rain, you have to explain why not exclude this data because it the term of sudden generally refers to unusual condition) at the sampling site, and the combined effects of shallow water and disturbances by passing ships (I think that the disturbance would lead to the lower emission rate of methane, because the disturbance from cruise and ship remains constant, which could deplete the source of methane in the waterbodies. For example, the turbulent flow leads to lower methane emission in XX). Consequently, WZ has the highest CH_4 flux among the three mainstream regions, with an average flux of 0.76±1.11, and 0.40±0.52 mmol m^{-2} d^{-1} after excluding the June value. The values for BD and ZG are 0.09±0.33 and 0.04±0.46mmol m^{-2} d^{-1}, respectively. Upstream, reservoir tail waters (CT, LX and QX) and tributary stations had relative higher CH_4 fluxes than the main stem of the reservoir (**Figure 2**), reflecting the greater autochthonous production in these areas as well as the greater deposition of reactive

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particulate organic matter entering TGR. Relative to ZT, the mainstem area had 59% lower CH_4 flux and tributary area was 65% less. It seems that surface CH4 flux showed a decreasing trend with the increasing water depth of the sites tested in this study. The annual average CH_4 fluxes (**Figure 2**) from the 2 downstream stations (XLB 0.17 mmol m^{-2} d^{-1} and HLM 0.53mmol m^{-2} d^{-1}) are slightly higher than fluxes at ZG immediately above the Dam wall. The water CH_4 concentrations (how did the authors measure water methane concentration?) are not significantly different suggesting that the losses through the turbines are limited and that the flux differences arise from much higher turbulence in the zone immediately downstream of the dam (Vachon et al., 2010). I was a bit confused about this phrase because I think the effect of turbines on methane eemission is equivalent to turbulence, is that right?

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N_2O fluxes were much lower compared to CO_2 and CH_4 fluxes (**Figure 4**), the total average fluxes at the mainstream and Xiangxi River were 0.01±0.01 and 0.004±0.01mmol m^{-2} d^{-1}, (please use nmol or picomol.) respectively, consistent with the suggestion of very small N_2O fluxes from freshwater reservoirs (Huttunen et al., 2003). Even after conversion to equivalent GHG fluxes (x 298) the N_2O contribution to total reservoir GHG flux is negligible.

4.3 Water environment dynamics

The temperature of the TGR surface water varies from *** to *** according to the regional climate and there were no significant differences between the four sampling water regions (Figure 6-a) (figure 6a must appear before figure 6b in the text). TGR had slightly basic waters with a mean pH value of 8.04 (Figure 6-b). Chlorophyll a concentration was

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The water temperature (**Figure 7**) showed an annual variation from ~10℃ to 30℃. Only in April and May is there substantial temperature stratification but this always occurs below the turbine offtake level (116 m above the dam floor). Meanwhile, DO concentrations (**Figure 8**) measured at different depths show that the complete water column has high DO concentrations (> 6 mg l^{-1}) everywhere. The water column of the reservoir is well mixed top to bottom for most of the year and we attribute this to the high flows/short residence time caused by the generally highflows required for maximum power generation (how to relate these parameters to GHG emission and integrate these parameters into the models?).

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5. Discussion

5.1 Patterns of GHG emission from the Three Gorges Reservior (I do not think the strongest point for this study is the mechanism. Rather, the huge effort has been made for GHG emission kinetics. Therefore, the

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authors can start the first paragraph by repeated the key findings of this study, followed by the possible mechanism)

To gain insights into the possible mechanisms controlling GHG fluxes, we examined the correlations between the measured fluxes of CO_2 and CH_4 and other environmental parameters measured at those sites (**Table 1**). There is a strong negative correlation (R=-0.368, p<0.001) between CO_2 flux and Chlorophyll-a (The data volume needs to be specified), suggesting that photosynthetic uptake of CO_2 reduces the net flux (I expect that temperature plays more important roles, although it is reasonable for this negative correlation. For example, how alga can grow if temperature is low). This conclusion is consistent with the temporal trends observed, with the Chlorophyll-a concentration reaching a maximum at summer low water when the water transparency was a maximum and the tributary water velocities lowest (**Figure 6**). Station XX is one of the tributary regions now prone to algal blooms post-dam completion due to the dramatically reduced current velocity and the excess input of nutrients. The strong negative correlation between DO and CO_2 fluxes also is consistent with the influence of algal photosynthesis processes on CO_2 fluxes, as O_2 is produced simultaneously by the same processes which are removing CO_2.

The observed negative correlation between transparency and CO_2 fluxes (r=-0.261, p=0.001) reflects the key role of allochthonous POC in reservoir CO_2 production, especially at the three mainstream sampling regions. Low transparency (< 1 m) occurs from May to September (Figure 6), when major inflows as well as rainfall events happens in the region. The input of particles from the drainage basin through surface runoff decreases the transparency, but increases both dissolved and particulate allochthonous carbon

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(Oelbemann et al., 2011). As precursors for heterotrophic organisms, these degradable organic carbon enhance CO_2 production, despite the dilution effects of the higher flows(you mean it is diluted after being brought into the river though runoff?). Similar findings were noted in several lakes and reservoirs in Finland (Huttunen et al., 2003), where the authors observed that both the autochthonous and allochthonous carbon sources were important in the GHG emissions from reservoirs. This result confirms earlier work suggesting that freshwater lakes, rivers and reservoirs play a major role in the transfer of terrestrially fixed carbon to the atmosphere, although they account for less than 0.4 percent of the earth's surface (Tremblay et al., 2005). Water temperature plays an important role in these processes also. Higher water temperature during the period results in higher rates of decomposition of organic carbon, and this temperature dependence explains also why CO_2 fluxes were much lower in colder seasons. (please refer to the figures)

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None of the analyzed variables showed high correlation with air-water interface CH_4 fluxes (can CO_2 flux be called air-water interface CO_2 fluxes. Please use as less as terms because it may lead to confusion unless you have clear definition for each term, and the usage of each term is important for your findings). Chlorophyll-a was related however to CH_4 fluxes (what is the difference between this CH4 flux and the air-water interface methane fluxes) with a high significance ($p<0.01$). This is consistent with much of the autochthonous production contributing to the formation of sediment anoxia due to the highly reactive phytoplankton detritus leading to conditions appropriate for CH_4 production. Earlier work noted that in eutrophic reservoirs with anoxic hypolimnion a large amount of organic carbon fixed by photosynthesis was recycled as CH_4 (Tremblay et al., 2005).

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The drawdown zone of a reservoir is generally considered to be a "hot spot" for CH_4 emissions (Bergstrom et al., 2007). Clearly it forms a quasi-littoral zone where riparian vegetation growth can occur and organic-rich sediment is deposited. On refilling, microbial metabolism of the organic carbon plus reduced oxygen supply leads to anoxic sediments and production of CH_4. The potential littoral zone of the main stem of TGR is quite limited due to the steep-sided configuration. The largest quasi-littoral zone in the TGR forms along the tributaries with a smaller zone extending along the edges of the mainstem as the water is progressively drawn down. CH_4 fluxes will rise in the still wetted regions here as water shallows, however, much of this area is scoured out during the first major flood event and CH_4 fluxes then fall back to closer to those elsewhere in the main stem (Figure 2). The tributaries, on the other hand, are less subject to scouring, as the power of the tributary remains the same, while the area of the wetted zone subject to drawdown is increased due to the raised water level. Thus, in the tributaries the draw down area takes on much of the character of a quasi-permanent littoral deposition zone with continuing accumulation of organic rich sediments occurring over repeated reservoir emptying and filling cycles. This conceptual description explains the phenomenon described by Bergstrom et al. (2007) and the high CH_4 fluxes observed from XJ, DN, and XX in this study and previously reported in another TGR tributary by Chen et al. (2009). The CH_4 fluxes we measured at these tributary sites are considerably low, however, than those reported by Chen et al (5.8mmol m^{-2} d^{-1}). The littoral CH_4 fluxes demonstrated significantly spatial variations, suggesting that caution needs to be fully considered in extrapolating these fluxes to the reservoir as whole, and to the total littoral area as previously reported (Qiu 2009).

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The seasonal variations of GHG flux across geologically distinct sites??? highlight the importance of samplings from regions representative of spatial–temporal dynamics in TGR. For instance, the relatively small areas showed a disproportionate effect on total GHG emissions (which figure and table can be referred to?), in particular for the ributaries and inter fluvial areas (is this right). Specific operational factors (water depth, high oxygen content due to the turbulent conditions, and short residence time) cause TGR to fall well outside the predictions of CH_4 emissions with age (Barros et al. 2011). Based on the age and latitude of TGR CO_2 fluxes are under-predicted while CH_4 fluxes are over predicted. The existence of other systems such as Lake Wohlen (DelSontro et al. 2011) which depart significantly from such predictions also, suggests that a more nuanced approach is needed in predicting GHG emissions from hydropower reservoirs. (This sentence may be placed more appropriate in the following paragraph?)

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5.2 Comparison with other reservoirs and other energy sources

The total area weighted average emission from the TGR (normalized by installed capacity) was 4.63mol kWh^{-1}d^{-1} and 0.02mol kWh^{-1}d^{-1} for CH_4. (total GHG fluxes can be expressed as mol per year per square km, which may be the number 1 priority.) Compared with other storages (Table 2), TGR showed significantly lower CH_4 emissions than most of the newly constructed reservoirs in temperate and tropical regions. We attribute this to less inundated biomass, and deep well-mixed, and oxygenated water in TGR. CO_2 emissions were higher than most temperate reservoirs but still lower than most tropical reservoirs. This observations might be explained in part by the high carbon load to TGR. The Yangtze River system had higher organic content and exports more organic carbon than some comparable

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large rivers such as Mississippi, but less than that of the Amazon River (Wu et al., 2007).

In 2010, our results indicated that about 1.3×10^6 t CO_2, 6×10^3 t CH_4 and 128 t N_2O were escaped from the reservoir surface water to the atmosphere(I think it could be used as the starting sentence for this subsection). Taking account of the global warming potential of CH_4 and N_2O, the annual emission of CO_2 equivalents was estimated to be 1.5×10^6 t. In 2010, the Three Gorges power station generated a total of 8.437×10^{10} kWh. Thus TGR will emit 17.88 g $CO_{2\ \mathrm{equiv}}$/kWh, which means $4.8*10^{-3}$tC/MWh. The equivalent emissions produced by thermal power plants burning different fuels such as coal, fuel oil, natural gas with different technology efficiency levels were calculated using emission factors from the IPCC Emission Factor Database (Table 3). Total GHG emissions from TGR were much lower than the annual CO_2 emissions from other power sources (1.7% of coal, and 3.9% of natural gas).

5.3 Uncertainties

As noted earlier we focus on gross surface fluxes here and do not differentiate between diffusive and bubble fluxes. It is possible, however, to infer from the number of discontinuities in the individual plots of the chamber measurements when a bubble (or a series of bubbles) has entered the measuring chamber. These bubble events are most frequent at tributary sites and occur mainly in summer, being consistent with previous observations of bubble emissions stimulated by declining pressure, as well as reduced gas transfer from the rising bubble to the surrounding water (McGinnis et al., 2006), as well as the enhanced CH_4 production in the sediments due to the higher temperatures (please add reference, because in this study no methane production was investigated). This conclusion

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is similar with other research that bubble emissions are a major component of the total flux under particular conditions including dendritic reservoirs with substantial vegetated littoral zones, shallow deltaic deposition zones (DelSontro et al., 2011, Chen et al., 2009) coupled with shallow depths (McGinnis et al., 2006). It is nice that the authors pointed out the possible drawbacks, but in the meantime it is wise to explain why this drawback shows no impact on the conclusion of this study. So this work deals with the gross fluxes only as this is the key measurement determining the "greenhouse" impact (GHG emission from surface water is the key for an accurate budget of GHG emission from the TGR.)

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Our approach overestimates the actual GHG impact of the TGR as we do not take account of river emissions before formation of the impoundment. (I have concerns about this phrase. I guess it is not comparable. Is there any reference about GHG emissions from TGR regions? As for the regions that were inundated by three gorges project, this calculation appears to have two sides. One is about CO2 emission from soil respiration, and the other is CO2 assimilation by the high-plants. However, the inundation makes GHG emission totally differently with those before impoundment. In addition, I guess it is not important to look back the GHG emission before TGR formation because one would care more about the GHG emission at present.) The pre-impoundment GHG emissions must be subtracted from our measured emissions to calculate the net GHG emissions .i.e. the extra emissions attributable to the dam. In our study of TGR, we don't have the requisite flux data before the dam construction. We overcome this gap using the IHA method (IHA, 2010). Here we use an upstream region such as Zhutuo (ZT), which is unaffected or less affected by reservoir backwater, as a reference, and examine the differences between the reference and the dam-affected sites further downstream.

Comparing the annual average flux from ZT with those of the other regions we see that the mainstem regions and the regions below the dam have marginally increased CO_2 emission. We attribute this increase to the construction and operation of the reservoir. All the tributary regions, however, have reduced CO_2 emissions compared to upstream regions. In those tributary regions, the impoundment has converted a rapidly flowing narrowly confined river into broader, quieter backwater with enhanced uptake of CO_2 by riparian vegetation and phytoplankton thus reducing the overall net CO_2 flux especially during spring and summer. During the high flow events much of this material is swept downstream and its subsequent conversion to CO_2 is attributed to the zone of its metabolism rather than to area where the CO_2 was fixed. On the whole, if we don't consider the area change of surface water before and after the dam construction, a estimate amount of 1.1×10^6 t CO_2 would be emitted without impoundment (I could not follow well. I do agree with CO2 uptake by vegetation and phytoplankton. But in the meantime, CO2 emission is quite clear if one put a chamber on the soil surface due to the heterotrophic respiration of organisms in soil), which indicated CO_2 emission have increased by 17.5% due to the impoundment.

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The situation is different for CH_4 emissions. Relative to our upstream reference regions(what does the reference region mean?), we see that CH_4 emissions from the mainstem are significantly lower (p=0.001). The value before the dam construction was estimated to be 16.1×10^3 t(please provide the reference), which means CH_4 emissions have decreased by 62.8% (what is the source of methane emission before dam construction, from

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water surface too?). Emission of CH_4 is contingent on the creation of anoxic zones within the sediments and the absence of other factors limiting CH_4 emissions from the surface. These limiting factors include an oxygenated water column where oxidation of dissolved CH_4 may occur (Bastviken et al., 2006), and deep waters promoting the dissolution of CH_4 bubbles thus reducing the "direct" bubble flux to the surface and prolonging the time dissolved CH_4 is exposed to oxidation in the water column (McGinnis et al., 2006). The high DO concentrations even in the deepest parts of the TGR storage minimize the scope for sediment anoxia. The great water depth favors dissolution of the bubbles emitted from the sediment before they reach the surface. Thus the surface emission of CH_4 is confined largely to diffusive fluxes. It is interesting to note that the inferred highest incidence of bubbles at the surface corresponds to the time of the summer drawdown with the warmest and most shallow waters. The upstream and tributary stations CH_4 emissions are significantly increased ($p=0.001$ and 0.083, for upstream and tributary, respectively) reflecting the increased scope for sedimentation in these areas, and for autochthonous production which contributes to the formation of the anoxic zones.

6. Conclusions

The results of this study provides insights into the patterns of GHG emission from the TGR and the underlying mechanisms. Compared to fossil-fuelled power plants of equivalent power output TGR is a very small GHG emitter. Relative to other hydroplants TGR‘s outputs of CH_4 and CO_2 per unit of generating capacity are comparable to temperate hydropower plants but considerably less than emissions from tropical hydrosystems.

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The construction of the dam has led to a marginal increase in the mainstem CO_2 fluxes. These are already high due to the high load of metabolizable soil carbon delivered by erosion to the Yangtze. The tributaries and increased interfluvial areas formed on damming, and the operations of the Dam have become more favourable to photosynthetic uptake of CO_2 especially in summer (I think this is relatively vague, why operation of the Dam make photosynthetic uptake of CO2 more favorable? I suppose there is no evidence in support of this statement). While this reduces the measured annual average CO_2 fluxes, however it is likely that some of this material will be converted back to CO_2 elsewhere diminishing any net effect.

The post dam construction conditions in these tributary areas however, have lead to increased CH_4 fluxes in the tributaries and the interfluvial zone upstream compared to the pre-dam state (It appears a bit confusing to compare data between post and pre-dam. I could not see the evidences for GHG emission before dam construction.). In the main body of the reservoir, the great depth of the water column, the lack of stratification and the high oxygen content of the water column limit CH_4 fluxes by providing sufficient depth for all bubbles to dissolve (McGinnis et al., 2006) before reaching the surface preventing ebullitive delivery of CH_4 to the atmosphere. Dissolved CH_4 is rapidly oxidized limiting diffusive emissions.

Comment [E14]: These sentence means Dam construction would lead to a decline in methane emission, which is in stark contrast to the starting sentence in this paragraph
In addition, these sentences are not appropriate as concluding remarks

The seasonally changing differences over time in emission behavior in the different spatial elements especially the tributaries and inter fluvial areas of the TGR underlines the need for a spatially and temporally representative sampling of gas emissions, as relatively small areas can have a disproportionate effect on total emissions. The operation of specific factors (depth, high oxygen content due to the turbulent conditions, and short residence time) cause TGR to fall well outside the predictions of CH_4 emissions with age [Barros et al., 2011). Based on the age and latitude of TGR CO_2 fluxes are under-predicted while CH_4 fluxes are over predicted. The existence of other systems such as Lake Wohlen (DelSontro et al., 2011) which depart significantly from such predictions also, suggests that a more nuanced approach is needed in predicting GHG emissions from hydropower reservoirs.

Comment [E15]: It is not recommended to use the same phrase in different places in a single paper.
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The concluding section needs to be re-organized. For example,

(1) The authors can start by describing the total budget of GHG emissions from TGR, and put it into the context of nationa budget of GHG in China. This will make a big sense for readers How significant TGR contribute to GHG emission budget across China.

(2) Then, the seasonal patterns may be described, with emphasis on the hotspots of GHG emission. This would be helpful for subsequent researches for intensive samplings and measurements

(3) The comparison between hydroelectric dam and fossil-fuelled plant can then be compared for GHG emissions. This may be helpful for policy makers, taking into account conclusion (2).

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Table 1. Correlation between GHG fluxes and water properties at 0.5m depth of the TGR.

	Tw(℃)	SD(cm)	chla(μg/L)	pH	DO(mg/L)	turb(NTU)	TOC
CO_2	0.142	-.261**	-.368**	-0.148	-.369**	.241**	0.116
CH_4	0.063	-0.145	.237**	0.048	.260**	-0.041	-.170*
N_2O	0.054	-.245**	-0.034	-0.038	-.294**	.303**	.228**

* Correlation is significant at the 0.05 level

** Correlation is significant at the 0.01 level

Please explain SD, Chla, DO, turb (NTU), TOC.

Please describe the analytical procedures in the materials and method. In addition, the samples volume has to be described. For example, how many sites are used and how many samples are pooled.

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Table 2. CO_2 and CH_4 emissions of per unit installed power generation capacity.

Reservoir	Location	Climate	Area	Installed Capacity	CO_2 fluxes	CH_4 fluxes	CO_2 emission	CH_4 emission	References
			km^2	MW	$mmol\ m^{-2}\ d^{-1}$	$mmol\ m^{-2}\ d^{-1}$	$mol\ kWh^{-1}d^{-1}$	$mol\ kWh^{-1}d^{-1}$	
Petit Saut	French Guiana	tropical	350	115	102	0.7	310	2.13	Guerin et al., 2006
Balbina	Brazil	tropical	2360	250	76	2.1	717	19.82	Guerin et al., 2006
Samuel	Brazil	tropical	540	216	976	5	2440	12.50	Guerin et al., 2006
Tucurui	Brazil	tropical	2850	8370	237.11	12.01	80.7	4.09	Santos et al., 2006
Itaipu	Brazil	tropical	1350	14000	27.39	0.78	2.64	0.08	Santos et al., 2006
Laforge 1	Canada	boreal	1288	878	46.86	1.71	2.51	68.74	Tremblay et al., 2005
Laforge 2	Canada	boreal	260	319	18.93	0.47	0.38	15.43	Tremblay et al., 2005
La Grande 3	Canada	boreal	2420	2418	38.80	0.51	0.51	38.83	Tremblay et al., 2005
La Grande 4	Canada	boreal	765	2779	26.77	0.68	0.19	7.37	Tremblay et al., 2005
Robert-Bourassa	Canada	boreal	2835	5616	38.77	0.49	0.25	19.57	Tremblay et al., 2005
F.D.Roosevelt	United States	temperate	306	6809	-9.89	0.14	-0.44	0.01	Soumis et al., 2004
Dworshak	United States	temperate	37	400	-23.41	0.21	-2.17	0.02	Soumis et al., 2004
Wallula	United States	temperate	157	1120	-9.48	0.53	-1.33	0.07	Soumis et al., 2004
Shasta	United States	temperate	77	629	31.02	0.69	3.80	0.08	Soumis et al., 2004
Lokka	Finland	boreal	417	1849*	35	2.1	0.47	7.89	Huttunen et al., 2003
TGR	China	subtropical	1084	22500	96.18	0.32	4.63	0.02	This study

* estimated from annual production of Lokka reservoir (675 GWh)

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Table 3. Emissions by thermal-power plant when generating power output equivalent to that of the Three Gorges power station in 2010

Fuels	Emission factor[a] (tC/MWh) pls give the full name or explain it as the note	Efficiency [b] (%)	Emissions (tC)	% of other energy sources
TGR	-	-	411,491	-
Natural gas	0.05508	44	10,561,590	3.9
Diesel oil	0.07272	34	18,045,254	2.3
Fuel oil	0.07596	34	18,849,251	2.2
Coal	0.09288	33	23,746,320	1.7

[a] data are etrieval from EFDB, IPCC 1997 (please give the full name)

[b] **data are ciated from Graus et al., 2007**

Emissions equals capacity equivalent with the Three Gorges power station × emission factor / fuel efficiency (DosSantos et al., 2006).

These figures are a bit abrupt. The authors can briefly explain what the emission factor is, and what efficiency is. In doing so, one would get get a good idea of how the study was done, and be able to interpret the table or figure without reference to the text. In addition, the detailed information may be provided in the materials and methods section if flexible.

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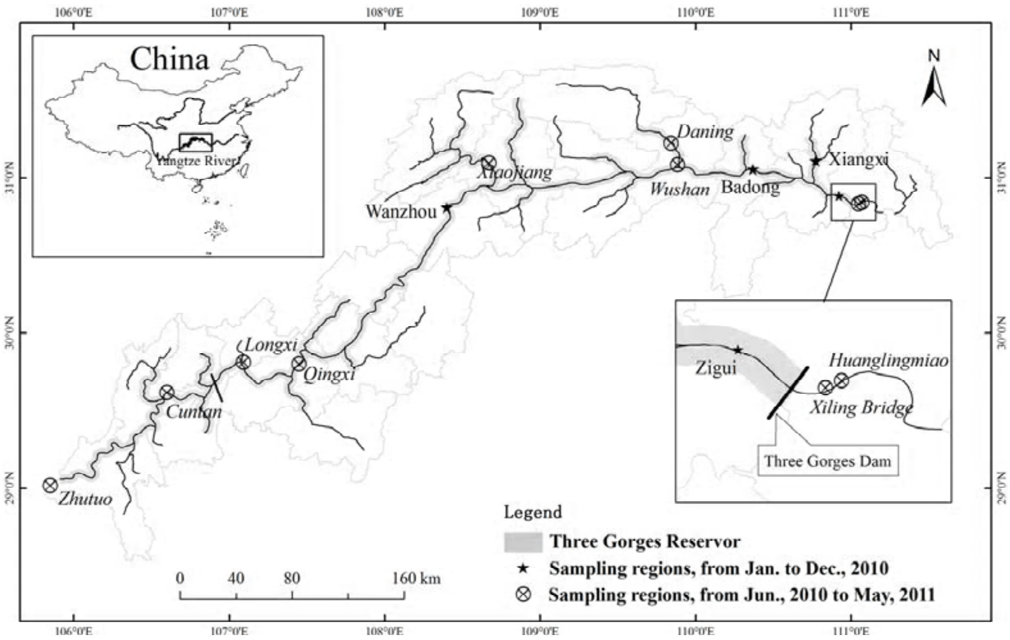

Figure 1. Location of the Three Gorges Reservoir and all sampling sites (The figure legend is certainly too simple to be used. The grey symbol for TGR on the map could be enlarged just for a better demonstration of TGR)

(1) indicate the direction of upstream

(2) explain what TGR means. I understand that the authors refer to all waterbodies as TGR right upstream of the Dam in Yi-chang? and GHG fluxes were measured only from the surface water

(3) I strongly suggest that the authors make a classification of mainstem sampling, tributary sampling, upstream sampling and downstream sampling. These can be indicated on the map. I think these informations are more important. The sampling time from Jan to Dec of 2010 could be removed but described in the figure legend. In addition, the authors could describe the sampling time for each site in the section of materials and methods.

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(4) I wonder how GHG determination was done? The sampling sites are far distant from one another. This means there were many colleagues who stayed in different sites for measurements. Pls eplain this point in the materials and methods.

(5) All of the abbrevations such as WZ should be described here.

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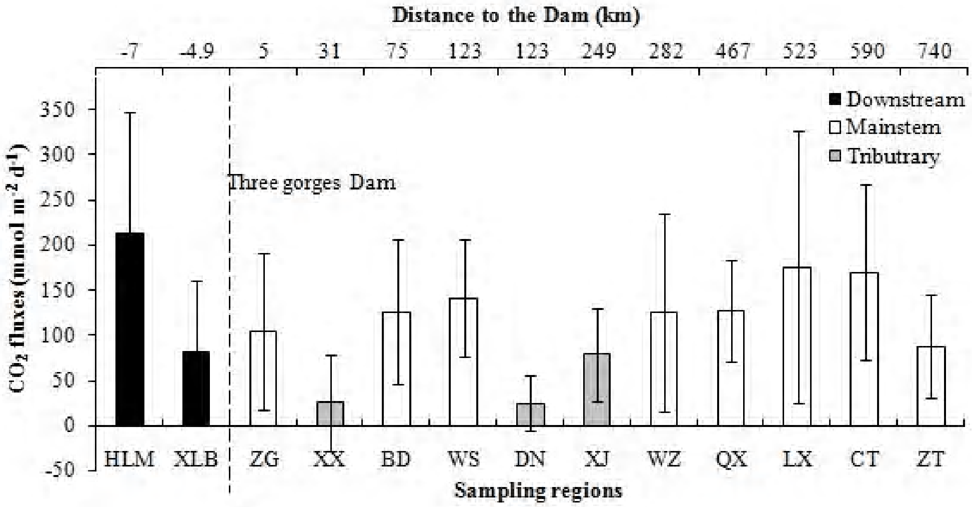

Figure 2. Annual average CO_2 fluxes from different sampling sites of TGR. The dash line demonstrated the location of the Three Gorges Dam and all the sampling sites are arranged according to their distance to the dam (see the axis on the top). For the sampled tributaries (XX, DN and XJ) distance between the dam and tributary estuaries are used. Error bars indicated standard deviations(the authors can specify the sample volume. i.e., the mean of the monthly measurements with 12 data points? It can be described in the text, or).

Annually, CO_2 flux at all the sites showed large variations with large standard deviation and flux at tributary sites show relatively lower values.

The abbreviation of XX could be replaced with XR or something else. XX generally refers to something unknown or uncertain. It may lead to confusion. In addition,

(1) the negative data need to be examined to make sure that XX could function as a sink of CO2 for a given period. If the data are 100% convincing, I would suggest the authors to specify the sampling date when CO_2 was consumed in the chambers.

Comment [E17]: Maybe the TGR could be termed as reservoir. Or the reservoir of the Three Gorges Dam (TGD)?

The reason is that Three Gorges Dam has greater reputation than Three Gorges Reservoir. Please think about this point

Comment [ZJ18]: This sentence could be removed because it is simply the same thing as what Figure 2 conveys

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(2) All abbreviations such as HLM and XLB should be explained (it may be better placed in the legend of Figure 1).

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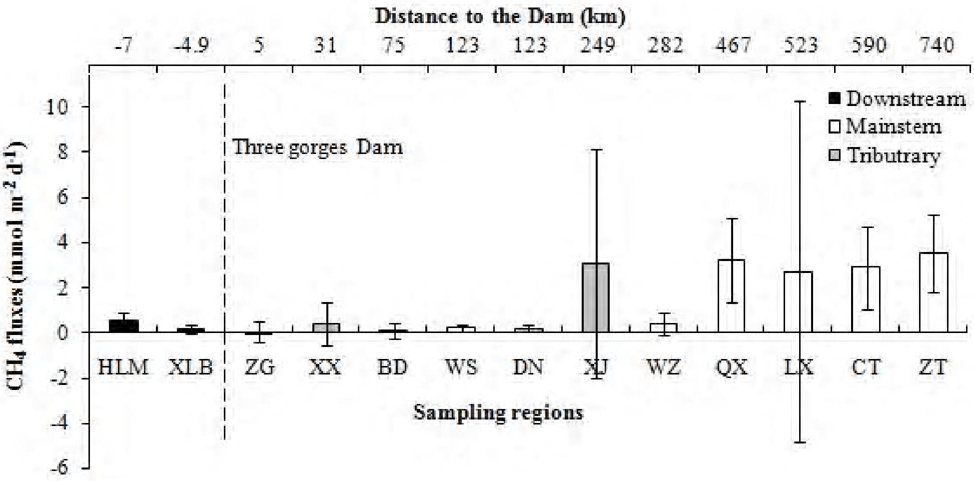

Figure 3. Annual average CH_4 fluxes from different sampling sites of TGR. Error bars indicated the standard deviation. CH_4 fluxes at upper reach at mainstream (QX, LX, CT and ZT) are higher than other parts of the reservoir, while tributary sites (like XJ and XX) show relative higher fluxes. For me, it is hard to believe that the reservoir waterbodies could function as a sink of CH4 (for example, at ZG, XX, XJ and in particular LX). I would expect that the decline of methane concentrations inside the chamber might have likely resulted from the disturbance. For instance, when the gas sample was collected at 0-time point under disturbance, this might lead to high centrations of methane because more methane might be emitted through bubbling. The subsequent collection of gas samples at 20 or 40 min intervals may have a relatively low concentration of methane, particularly under the circumstance that there was no serious disturbance during sampling. please check your data and the measurements of standard gases. The exceptional data should be checked, and the abnormal data could be removed for clarity. Figure 3 and Figure 4 could be merged into one Figure 2 as a new Fig. 2a (CO2), 2b (CH4), and 2c(N2O) .

Comment [ZJ19]: This should have been placed in the sections of results or discussions.

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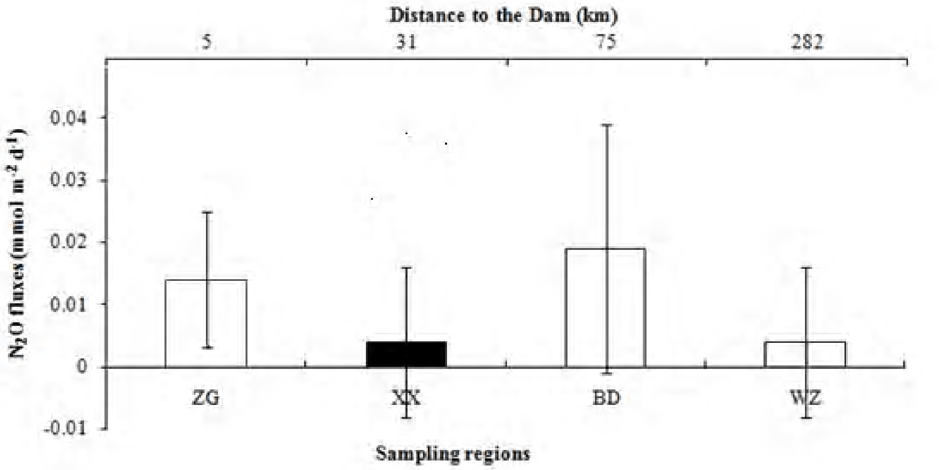

Figure 4. Annual average N_2O fluxes from the four primary sampling regions of TGR. Basically fluxes at the three mainstream sites (white bars) are higher than tributary site of Xiangxi (XX, black bar)

Comment [ZJ20]: Mainstream or mainstem?
If there is no significant difference between mainstem and mainstream, please use either one throughout the text and figures for consistency

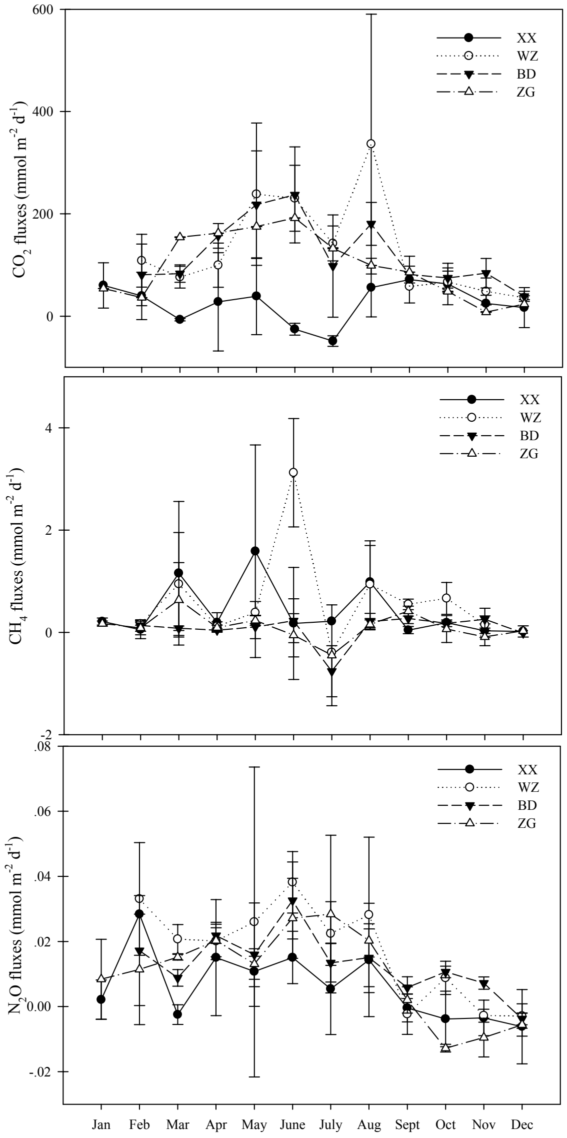

Figure 5. Monthly (seasonal ?) variations of GHG fluxes from the four primary sampling sites. Each site have made 4 to 5 measurements (GHG measurement is the core data of this study. I understand that 4 to 5 measurments were made at each site for every month. This is

Comment [ZJ21]: Can be more specific, for example mainstems, tributary or downstream a huge effort and it might be better to specify samplings date, time, and replicates in a supplementary table?) to consider the great spatial variation of GHG fluxes and the error bars indicated the standard deviations which partly quantified these variations. CO_2 fluxes at mainstream sites (Zigui: ZG, Badong: BD, Wanzhou: WZ) have similar changing trend while the monthly variation in the tributary of Xiangxi (XX) is totally different in warm season due to the absorption of algae in Xiangxi River; changing trend of N_2O fluxes are more or less like the CO_2 fluxes at mainstream, indicating that there may be some common parameters influencing these two gas emissions; CH_4 have a more complex temporal variation indicating more complicated processes and parameters are involved.

Comment [E22]: These sentences is better placed in the sections of Results and/or discussion.

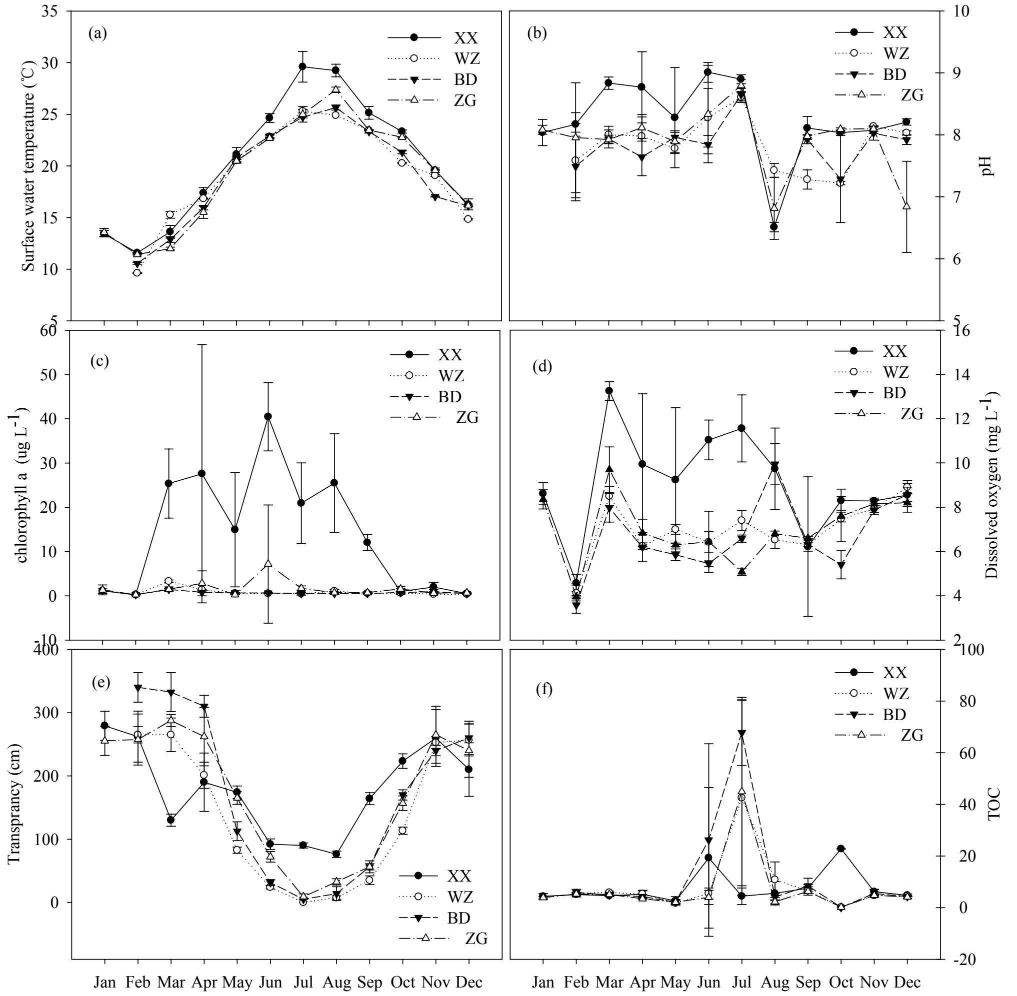

Figure 6. Monthly variation of water quality parameters, from January to December,

Comment [E23]: How water quality is related to GHG emissions.
In addition, the authors can specify the detailed information of measurements. i.e., how water temepratuer is measured, for example water depth, sampling site, sampling date or time. It is no need to describe the results.

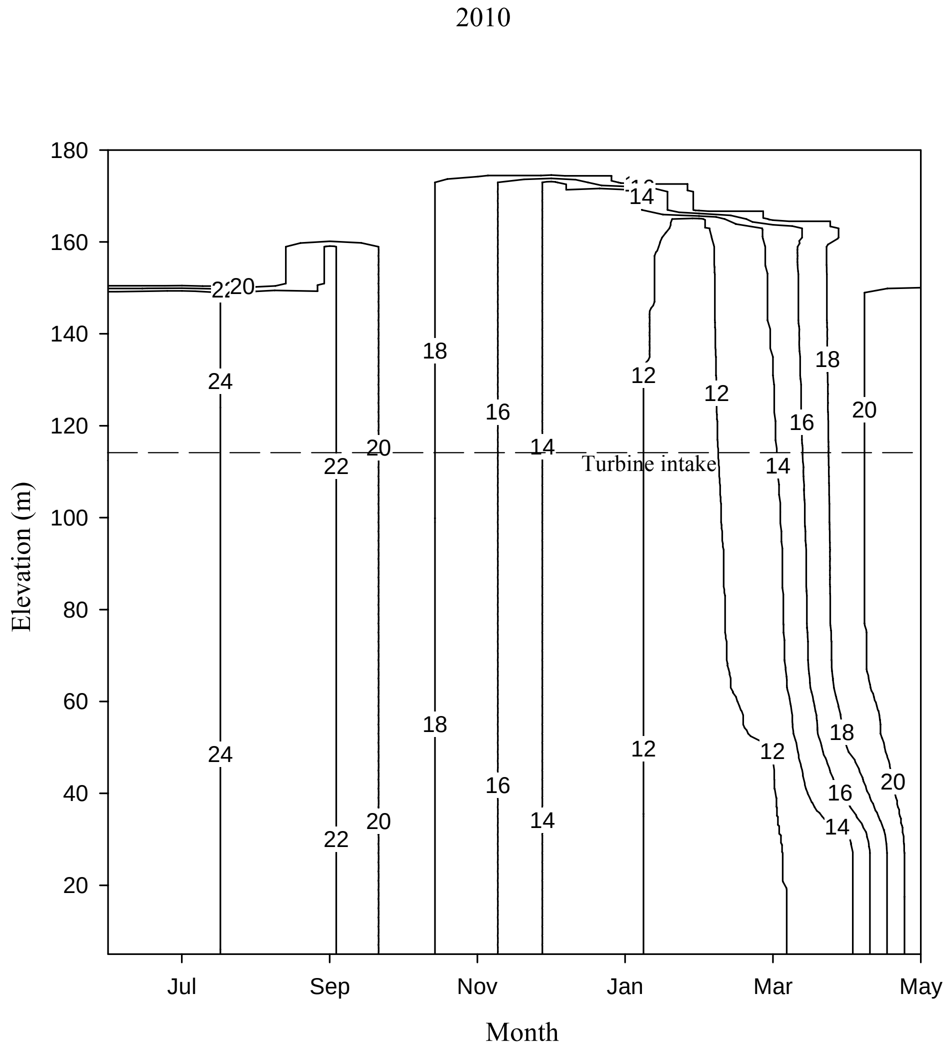

Figure 7. Temperature profile at Three Gorges Dam region, from July 2008 to June 2009. The horizontal dotted line indicates the bottom of the turbine intake (116m above the sea level, 15 m high and 9.5 m wide). During most time of the year water in this area is well mixed and there is no obvious stratification except at April and May. This phenomenon happens at most part of the reservoir, especially at the mainstream, mainly due to the deep

discharge of the dam and water interchange between the mainstream and tributaries. I could not get the clear message from this manuscript. Does y axis Elevation means above seal level? The authors mentioned in the text that temperature at different water depth was determined. Do authors refer to these data by Fig.7. In addition, how to relate this temperature with GHG emission?

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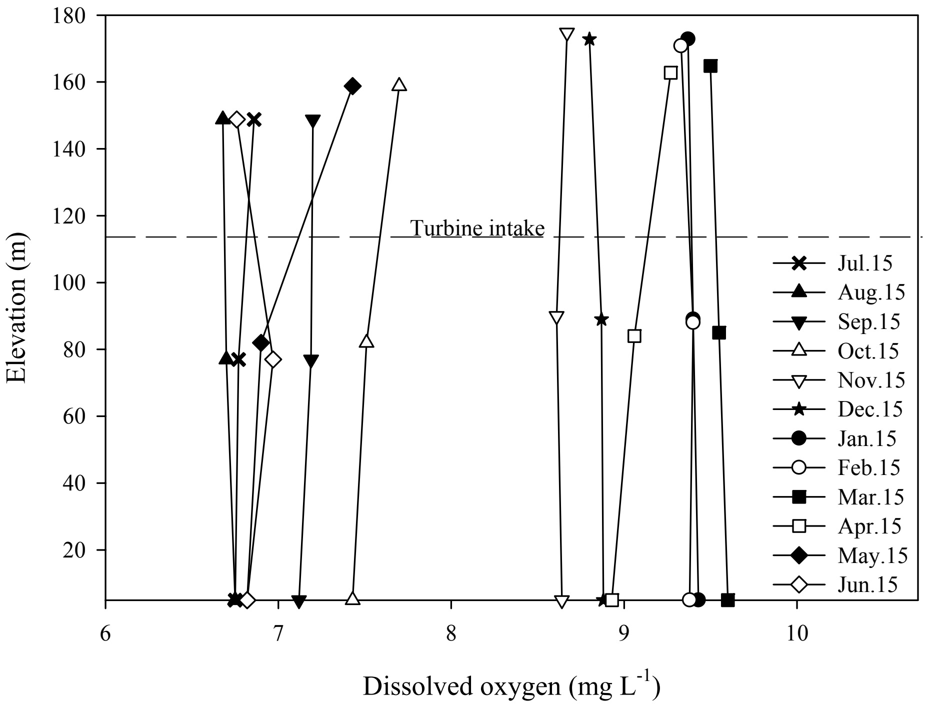

Figure 8. Monthly variation of DO concentrations at surface water (0.2 m), bottom layer (0.5 m above the sediment) and the middle layer, from July, 2008 to Jun, 2009. The high DO concentration even at bottom of the reservoir is again approved that there are no significant stratification at these regions.

Comment [E24]: This is not appropriate being placed in the figure legend.

The importance of DO to GHG emission needs to be specified.

I imagine y axis represent the different sampling sites. I feel that the presentation of Figure 2 is concise, clear and straightforward. In this figure, we could not relate to the DO to the exact sampling point. Another way is that the authors can use the symbols of each sites in the Fig.1, which can then be further used without explaination.

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N_2O is emitted also. All these gases are radiatively active “greenhouse gases”. While the CO_2 emissions have no net greenhouse impact as they are derived from photosynthetically fixed CO_2, the emissions of CH_4 and N_2O are especially important. Their relative molar atmospheric impacts are respectively 25 and 298 times that of CO_2 (Forster et al., 2007).

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It has been argued, based primarily on

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may be comparable to, or exceed those of,

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and thus vitiate their low GHG claims

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Against these background differences, our investigations of TGR have the objective of (1) evaluating the TGR GHG emissions and compare them to other hydro-reservoirs and other energy sources, (2) contributing (by providing data) to the development of an empirical model(Barros et al., 2011) to predict GHG emission from future reservoirs. Very recent research (Sobek et al., 2012; DelSontro et al., 2011) has shown that specific reservoir characteristics, not well reflected in some models, play a key role in high reservoir GHG emissions. Such models may play a role in future decisions on the construction of additional hydro-power reservoirs. It is important that they be robust, accurate and covers the widest range of circumstances. We address our results from this perspective later.

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their potential significance, there have only been limited investigations of the GHG emissions of TGR

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