

## Preliminary report on methane emissions from the Three Gorges Reservoir in the summer drainage period

Fei Lu<sup>1,2</sup>, Le Yang<sup>1,2</sup>, Xiaoke Wang<sup>1,\*</sup>, Xiaonan Duan<sup>3</sup>, Yujing Mu<sup>4</sup>, Wenzhi Song<sup>1</sup>,  
Feixiang Zheng<sup>1</sup>, Junfeng Niu<sup>1,2</sup>, Lei Tong<sup>1,2</sup>, Hua Zheng<sup>1</sup>,  
Yongjuan Zhou<sup>1</sup>, Jiangxiao Qiu<sup>1,2</sup>, Zhiyun Ouyang<sup>1</sup>

1. State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China. E-mail: [lu\\_fei@yahoo.cn](mailto:lu_fei@yahoo.cn)

2. Graduate University of Chinese Academy of Sciences, Beijing 100049, China

3. General Office of Chinese Academy of Sciences, Beijing 100864, China

4. Laboratory of Atmospheric Chemistry and Air Pollution Control Techniques, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

Received 21 December 2010; revised 14 February 2011; accepted 06 April 2011

### Abstract

Recently reported summertime methane (CH<sub>4</sub>) emissions ( $6.7 \pm 13.3$  mg CH<sub>4</sub>/(m<sup>2</sup>·hr)) from newly created marshes in the drawdown area of the Three Gorges Reservoir (TGR), China have triggered broad concern in academic circles and among the public. The CH<sub>4</sub> emissions from TGR water surfaces and drawdown areas were monitored from 3rd June to 16th October 2010 with floating and static chambers and gas chromatography. The average CH<sub>4</sub> emission flux from permanently flooded areas in Zigui, Wushan and Yunyang Counties was ( $0.33 \pm 0.09$ ) mg CH<sub>4</sub>/(m<sup>2</sup>·hr). In half of these hottest months of the year, the wilderness, cropland and deforested drawdown sites were aerobic and located above water level, and the CH<sub>4</sub> emissions were very small, ranging from a sink at 0.12 mg CH<sub>4</sub>/(m<sup>2</sup>·hr) to a source at 0.08 mg CH<sub>4</sub>/(m<sup>2</sup>·hr) except for one mud-covered site after flood. Mean CH<sub>4</sub> emission in flooded drawdown sites was 0.34 mg CH<sub>4</sub>/(m<sup>2</sup>·hr). The emissions from the rice paddy sites in the drawdown area were averaged at ( $4.86 \pm 2.31$ ) mg CH<sub>4</sub>/(m<sup>2</sup>·hr). Excepting the rice-paddy sites, these results show much lower emission levels than previously reported. Our results indicated considerable spatial and temporal variation in CH<sub>4</sub> emissions from the TGR. Human activities and occasional events, such as flood, may also affect emission levels. Long-term CH<sub>4</sub> measurements and modeling in a large region are necessary to accurately estimate greenhouse gas emissions from the TGR.

**Key words:** methane; the Three Gorges Reservoir; drawdown area; summer, drainage; uncertainty; flood

**DOI:** 10.1016/S1001-0742(10)60668-7

**Citation:** Lu F, Yang L, Wang X K, Duan X N, Mu Y J, Song W Z et al., 2011. Preliminary report on methane emissions from the Three Gorges Reservoir in the summer drainage period. *Journal of Environmental Sciences*, 23(12): 2029–2033

### Introduction

Methane (CH<sub>4</sub>) is the second largest anthropogenic greenhouse gas in terms of radiation forcing to global warming, just following carbon dioxide. The atmospheric CH<sub>4</sub> concentrations have been doubted since preindustrial time (Frankenberg et al., 2005), and most of the CH<sub>4</sub> is produced from fossil fuel combustion, wetlands, rice paddies, waste management and ruminants (Zhuang et al., 2009). Over the past decade, researchers have suggested that CH<sub>4</sub> emissions from reservoirs contribute considerably to anthropogenic CH<sub>4</sub> (Giles, 2006; Zheng et al., 2011a). It is reported that, global CH<sub>4</sub> emissions from reservoirs are 70 Tg/yr, representing 18% of other anthropogenic emissions (St Louis et al., 2000).

The emissions of CH<sub>4</sub> and other greenhouse gases

(GHGs) from the Three Gorges Reservoir (TGR) have drawn broad national and international attention. Chen et al. (2009) measured CH<sub>4</sub> emission flux from a newly created marsh in a wetland reserve of the TGR, located in the drawdown area of a branch of the Yangtze River. He found a mean CH<sub>4</sub> emission of ( $6.7 \pm 13.3$ ) mg CH<sub>4</sub>/(m<sup>2</sup>·hr) that exceeded those from some tropical reservoirs (Qiu, 2009). This finding led to the assumption that CH<sub>4</sub> emission from the TGR surface was similar to that emitted by tropical reservoirs, and that the additional methane emitted by the marshes formed during summer drainage, which accounted for 100 km<sup>2</sup> and 10% of the total reservoir area, might comprise one-fifth of that emitted from the reservoir surface (Chen et al., 2009; Qiu, 2009). A subsequently published research (Zheng et al., 2011a) reported a low mean annual CH<sub>4</sub> emission flux of only 2.8 mg CH<sub>4</sub>/(m<sup>2</sup>·day) (0.117 mg CH<sub>4</sub>/(m<sup>2</sup>·hr)) from the Ertan

\* Corresponding author. E-mail: [wangxk@rcees.ac.cn](mailto:wangxk@rcees.ac.cn)

Reservoir, located in a subtropical region of China. These low values were likely associated with biomass clearing before flooding, a low supply of organic matter, and the subsequent limitation of sediment CH<sub>4</sub> production (Rosa et al., 2004; Zheng et al., 2011a).

The same work was also performed during the construction of the TGR. Before the initial water storage, workers and nearby residents cleared the reservoir drastically following the “Technical Standard of Solid Waste Cleaning for Reservoir Bed of The Three Gorges on Yangtze River” (Professional Standard of Environmental Protection, China, HJ85-2005, promulgated by State Environmental Protection Administration and State Council Three Gorges Project Construction Committee Executive Office in 2002 and revised in 2005). In the course of clearing, trees were felled and organic waste was removed from the region. Later, under the direction of “the Guideline on Soil Removal for Fertility Improvement” (promulgated by Ministry of Land and Resources and Ministry of Finance of the People’s Republic of China in 2006), fertile top soils (at least 12–16 cm in thickness) from the elevation of 139–175 m were moved to the areas at the elevation of over 182 m and a distance of more than 5 km from the bank of the TGR. Given that the TGR and the Ertan Reservoir were both cleared before flooding, it is necessary to establish whether CH<sub>4</sub> emission fluxes from the non-wetland portions of the drawdown area and from the water surfaces of continuously flooded areas in the TGR are similar to those from tropical reservoirs, as Chen et al. (2009) assumed, or whether these values are lower, as reported for the Ertan Reservoir (Zheng et al., 2011a).

To provide a preliminary answer to the above question, we conducted an observation research in the TGR area from 3rd June to 16th October 2010. This observation period encompassed water sluicing and storage processes in the TGR, the July 2010 flood, and the months during which Chen et al. (2009) conducted research in the TGR. This study aimed to: (1) measure CH<sub>4</sub> emission flux from the water surfaces and drawdown areas in the TGR, (2) compare the CH<sub>4</sub> emissions of different drawdown-area types and hydrological conditions in the TGR, and (3) discuss sources of variation in the estimation of CH<sub>4</sub> emission from the entire TGR and the possibility that previously reported values (Chen et al., 2009) were overestimated.

## 1 Methodology

### 1.1 Sampling sites

Gas samples were collected from water surfaces and drawdown areas in three counties in the TGR area: Zigui (30°51'N, 110°58'E), the site of the Three Gorges Dam (TGD); Wushan (31°03'N, 109°51'E), about 120 km from TGD and representing the eastern TGR region; and Yunyang (30°56'N, 108°39'E), about 220 km from TGD and representing the western TGR region. Sampling sites were distributed along the longitudinal axis of the reservoir, from the TGD to the upper reaches of the Yangtze River (Fig. 1, Zhou et al., 2010). To avoid the impact of pollution

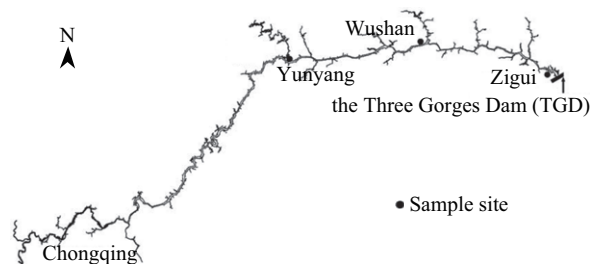


Fig. 1 Location of the sampling sites.

from county seats and ports, all sites in Wushan and Yunyang were about 5 km upstream from major ports.

In each county, three sites were located in the permanently flooded area for different depths. The depths of the sites for deep water, medium depth and shallow water were respectively 105, 70 and 48 m in Zigui County, 135, 100 and 60 m in Wushan County and 135, 55 and 45 m in Yunyang County, at the water level of about 170 m in December 2009. Site selection in the drawdown area included three kinds of land use in each county: wilderness, cropland and deforested areas. Drawdown site types were determined in September 2009 when the drawdown area was not submerged. During the sampling period, the wilderness sites in Zigui and Yunyang Counties were covered primarily with Siberian cocklebur (*Xanthium sibiricum* Patrin.), crabgrass (*Digitaria sanguinalis* (L.) Scop.), setaria (*Setaria viridis* (L.) Beauv.), and cogon grass (*Imperata cylindrica* var. Major); deforested sites in these two counties had similar land cover. The cropland site in Zigui County contained maize (*Zea mays*) and that in Yunyang County contained sesame (*Sesamum indicum*). All three kinds of sites in Wushan County were taken for agricultural use in 2010. Maize was raised in the wilderness site and sesame was grown in the deforested area. Vegetable seedlings grew on the cropland site, where maize had been planted in the previous year, but these were destroyed in the July 2010 flood and then no crop was planted. In Yunyang County, we also chose a piece of terraced rice (*Oryza sativa*) paddy for the research, and began to take samples on 3rd June, when the rice had just been transplanted. At the beginning of the sampling (3rd June, with the water level at 149.4 m), all drawdown sites except the deforested site in Yunyang were above water level. The TGR began to store water on 10th September. Our sampling period ended on 16th October when the water level had reached 172.8 m and all the drawdown sites were submerged. Because the water level of the TGR changed frequently during the experimental period, we recorded all the sampling sites with a global positioning system (GPS; eTrex-summit, Garmin, China) to ensure the consistency of sampling locations.

### 1.2 Gas sampling

Floating and static chambers and gas chromatography were used to measure CH<sub>4</sub> emissions from water surfaces and drawdown areas in the TGR. The floating chamber technique was used to collect gas samples at water surfaces and the sites in the drawdown area under anaerobic condition. The outer surface of the plastic chamber (65 cm

in length, 45 cm in width and 40 cm in height) was covered with light- and heat-isolating film to avoid increases in internal temperature. Plastic foam was bound to the chamber to maintain the waterline at 10 cm from the chamber base and an atmospheric height of 30 cm inside the chamber. At aerobic sites in the drawdown area, permanently positioned iron chamber bases (65 cm in length, 45 cm in width and 10 cm in height) with water-filled grooves in the upper end were used to ensure gas tightness. The July 2010 flood removed the chamber bases from Wushan cropland sites and Yunyang wilderness and deforested sites; new bases were positioned in almost the same locations. The static transparent chamber technique was employed to collect gas samples in rice paddies (Zheng et al., 2011b). This technique used a steel-frame chamber (50 cm in length, 50 cm in width and 75 cm in height) covered with polyethylene plastic film (85% transparency). A buffer pipe (0.6 cm outer diameter, 0.4 cm inner diameter) was inserted through the top of the chamber to maintain balance between internal and external air pressure. CH<sub>4</sub> samples (0.5 L) were pumped from the chamber at 0, 8, 16, 24 and 32 min after the chamber was laid at the site, and stored into multi-layered film aluminum bags (0.5 L, Hedetech, China). At each site, CH<sub>4</sub> emission was measured simultaneously using three chambers to provide replicate data.

### 1.3 Determination of CH<sub>4</sub> emission flux

The CH<sub>4</sub> samples were analyzed by gas chromatography with a flame-ionization detector (Agilent 6820, Agilent Technologies, USA) at the laboratory of Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing. The temperatures of injection, detection and column-oven chambers were 150, 300 and 80°C, respectively, and pure nitrogen (N<sub>2</sub>) was used as a carrier gas. The chromatographic column was filled with XMS-filler of 60–80 mesh, 2 m in length and 2 mm in diameter. The flow rates of the carrier gas (N<sub>2</sub>), fuel gas (H<sub>2</sub>) and compressed air were 30, 20 and 30 mL/min, respectively (Zheng et al., 2011b). The standard CH<sub>4</sub> gas (10.2 ppm in air; provided by Chinese CRM/RM Information Center) was used to quantify the CH<sub>4</sub> concentrations for every 15 samples. The rate of CH<sub>4</sub> concentration increase ( $dc/dt$ , ppm/hr) within the static chamber was calculated as the slope of a linear regression of CH<sub>4</sub> concentration versus time ( $R^2 > 0.90$ ). This value was used to obtain CH<sub>4</sub> emission ( $F$ , mg CH<sub>4</sub>/(m<sup>2</sup>·hr)) by the following equation:

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

where,  $\rho$  (kg/m<sup>3</sup>) is the density of CH<sub>4</sub> in standard state (0.714 kg/m<sup>3</sup>).  $H$  (m) is the height from the chamber top to the water surface, and  $T$  (°C) is the air temperature (Zheng et al., 2011b).

### 1.4 Statistic analysis

One-way analysis of variance (ANOVA) combined with the LSD test was used to analyze the differences in mean CH<sub>4</sub> emissions from permanently flooded areas among the three counties. An independent-sample  $t$ -test

was used to test the difference in mean CH<sub>4</sub> emissions. Repeated-measures multivariate analyses using different water depths as the between-subjects factors were also employed to determine the effect of water depth on CH<sub>4</sub> emissions in each county. As the inundation condition of the drawdown area altered (more than once in some sites) due to the drastic change of water level in the research period, only weight average and arithmetic average values of the CH<sub>4</sub> emissions from different drawdown sites were calculated and compared.

## 2 Results

### 2.1 CH<sub>4</sub> emission from permanently flooded sites

During the study period, the CH<sub>4</sub> emission flux from permanently flooded sites in Zigui County (mean:  $(0.11 \pm 0.05)$  mg CH<sub>4</sub>/(m<sup>2</sup>·hr)) was significantly lower than that in Wushan County (mean:  $(0.39 \pm 0.10)$  mg CH<sub>4</sub>/(m<sup>2</sup>·hr),  $p = 0.005$ ) and Yunyang County (mean:  $(0.48 \pm 0.12)$  mg CH<sub>4</sub>/(m<sup>2</sup>·hr),  $p = 0.000$ , Fig. 2), but the fluxes in the latter two counties did not show significant difference ( $p = 0.151$ ). The mean CH<sub>4</sub> emission flux from the permanently flooded sites during the entire study period

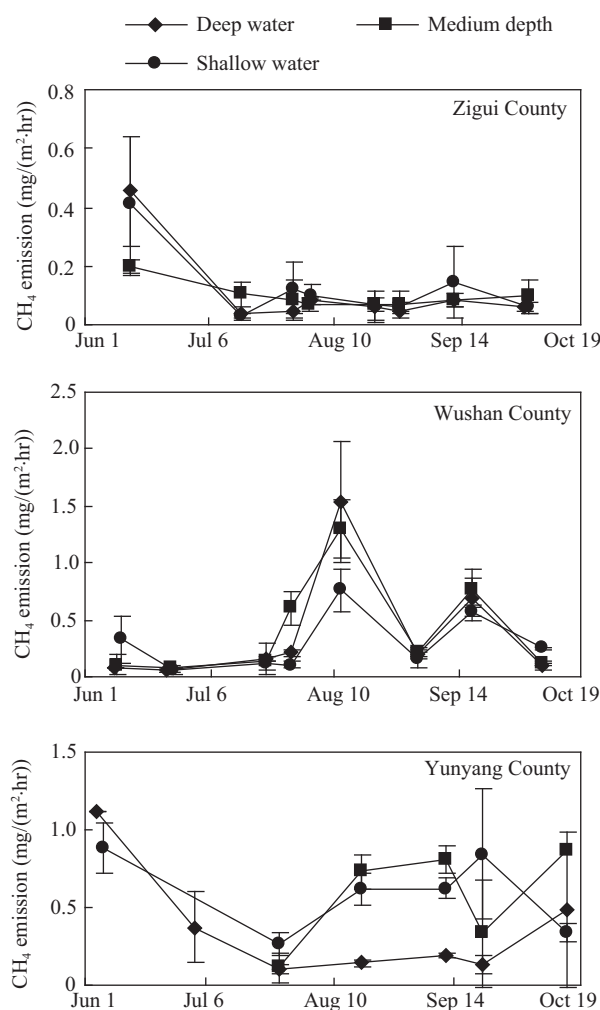


Fig. 2 CH<sub>4</sub> emission from water surfaces in the TGR during the sampling period in 2010.

was  $(0.33 \pm 0.09)$  mg CH<sub>4</sub>/(m<sup>2</sup>·hr) (Fig. 2). The results of repeated-measures multivariate analyses indicated that, in Yunyang County, the CH<sub>4</sub> flux of deep-water sites differed significantly from those of shallow water ( $p = 0.026$ ) and medium depth ( $p = 0.008$ ) sites, but no significant difference in CH<sub>4</sub> flux was found among sites of different water depths in the other two counties.

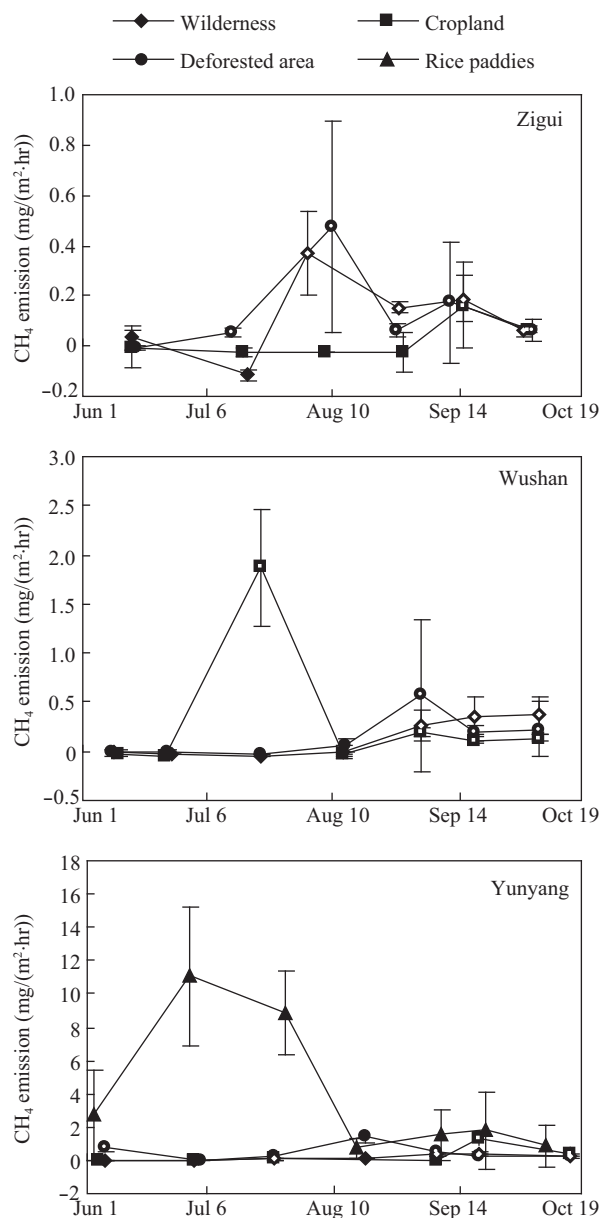
## 2.2 CH<sub>4</sub> flux from the drawdown sites

In the summer drainage period, the majority part of the drawdown area is above water level when the TGD sluice gates are opened to discharge floodwater and lower the water level to 145 m (Zhou et al., 2010). In our study, when the sites in wilderness, cropland and deforested areas were above the water level and in aerobic condition, the CH<sub>4</sub> emission fluxes were very small, ranging from a sink at 0.12 mg CH<sub>4</sub>/(m<sup>2</sup>·hr) to a source at 0.08 mg CH<sub>4</sub>/(m<sup>2</sup>·hr), except for the deforested area in Yunyang County on 19th August when the site was covered by mud after the July 2010 flood, and the CH<sub>4</sub> flux reached 1.38 mg CH<sub>4</sub>/(m<sup>2</sup>·hr) (Fig. 3). When these sites were flooded, the CH<sub>4</sub> emissions, which arithmetically averaged at 0.34 mg CH<sub>4</sub>/(m<sup>2</sup>·hr), were similar to those from the permanently flooded sites, except for Wushan cropland site on 21st July, following the peak flow of the Yangtze River flood (Fig. 3). During the sampling period, the rice paddies in Yunyang Country were consistently anaerobic and produced a mean CH<sub>4</sub> emission flux of  $(4.86 \pm 2.31)$  mg CH<sub>4</sub>/(m<sup>2</sup>·hr), with a peak of 11.06 mg CH<sub>4</sub>/(m<sup>2</sup>·hr) at the end of June (Fig. 3). The CH<sub>4</sub> emission flux of the rice paddies showed a distinct pattern as compared with other kinds of drawdown sites.

## 3 Discussion and conclusions

The CH<sub>4</sub> emission fluxes from the water surface averaged  $(0.3305 \pm 0.0940)$  mg CH<sub>4</sub>/(m<sup>2</sup>·hr) from the beginning of June to the middle of October, which was very close to the annual average CH<sub>4</sub> emission fluxes of some temperate reservoirs in Canada (St. Louis et al., 2000) and the United States (Soumis et al., 2004), but about twice larger than the result of Zheng et al. (2011a) in Ertan Reservoir. It should be noticed that water temperature is an important factor influencing CH<sub>4</sub> emissions from reservoirs (Soumis et al., 2004). In the study of Zheng et al. (2011a), an annual average value was reported, but the average CH<sub>4</sub> emission flux from the TGR in the hottest months of the year was determined in the present study.

In order to keep the available capacity of the TGR in the long term, the reservoir operates in a mode of storing clear water and releasing the silt laden flow, i.e., in the flood season from June to September and before the silt laden flow comes from the upper reaches of the Yangtze River, the sluice gates of the TGD are opened to discharge the flood water and lower the water level to 145 m; and after the flood season (in October), the reservoir begins to store clear water to the water level of 175 m (Zhou et al., 2010). As a result, in the hottest months of the year, the majority part of the drawdown area will be above the water level of the TGR and would be in the aerobic condition with trivial



**Fig. 3** CH<sub>4</sub> emission from drawdown areas in the TGR during the sampling period. CH<sub>4</sub> emissions were represented by hollow signs when the sites were below water level.

CH<sub>4</sub> emission for all kinds of land covers except for some rice paddies and the mud-covered site in the deforested area in Yunyang County. When the drawdown sites were submerged, the CH<sub>4</sub> emissions were close to those from the permanently flooded sites except for the cropland site in Wushan County on 21 July when the peak flow of the flood of the Yangtze River in 2010 just went through. Our results on the wilderness, cropland and deforested sites in the drawdown area were distinct from the result of Chen et al. (2009), but the CH<sub>4</sub> emission fluxes from rice paddy sites were similar to those from marshes with four types of wetland plant stands (*Typha angustifolia*, *Juncus amuricus*, *Scirpus triqueter* and *Paspalum distichum*, Chen et al., 2009). These results indicated that different land uses or covers in drawdown areas could effect the CH<sub>4</sub> emission greatly.

There appeared high CH<sub>4</sub> emissions on the submerged cropland site in Wushan County just after the peak flow of

the flood in the Yangtze River in 2010 and on the mud-covered site in the deforested area in Yunyang County after that flood. The flood could bring sediment with large amount of organic matter to the drawdown area and change the drawdown area into anoxic condition, both of which would raise the CH<sub>4</sub> emission fluxes (dos Santos et al., 2005). These results indicated that occasional incidents such as the flood in the Yangtze River in 2010 might also have influence on CH<sub>4</sub> emissions from the drawdown area, although this influence could be site-specific.

Previous research (Rosa et al., 2004) on CH<sub>4</sub> emissions from reservoirs has found significant variations among hydroelectric plants. The results of the present study differ from those of Chen et al. (2009), indicating the presence of considerable spatial and temporal heterogeneity in CH<sub>4</sub> emissions in a single large-scale reservoir, such as in the TGR. Human activities, such as desolation or reclamation of rice paddies, can be another important factor. Occasional events, such as the July 2010 flood, may also substantially influence CH<sub>4</sub> emissions from the TGR. Due to these sources of variation, an estimation of CH<sub>4</sub> emissions from the TGR based on extrapolation from measurements taken in drawdown marshes may lead to great overestimation. Here, we employed results from Chen et al. (2009) for the newly created marshes and rice paddies for 10% of the total area of the TGR, i.e., 104.5 km<sup>2</sup> of the drawdown area, 0.3443 mg CH<sub>4</sub>/(m<sup>2</sup>·hr) for the rest of the drawdown area (204.5 km<sup>2</sup>) in consideration of the different time lengths of the aerobic period for drawdown areas of different elevations and the influence of flood, and 0.3305 mg CH<sub>4</sub>/(m<sup>2</sup>·hr) for 700 km<sup>2</sup> of water surface, then our preliminary estimation of the total CH<sub>4</sub> emission from the whole TGR based on the same scenario was only 27.5% of that reported by Chen et al. (2009) even though this estimation did not take into account the CH<sub>4</sub> sink of the submerged areas for the drawdown area.

The results of our study underline the point that to give an objective and precise estimation of the GHG emission from the TGR, it is necessary to take the temporal-spatial heterogeneity and other factors of uncertainty into consideration, and make long term GHGs monitoring on a large special scale systematically and simultaneously, which should cover the water surface and drawdown areas of the main stream and branches of the Yangtze River in the TGR region. Simulation research using robust models would also facilitate the characterization of GHG emissions in large-scale reservoirs, such as the TGR.

### Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 50809067), the National Basic Research Program (973) of China (No.

2010CB955904-03) and the Chinese Academy of Sciences for Strategic Priority Research Program (No. XDA05060102, XDA05050602). We gratefully acknowledge the constructive comments of the editor and two anonymous reviewers on an earlier version of this manuscript. We also acknowledge Ms. Yafei Yuan for her suggestions.

### References

- Chen H, Wu Y Y, Yuan X Z, Gao Y H, Wu N, Zhu D, 2009. Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir. *Journal of Geophysical Research*, 114: D18301. DOI: 10.1029/2009JD012410.
- dos Santos M A, Matvienko B, Rosa L P, Sikar E, dos Santos E O, 2005. Gross greenhouse gas emissions from Brazilian hydro reservoirs. In: *Greenhouse Gas Emissions-Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments* (Tremblay A, Varfalvy L, Roehm C, Garneau M, eds.). Springer, New York. 267–291.
- Frankenberg C, Meirink J F, van Weele M, Platt U, Wagner T, 2005. Assessing methane emissions from global spaceborne observations. *Science*, 308(5724): 1010–1014.
- Giles J, 2006. Methane quashes green credentials of hydropower. *Nature*, 444(7119): 524–525.
- Qiu J, 2009. Chinese dam may be a methane menace: Wetlands around Three Gorges produce tonnes of the greenhouse gas. *Nature*. DOI:10.1038/news.2009.962.
- Rosa L P, dos Santos M A, Matvienko B, dos Santos E O, Sikar E, 2004. Greenhouse gas emissions from hydroelectric reservoirs in tropical regions. *Climatic Change*, 66(1-2): 9–21.
- Soumis N, Duchemin É, Canuel R, Lucotte M, 2004. Greenhouse gas emissions from reservoirs of the western United States. *Global Biogeochemical Cycles*, 18: GB3022. DOI: 10.1029/2003GB002197.
- St Louis V L, Kelly C A, Duchemin É, Rudd J W M, Rosenberg D M, 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. *BioScience*, 50(9): 766–755.
- Zheng H, Zhao X J, Zhao T Q, Chen F L, Xu W H, Duan X N et al., 2011a. Spatial-temporal variations of methane emissions from the Ertan hydroelectric reservoir in southwest China. *Hydrological Processes*, 25(9): 1391–1396.
- Zheng F X, Wang X K, Lu F, Hou P Q, Zhang W W, Duan X N et al., 2011b. Effects of elevated ozone concentration on methane emission from a rice paddy in Yangtze River Delta, China. *Global Change Biology*, 17(2): 898–910.
- Zhou Y J, Wang X K, Wu Q B, Lu F, Qiu J X, 2010. Ecological Vulnerability and Protection in the Drawdown Area of the Three Gorges Reservoir. China Environmental Science Press, Beijing. 30–37.
- Zhuang Q L, Melack J M, Zimov S, Walter K M, Butenhoff C L, Khalil M A K, 2009. Global methane emissions from wetlands, rice paddies, and lakes. *Eos, Transactions American Geophysical Union*, 90(5): 37–44.