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

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Abstract

Recently reported summertime methane (CH_4) emissions (6.7 ± 13.3 mg $CH_4/(m^2 \cdot hr)$) 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_4 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_4 emission flux from permanently flooded areas in Zigui, Wushan and Yunyang Counties was (0.33 ± 0.09) mg $CH_4/(m^2 \cdot hr)$. 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_4 emissions were very small, ranging from a sink at 0.12 mg $CH_4/(m^2 \cdot hr)$ to a source at 0.08 mg $CH_4/(m^2 \cdot hr)$ except for one mud-covered site after flood. Mean CH_4 emission in flooded drawdown sites was 0.34 mg $CH_4/(m^2 \cdot hr)$. The emissions from the rice paddy sites in the drawdown area were averaged at (4.86 ± 2.31) mg $CH_4/(m^2 \cdot hr)$. 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_4 emissions from the TGR. Human activities and occasional events, such as flood, may also affect emission levels. Long-term CH_4 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

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Introduction

Methane (CH_4) is the second largest anthropogenic greenhouse gas in terms of radiation forcing to global warming, just following carbon dioxide. The atmospheric CH_4 concentrations have been doubted since preindustrial time (Frankenberg et al., 2005), and most of the CH_4 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_4 emissions from reservoirs contribute considerably to anthropogenic CH_4 (Giles, 2006; Zheng et al., 2011a). It is reported that, global CH_4 emissions from reservoirs are 70 Tg/yr, representing 18% of other anthropogenic emissions (St Louis et al., 2000).

The emissions of CH_4 and other greenhouse gases (GHGs) from the Three Gorges Reservoir (TGR) have drawn broad national and international attention. Chen et al. (2009) measured CH_4 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_4 emission of (6.7 ± 13.3) mg $CH_4/(m^2 \cdot hr)$ that exceeded those from some tropical reservoirs (Qiu, 2009). This finding led to the assumption that CH_4 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^2 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_4 emission flux of only 2.8 mg $CH_4/(m^2 \cdot day)$ (0.117 mg $CH_4/(m^2 \cdot hr)$) from the Ertan

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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_4 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_4 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_4 emission flux from the water surfaces and drawdown areas in the TGR, (2) compare the CH_4 emissions of different drawdown-area types and hydrological conditions in the TGR, and (3) discuss sources of variation in the estimation of CH_4 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

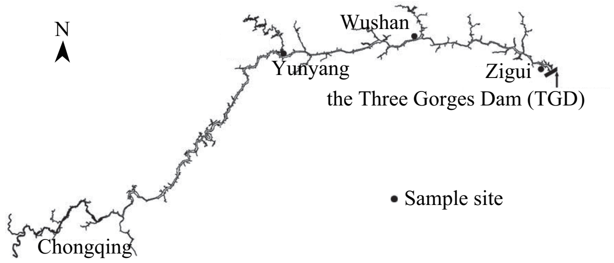

Fig. 1 Location of the sampling sites.

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 cylindraca* 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_4 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_4 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_4 emission was measured simultaneously using three chambers to provide replicate data.

1.3 Determination of CH_4 emission flux

The CH_4 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_2) 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_2), fuel gas (H_2) and compressed air were 30, 20 and 30 mL/min, respectively (Zheng et al., 2011b). The standard CH_4 gas (10.2 ppm in air; provided by Chinese CRM/RM Information Center) was used to quantify the CH_4 concentrations for every 15 samples. The rate of CH_4 concentration increase (dc/dt, ppm/hr) within the static chamber was calculated as the slope of a linear regression of CH_4 concentration versus time ($R^2 > 0.90$). This value was used to obtain CH_4 emission (F, mg CH_4/(m^2·hr)) by the following equation:

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

where, ρ (kg/m^3) is the density of CH_4 in standard state (0.714 kg/m^3). 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_4 emissions from permanently flooded areas among the three counties. An independent-sample t-test was used to test the difference in mean CH_4 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_4 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_4 emissions from different drawdown sites were calculated and compared.

2 Results

2.1 CH_4 emission from permanently flooded sites

During the study period, the CH_4 emission flux from permanently flooded sites in Zigui County (mean: (0.11 ± 0.05) mg CH_4/(m^2·hr)) was significantly lower than that in Wushan County (mean: (0.39 ± 0.10) mg CH_4/(m^2·hr), $p = 0.005$) and Yunyang County (mean: (0.48 ± 0.12) mg CH_4/(m^2·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_4 emission flux from the permanently flooded sites during the entire study period

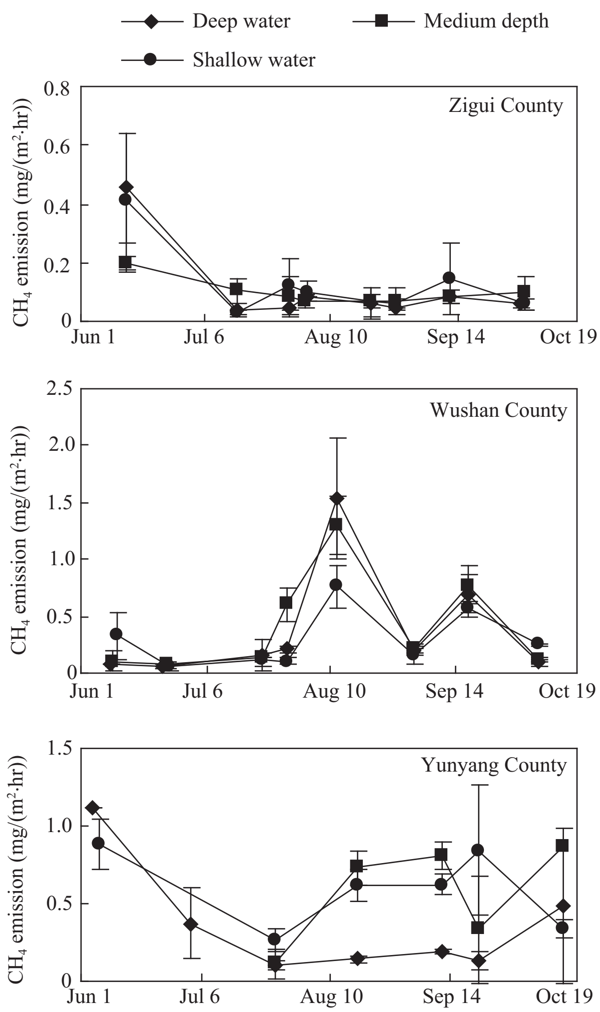

Fig. 2 CH_4 emission from water surfaces in the TGR during the sampling period in 2010.

was (0.33 ± 0.09) mg CH_4/(m^2·hr) (Fig. 2). The results of repeated-measures multivariate analyses indicated that, in Yunyang County, the CH_4 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_4 flux was found among sites of different water depths in the other two counties.

2.2 CH_4 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_4 emission fluxes were very small, ranging from a sink at 0.12 mg CH_4/(m^2·hr) to a source at 0.08 mg CH_4/(m^2·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_4 flux reached 1.38 mg CH_4/(m^2·hr) (Fig. 3). When these sites were flooded, the CH_4 emissions, which arithmetically averaged at 0.34 mg CH_4/(m^2·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_4 emission flux of (4.86 ± 2.31) mg CH_4/(m^2·hr), with a peak of 11.06 mg CH_4/(m^2·hr) at the end of June (Fig. 3). The CH_4 emission flux of the rice paddies showed a distinct pattern as compared with other kinds of drawdown sites.

3 Discussion and conclusions

The CH_4 emission fluxes from the water surface averaged (0.3305 ± 0.0940) mg CH_4/(m^2·hr) from the beginning of June to the middle of October, which was very close to the annual average CH_4 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_4 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_4 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 lever 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

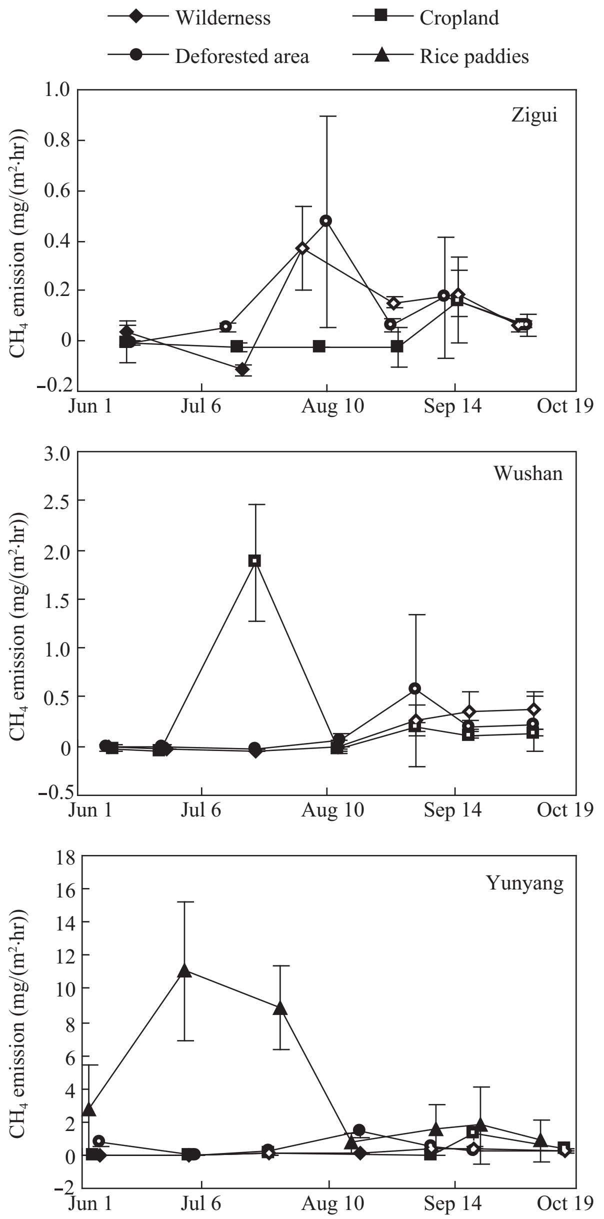

Fig. 3 CH_4 emission from drawdown areas in the TGR during the sampling period. CH_4 emissions were represented by hollow signs when the sites were below water level.

CH_4 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_4 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_4 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_4 emission greatly.

There appeared high CH_4 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_4 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_4 emissions from the drawdown area, although this influence could be site-specific.

Previous research (Rosa et al., 2004) on CH_4 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_4 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_4 emissions from the TGR. Due to these sources of variation, an estimation of CH_4 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^2 of the drawdown area, 0.3443 mg $CH_4/(m^2 \cdot hr)$ for the rest of the drawdown area (204.5 km^2) 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 $CH_4/(m^2 \cdot hr)$ for 700 km^2 of water surface, then our preliminary estimation of the total CH_4 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_4 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.

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