Methane emissions from two tundra wetlands in eastern Antarctica

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Abstract

During the summertime of 2005/2006 net methane (CH\textsubscript{4}) fluxes and environmental variables were investigated in two tundra wetlands Wolong Marsh and Tuanjie Marsh of eastern Antarctica, using the closed chamber technique. At Wolong Marsh, the measurements were made at four wet tundra sites, four mesic tundra sites, and two dry sites. CH\textsubscript{4} flux for wet tundra sites averaged 163.4 \(\mu\text{g m}^{-2}\text{h}^{-1}\) and for the mesic sites 132.4 \(\mu\text{g m}^{-2}\text{h}^{-1}\). For the dry sites, all the CH\textsubscript{4} fluxes showed the negative values with an average of −99.9 \(\mu\text{g m}^{-2}\text{h}^{-1}\). At Tuanjie Marsh, flux measurements were made at two open ponds, two shallow fens and two dry sites. The average CH\textsubscript{4} flux for the pond sites was 170.4 \(\mu\text{g m}^{-2}\text{h}^{-1}\) and for the fen sites 134.7 \(\mu\text{g m}^{-2}\text{h}^{-1}\). For the dry sites CH\textsubscript{4} fluxes were approximately one order of magnitude lower than those for pond and fen sites and averaged 18.4 \(\mu\text{g m}^{-2}\text{h}^{-1}\). Spatial variations in CH\textsubscript{4} flux were primarily driven by the water table position at two tundra wetlands, whereas temporal variations in CH\textsubscript{4} flux from wet and mesic sites were related with the thermal regime of tundra soil layers. The fluxes from six observation sites showed a consistent diurnal cycle with the peak at 14:00 and the lowest at 2:00 (local time), which was correlated with ground temperature at the depth of 0–10 cm. The CH\textsubscript{4} emissions from coastal wetlands could constitute an important part of the annual CH\textsubscript{4} budget for Antarctic tundra ecosystems.

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1. Introduction

Methane (CH\textsubscript{4}) is an important greenhouse gas, and its concentration has been increasing at the rate of 0.5–0.8% annually since the industrial revolution began and at a rate of 4.9 ppb yr\textsuperscript{-1} over the period 1992–1998 (IPCC, 2001). CH\textsubscript{4} contribution to climate forcing has been about 35% of the climate forcing by CO\textsubscript{2} and about 22% of the forcing by all long-lived greenhouse gases in the past 150 years (Lelieveld et al., 1998). Natural wetlands are an important source for CH\textsubscript{4} emission because of the prevalence of waterlogged and anoxic conditions, contributing to 24.8% of the global budget (IPCC, 2001).

Most studies of CH\textsubscript{4} flux in natural wetlands have focused on boreal regions (Bartlett et al., 1992; Morrissey and Livingston, 1992; Whalen and...
Reeburgh, 1992; Christensen et al., 1995; Nakano et al., 2000; Huttunen et al., 2003), because these ecosystems are of importance for storing about one-third of the global carbon pool in the soils (Gorham, 1991). In recent years CH4 emissions from some temperate, subtropical and tropical wetlands, and lakes have also been observed (Ding et al., 2003; Wang and Han, 2005; Xing et al., 2006; Marani and Alvalá, 2007). These studies on methane emission in high-latitude boreal and temperate wetlands indicate that CH4 flux is correlated with ground temperature (Bartlett et al., 1992; Christensen et al., 1995; MacDonald et al., 1998; Nakano et al., 2000), thaw depth (Whalen and Reeburgh, 1992), and soil moisture or position of the water table (Morrisey and Livingston, 1992; Ding et al., 2003). However, CH4 emissions from Antarctic tundra wetlands have not been extensively studied (Sun et al., 2002; Zhu and Sun, 2005).

In coastal Antarctica, tundra soils covered with mosses or lichens are part of an area free of permanent snow cover. These soils are mixed thoroughly with humus of plant and animal origin, which accumulates and decomposes. Trophic resources in the coastal tundra soils are also strongly influenced by continual input of organic matter of marine origin (e.g. penguin guano or macroalgae dispersed by wind) (Sun et al., 2000; Zdanowski and Weglen’ski, 2001). We have conducted a three-year study of CH4 fluxes from exposed normal tundra soils, particularly fertile ornithogenic soils and tundra snowpacks on the Filde’s Peninsula of western Antarctica in the summers of 1999, 2000, and 2002 (Sun et al., 2002; Zhu and Sun, 2005).

Recently, the CH4 emissions from the lakeshore soils in Garward Valley of southern Antarctica have also been preliminarily observed by Gregorich et al. (2006). However, CH4 fluxes have been observed only in these very limited areas of western and southern Antarctica, and especially the flux from the tundra of eastern Antarctica has not been observed yet (Sun et al., 2002; Zhu and Sun, 2005; Gregorich et al., 2006). Therefore CH4 fluxes from Antarctic tundra and their influencing factors are still poorly understood.

In this paper, we selected two tundra wetlands (named as Wolong Marsh and Tuanjie Marsh, respectively) of eastern Antarctica as study areas and observed CH4 fluxes from tundra wetlands in the summertime of 2005/2006 during the 22nd Chinese Antarctic Research Expedition (CHINARE-22). The objectives of this study were (1) to study temporal and spatial variations of CH4 fluxes from tundra wetlands of eastern Antarctica and (2) investigate the physical environmental parameters affecting net CH4 flux from the wetlands.

2. Materials and methods

2.1. Study area

During the summertime of 2005/2006 (December 2005–February 2006), this project was carried out at Chinese Zhongshan Station (69°23’S, 76°20’E). This research station is located on Millor Peninsula of the Larseman Hills, eastern Antarctica (Fig. 1). The Larseman Hills are located within the Antarctic Circle with an ice-free area of approximately 50 km². It has a cold and dry Antarctic climate due to the effects of circular cyclone and high pressure from the Antarctic continent (Burgess et al., 1994). According to the meteorological records from Chinese Zhongshan Station, mean annual air temperature is around −10°C. Precipitation occurs as snow and is unlikely to exceed 250 mm water equivalent annually. Mean annual relative humidity is about 60%. More than 150 freshwater lakes and tundra wetlands are found on the Larseman Hills, ranging from large water bodies to small ephemeral ponds and tundra wetlands such as Wolong Marsh and Tuanjie Marsh. Many lakes and wetlands contain some sediments or soils up to 3 m thick, comprising the fine laminae, which are interpreted as the remains of benthic microbial mats (Liu et al., 2004). The environmental background of study area has also been described by Zhu et al. (2006).

CH4 flux observation sites were set up in two tundra wetlands (named as Wolong Marsh and Tuanjie Marsh, respectively), which are located in the northeast of Millor Peninsula and separated from each other by local exposed bedrock (Fig. 1). During most of the time every year, these tundra wetlands are covered with accumulated snow and the soils are frozen. Accumulated snow and frozen soils melt, and tundra wetlands are exposed every summer (from December to February). Penguins (for example, Empire penguin and Adelie penguin) and other seabirds such as skua (C. maccormicki) can be found on the upland around the wetland during the summertime. The depositions of seabird guanos have been confirmed to strongly impact the physical and chemical properties of sediments/soils in these tundra wetlands and adjacent lakes (Liu
et al., 2004). Therefore the concentrations of nutrient elements are particularly high in these coastal tundra wetlands. The local algae community dominated by *Lynobya*, *Nostoc*, *Cosmarium*, moss cyanobacteria and bacteria form the bulk of biomass in the wetlands (Liu et al., 2004). These wetlands are partly eutrophic and a thin layer of peat has also been formed.

During the summertime of 2005/2006, a series of measurement sites for the CH$_4$ flux were selected within Wolong Marsh and Tuanjie Marsh as representative of the tundra types: dry tundra, mesic tundra, waterlogged tundra, fens and ponds (Fig. 1). The study area covered an area of about 2 km$^2$. Ten observation sites were established within three different zones of Wolong Marsh: (1) two dry tundra sites (DW1 and DW2) with little moss and algae; (2) four temporarily flooded mesic sites (GW1, GW2, GR1, and GR2) with much moss and alga; and (3) four continuously flooded wet sites (ZM1, ZM2, ZW1, and ZW2). In addition, six observation sites were also set up within three different zones of Tuanjie Marsh: (1) two dry sites (TS1 and TS2) covered by a thin layer of moss and alga; (2) two shallow fens (TR1 and TR2); and (3) two ponds (TJ1 and TJ2) with a thick layer of alga at the bottom. These sites were comprised of distinct ecosystem types and they were chosen to obtain a comprehensive representation of the coastal tundra environment, eastern Antarctica.

2.2. CH$_4$ flux measurement

The net CH$_4$ fluxes from Wolong Marsh and Tuanjie Marsh were determined by a static chamber technique at 16 observation sites along the topographic/moisture gradient (Sun et al., 2002; Zhu and Sun, 2005). A boardwalk system was constructed into the study area in December 2005 to avoid the disturbance of soil/sediment during the sampling. Open-bottomed acrylic resin cylinder chambers (inner diameter 38.5 cm × 45 cm) were placed on stainless-steel collars installed at the measurement sites for the entire study period. Only one plot was established at each site due to the limited manpower.
and local severe climatic conditions. The collars enclosed an area of about 0.12 m² and were inserted into the ground to a depth of about 10 cm below the soil or sediment surface at the dry and mesic sites. At wet tundra and pond sites, similar collars were hung by height-adjustable wooden frames keeping the lower parts of the collars about 5–10 cm below the water surface. The use of flux collars allows the same spot to be measured repetitively, minimizes site disturbance, and ensures that flux chambers are well sealed since the chambers fit into a water-filled notch in the collars.

During CH₄ flux measurements, the chambers were inserted into the water-filled notch of the collars. Headspace gas samples were transferred from the chamber into vacuum vials (17.5 ml) at 15 min intervals over a 45 min period after enclosure. These vacuum vials had been pre-evacuated to close to 0 Pa. Air was mixed inside the chambers by electrical, brushless fans. A total of four samples were collected during a flux measurement. Air temperature inside the chambers was simultaneously measured. Fluxes of CH₄ were determined two or three times every week between 9:00 and 11:00 from six sites ZW1, ZW2, GW1, GW2, TJ1, and TJ2. During the period from December 26, 2005 to February 15, 2006, CH₄ fluxes were measured 11–14 times from these six sites; Fluxes were measured only 3–7 times from other 10 sites (ZM1, ZM2, DW1, DW2, GR1, GR2, TS1, TS2, TR1, and TR2) on occasional days due to the limited manpower. To investigate the daily variations of the flux from the wetlands, CH₄ fluxes were observed by two persons at six time intervals of 2:00–2:45, 6:00–6:45, 10:00–10:45, 14:00–14:45, 18:00–18:45, and 22:00–22:45 within one day at six sites ZW1 and ZW2 (December 30–31, 2005), ZM1 and ZM2 (December 30–31, 2005), TR1 and TR2 (February 5, 2006).

CH₄ concentrations in gas samples were determined by GC using a flame ionization detector (FID) in State Key Laboratory of Soil and Sustainable Agriculture, Nanjing Institute of Soil Science, Chinese Academy of Sciences (Sun et al., 2002; Zhu and Sun, 2005). The standard gas for CH₄ is 8 ppmv demarcated by the National Institute of Japanese Agricultural Environment. The variance coefficient for standard samples was within 0.1–0.3% in 24 h. High vacuum inside the vial can maintain for a year at least (Sun et al., 2002; Zhu et al., 2005; Zhu and Sun, 2005). Gas standards for CH₄ (8 ppmv) stored in the vials also showed no significant changes in concentration during three months of storage in the laboratory or during transport from the Antarctic field site to the laboratory in China. Furthermore, we repeatedly determined the same air samples collected from Antarctica during different periods within one year in the laboratory, and found that CH₄ concentration for the same sample was almost stable, suggesting that the quality of sample air in the vials did not change. CH₄ fluxes were calculated using a linear least squares fit to four points in the time series of concentration with an average chamber temperature for each experiment. The flux rates were usually omitted if the slope of the linear fitting had a $r^2 < 0.96$. The methods for gas sampling, gas chromatography analysis, and flux calculation can be found in the references (Sun et al., 2002; Zhu and Sun, 2005).

2.3. Environmental variables and data analysis

Environmental data were in situ collected concurrently with flux measurement at both Wolong Marsh and Tuanjie Marsh. Air temperature inside the chambers was measured with a thermometer inserted into the chambers. Surface, 5 and 10 cm ground temperatures were determined with a ground thermometer inserted into the corresponding depths. The water table was monitored by digging a small well adjacent to each collar (Nakano et al., 2000; Zhu and Sun, 2005).

Statistical analysis was done with SPSS and Microsoft Excel for Window 2000. In all analyses where $p < 0.05$, the factor tested and the relationship were considered statistically significant.

3. Results

3.1. Summertime variations in CH₄ fluxes and environmental variables

3.1.1. At Wolong Marsh

The summertime variations of CH₄ fluxes from the wet site ZW1 were almost consistent with those from the site ZW2 (Fig. 2a), suggesting that small-scale variability was relatively low ($t$ test: $t = 1.41$, $p = 0.17$). CH₄ fluxes varied from $-46.7$ to $293.3$ mg m⁻² h⁻¹ at the site ZW1 and from $-72.7$ to $588.3$ mg m⁻² h⁻¹ at site ZW2. Negative CH₄ was sometimes observed under the relatively low ground temperatures at these two sites. Three CH₄ emission peaks coincided with similar peaks in the ground
temperature, suggesting that high ground temperature increased CH$_4$ fluxes from tundra wetlands (Fig. 2a). In addition, 5 and 10 cm ground temperatures showed a consistent response to changes in the surface temperatures and the temperature peak occurred around 10 January. Mean daily ground temperature, calculated from 0 to 10 cm ground temperature profile, fluctuated between $^{-2.5}$ and 20.0°C and water table ranged from 5.5 to 12.0 cm (Table 1).

The variations of CH$_4$ fluxes at two mesic sites GW1 and GW2 also showed a consistent trend, indicating a small spatial variation ($t$ test: $t = -0.42$, $p = 0.68$). CH$_4$ fluxes ranged from $-123.3$ to 394.5 µg m$^{-2}$ h$^{-1}$ at site GW1 and from $-91.0$ to 390.9 µg m$^{-2}$ h$^{-1}$ at site GW2. Three evident peaks occurred on December 31, 2005, January 26, and February 13, 2006, respectively, although these peaks did not almost coincide with similar peaks in surface–ground temperatures. The 0, 5, and 10 cm ground temperatures showed a similar summertime variation at the two sites, fluctuating between $-1.5$ and 14.3°C, which is very similar to that at sites ZW1 and ZW2. However, water table varied from 0.5 to 5.0 cm, evidently lower than that at ZW1 and ZW2.

As summarized in Table 1, the magnitudes of the flux were obviously different between the different types of tundra sites at Wolong Marsh. The CH$_4$ fluxes for the wet sites averaged 163.4 µg m$^{-2}$ h$^{-1}$ ($n = 40$) and for the mesic sites 132.4 µg m$^{-2}$ h$^{-1}$ ($n = 32$). Only a few negative CH$_4$ fluxes of the total of 72 measurements were observed at these sites. However, for the dry sites all the CH$_4$ fluxes showed negative values (net methane consumption), ranging from $-126.3$ to $-46.7$ µg m$^{-2}$ h$^{-1}$ and averaged $-99.9$ µg m$^{-2}$ h$^{-1}$ ($n = 6$). Spatial variations of CH$_4$ fluxes at Wolong Marsh can be clearly ascribed to the position of water table. As illustrated in Fig. 3a, average CH$_4$ flux and the position of water

![Fig. 2. The seasonal variation of net CH$_4$ fluxes from tundra wetlands and environmental variables in the summertime of 2005/2006. (a) Continuously flooded wet sites ZW1 and ZW2; (b) Temporarily flooded mesic sites GW1 and GW2; tundra ponds TJ1 and TJ2.](image-url)
table showed a significant positive correlation at the different types of observation sites ($r = 0.94; p = 0.02$), suggesting that water table controls spatial variations of CH$_4$ fluxes from Wolong Marsh.

### 3.1.2. At Tuanjie Marsh

As illustrated in Fig. 2c, the CH$_4$ fluxes at two pond sites TJ1 and TJ2 showed a similar summertime variation ($t$ test: $t = 1.03, p = 0.31$). CH$_4$ emissions rapidly increased with time in early January and the highest flux occurred on 12 January. Then the flux gradually decreased to the lowest on 3 February. Methane flux ranged from $-39.8$ to $224.1$ µg m$^{-2}$ h$^{-1}$ at pond site TJ1 and from $-4.2$ to $365.4$ µg m$^{-2}$ h$^{-1}$ at pond site TJ2. On average, the CH$_4$ fluxes at TJ1 and TJ2 were $105.5$ µg m$^{-2}$ h$^{-1}$ ($n = 11$) and $144.6$ µg m$^{-2}$ h$^{-1}$ ($n = 11$), respectively. The variation in flux corresponding to 0, 5, and 10 cm ground temperature fluctuation found in Wolong Marsh data was also obtained at TJ1 and TJ2. All ground temperatures also showed a consistent variation at two sites and they gradually decreased along with the position of water table.

As listed in Table 1, for the shallow fen sites TR1 and TR2 CH$_4$ fluxes averaged 134.7 µg m$^{-2}$ h$^{-1}$ ($n = 12$). For the dry sites TS1 and TS2, the fluxes were approximately one order of magnitude lower than those at the pond or fen sites with an average of 18.4 µg m$^{-2}$ h$^{-1}$ ($n = 6$). The average daily ground temperature during the observation period was 5.5°C at TJ1 and TJ2, 0.1°C at TR1 and TR2, and 0.4°C at TS1 and TS2, suggesting that the thermal regimes in the soil layers were not similar at the different types of tundra sites. Furthermore soil moisture conditions were quite different. Mean water table positions were about 5.6 cm above the surface at TJ1 and TJ2 and about 2.6 cm above the surface at TR1 and TR2, but 5.4 cm below the surface at TS1 and TS2 (Table 1). The CH$_4$ flux and water table at the different types of sites also showed a significant correlation in Tuanjie Marsh ($r = 0.999; p = 0.03$), further indicating that water table controls spatial variation of CH$_4$ emissions from the different sites (Fig. 3b).

### 3.2. Daily variations in CH$_4$ fluxes and environmental variables

A diurnal cycle in flux was obtained for six sites ZW1, ZW2, ZM1, ZM2, TR1, and TR2 (Fig. 4). The pattern of variation was the same: a maximum and a minimum occurred at 14:00 and 2:00 (local time), respectively. Some previous work reported strong diurnal fluctuation in net CH$_4$ flux from a natural northern peatland (Alm et al., 1996) and from a rice paddy (Chanton et al., 1997) at mid-latitudes. In these studies, the emission increased after sunrise and peaked around midday. Our results are almost consistent with these earlier studies.

The diurnal cycle of CH$_4$ flux from the tundra of western Antarctica was not obtained due to local unstable weather conditions (Zhu and Sun, 2005). In contrast, our study areas are located in eastern Antarctica and weather conditions are very stable (mainly clear days). The ground temperature showed an apparent diurnal variation at all the sites over this summer, which reached the peak at 10:00 or 14:00 and was lowest at 2:00 (Fig. 4a–c). Ground temperatures at different depths showed
the similar variations but surface temperature was higher than those for depths 5 and 10 cm at daytime. However, surface temperature was lower than those for other depths at nighttime. The difference between the highest and lowest temperature gradually decreased as the vertical profile depth increased. Furthermore, daily variations of ground temperatures were very consistent with those of CH₄ fluxes from all the sites, suggesting that the ground temperature was the main factor controlling daily CH₄ emissions (Fig. 4).

4. Discussion

4.1. Methane flux and environmental variables

In this study, there were a sufficient number of sites to test whether the persistent hydrological
Regime of a wetland was a critical factor in determining the magnitude of mean seasonal CH$_4$ flux from Wolong Marsh and Tuanjie Marsh. At a spatial scale water table can greatly affect net CH$_4$ flux by influencing CH$_4$ production and oxidation (Waddington et al., 1996; Ding et al., 2003). As illustrated in Fig. 3, we observed a strong positive correlation between average CH$_4$ flux and water depth in the different types of tundra environment at Wolong Marsh and Tuanjie Marsh during the summertime. In many boreal and Arctic wetlands, water table drops during summer below the soil surface, suppressing methanogenesis, stimulating methane oxidation and favoring aerobic mineralization (Juutinen et al., 2003). Other studies have found that CH$_4$ flux from wetlands and shallow lakes are correlated with the position of water table (Crill et al., 1988; Moore et al., 1990). Hence, water
The table is important as one of the main factors affecting the spatial variations of CH$_4$ fluxes from Wolong Marsh and Tuanjie Marsh.

However, no statistically significant correlation was obtained between summertime CH$_4$ flux and water table at the individual site (Table 2), suggesting that water table was not the key factor controlling the temporal variation of CH$_4$ fluxes from Wolong Marsh and Tuanjie Marsh. However, the CH$_4$ flux shows a weak correlation with ground temperature at the individual site. Furthermore, the mean 0–10 cm ground temperatures were significantly correlated with summertime CH$_4$ fluxes when more data were analyzed from the different sites (Table 2), suggesting that the temporal variations of CH$_4$ fluxes were related to the thermal regime of tundra soil layers. On the other hand, methane emissions are a function of (1) CH$_4$ production in an anaerobic zone; (2) CH$_4$ consumption in an aerobic zone; and (3) the transport mechanism by which CH$_4$ is delivered to the wetland surface. Therefore CH$_4$ emissions from Wolong Marsh and Tuanjie Marsh could not be controlled by the single environmental variable. Studies to date have also found that single-parameter relationships between environmental factor and methane flux are insufficient to predict the variation in the CH$_4$ flux from the boreal wetlands (Bartlett et al., 1992; Whalen and Reeburgh, 1992; Christensen, 1993; Christensen et al., 1995; Nakano et al., 2000). Nykänen et al. (1998) suggested that seasonal variations in CH$_4$ flux have been found to correlate with temperature at wet tundra sites, whereas at dry tundra sites the fluxes correlated only with the water table. Whalen and Reeburgh (1992) and Nakano et al. (2000) obtained the best correlations between CH$_4$ flux and centimeter-degree (the absolute value of the product of thaw soil depth and mean ground temperature). Zhu and Sun (2005) found that the correlation between the CH$_4$ flux and PT$_0$, which is the product of the precipitation and surface ground temperature, was quite strong at the tundra of western Antarctica. The moisture regime controls both the thermal conductivity and the heat capacity of the soil or sediment. Thus water table and ground temperature are not independent variables affecting summertime CH$_4$ flux from Wolong Marsh and Tuanjie Marsh.

The plants with lacuna structure are important in determining net CH$_4$ fluxes from some boreal wetlands on the Northern Hemisphere (King et al., 1998; Joabsson and Christensen, 2001). As the plant density increases, the rate of CH$_4$ transport increases through lacuna structure, so that with sufficient plant density, almost all CH$_4$ passes to the atmosphere through plant (Bazhin, 2004). However, in our study areas the majority of the surface at Wolong Marsh and Tuanjie Marsh was covered with algae and mosses, which are nonvascular, and would not be expected to act as a conduit of gas transport, suggesting that the vegetation such as algae, mosses, and lichens were not an important factor influencing CH$_4$ emission from Antarctic tundra wetlands.

Bubble ebullition may also be a significant CH$_4$ release mechanism in the boreal wetlands (Lansdown et al., 1992). CH$_4$ measurements in a variety of natural wetland systems have shown that

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**Table 2**

<table>
<thead>
<tr>
<th>Site (n)</th>
<th>Ground temperature (°C)</th>
<th>Water table (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>ZW1 (14)</td>
<td>0.685**</td>
<td>0.631*</td>
</tr>
<tr>
<td>ZW2 (14)</td>
<td>0.480</td>
<td>0.420</td>
</tr>
<tr>
<td>GW1 (10)</td>
<td>0.754*</td>
<td>0.679*</td>
</tr>
<tr>
<td>GW2 (10)</td>
<td>0.698*</td>
<td>0.660*</td>
</tr>
<tr>
<td>TJ1 (11)</td>
<td>0.783**</td>
<td>0.750**</td>
</tr>
<tr>
<td>TJ2 (11)</td>
<td>0.771**</td>
<td>0.783**</td>
</tr>
<tr>
<td>ZW1 and ZW2 (28)</td>
<td>0.507**</td>
<td>0.468*</td>
</tr>
<tr>
<td>GW1 and GW2 (20)</td>
<td>0.722**</td>
<td>0.665**</td>
</tr>
<tr>
<td>TJ1 and TJ2 (22)</td>
<td>0.737**</td>
<td>0.749*</td>
</tr>
<tr>
<td>TR1, TR2, ZM1, and ZM2 (24)</td>
<td>0.776**</td>
<td>0.718**</td>
</tr>
</tbody>
</table>

$n$ indicates the number of individual successful measurements. ND: not detection. Significant correlations: *0.05 level and **0.01 level. The data from the sites DW1, DW2, TS1, and TS2 were not analyzed due to less number of the measurements.
although bubbling does not have the same importance in all ecosystems, it does make a significant contribution to the CH$_4$ emission from wetland ecosystems (Bartlett et al., 1988). However, the frequency of the high fluxes is very low in Wolong Marsh and Tuanjie Marsh compared with the boreal wetlands (Figs. 2, 4 and Table 1), suggesting these emission fluxes may be more reasonable to be attributed to a diffusive transport mechanism. On the other hand, the CH$_4$ fluxes were considered diffusive if the linear correlation between the CH$_4$ concentration change in the chamber and the elapsed time had $r$ greater than 0.9 (Sass et al., 1992). A second criterion was that the initial concentration obtained by the linear regression (at time $t = 0$) must be close to the measured environmental air concentration (Marami and Alvalá, 2007). The fluxes observed from our study areas followed two criteria above and therefore they were taken as diffusive fluxes. The diffusion fluxes vary with the different types of tundra environment, possibly indicating the degree of nonhomogeneity of the sites in Wolong Marsh and Tuanjie Marsh.

4.2. Comparisons with other measurements

In recent years, CH$_4$ emissions from the Antarctic tundra have been measured on the Fildest Peninsula and its adjacent Ardley Island of western Antarctica and Garward Valley of southern Antarctica (Sun et al., 2002; Zhu and Sun, 2005; Gregorich et al., 2006). In this study, CH$_4$ fluxes from tundra wetlands of eastern Antarctica (from $-4.7$ to $14.1$ mg CH$_4$ m$^{-2}$ d$^{-1}$) are greatly higher than those from moss tundra (from $-1.3$ to $0.9$ mg CH$_4$ m$^{-2}$ d$^{-1}$), lichen tundra (from $-1.4$ to $0.6$ mg CH$_4$ m$^{-2}$ d$^{-1}$), and tundra snowpacks (from $-1.1$ to $0.4$ mg CH$_4$ m$^{-2}$ d$^{-1}$) on the Fildest Peninsula of western Antarctica (Sun et al., 2002; Zhu and Sun, 2005), and they are comparable to those from penguin rookeries with fertile ornithogenic soils (0.6–18.0 mg CH$_4$ m$^{-2}$ d$^{-1}$) on Ardley Island of western Antarctica (Sun et al., 2002). However, our data from tundra wetlands of eastern Antarctica are one order of magnitude lower than those from the lakeshore soils (11.5–345.6 mg CH$_4$ m$^{-2}$ d$^{-1}$) in Garwood Valley of southern Antarctica (Gregorich et al., 2006).

Net CH$_4$ fluxes from tundra and tundra-like wetlands have been extensively measured in boreal regions in the Northern Hemisphere (Bartlett et al., 1992; Whalen and Reeburgh, 1992; Christensen et al., 1995; Nakano et al., 2000; Huttunen et al., 2003), although those were observations on spatial variation in flux. These studies show that there is the fairly general coincidence that the flux from wet (waterlogged) sites is higher than that from dry and mesic sites. The fluxes from relatively dry sites are near zero and frequently negative, which is in accordance with our results (Fig. 3). CH$_4$ fluxes from dry ($-3.2$–$5.5$ mg CH$_4$ m$^{-2}$ d$^{-1}$), upland ($-2.1$–$18$ mg CH$_4$ m$^{-2}$ d$^{-1}$) and mesic ($0.3$–$12$ mg CH$_4$ m$^{-2}$ d$^{-1}$) boreal tundras are comparable with our data from eastern Antarctic tundra (Sebacher et al., 1986; Bartlett et al., 1992; Morrissey and Livingston, 1992; Nakano et al., 2000; Turetsky et al., 2002). However, the fluxes from Antarctic wet tundra are low compared to those from the wet tundra (46.8–144 mg CH$_4$ m$^{-2}$ d$^{-1}$) and grassland ($-1.9$–$73.2$ mg CH$_4$ m$^{-2}$ d$^{-1}$) in the boreal regions (Sebacher et al., 1986; Whalen and Reeburgh, 1990; Bartlett et al., 1992; Christensen et al., 1995; Tsuyuzaki et al., 2001; Huttunen et al., 2003). The summertime low temperature and little precipitation probably contribute to the small CH$_4$ flux from tundra wetlands of coastal Antarctica (Zhu and Sun, 2005).

Studies in Arctic systems indicate that wetland and tundra soils may make a significant contribution to global atmospheric input of CH$_4$ and may be highly sensitive to temperature change (Christensen et al., 1996). In coastal Antarctica, the emissions of CH$_4$ may occur mainly in key areas (i.e. sea animal colonies, ice-free marshes, lakeshore soils). These fluxes could constitute an important part of the annual CH$_4$ budget for the coastal Antarctic tundra ecosystems. However, CH$_4$ fluxes from Antarctic systems have been observed only in very limited areas (Sun et al., 2002; Zhu and Sun, 2005; Gregorich et al., 2006). For coastal Antarctic tundra, the strength as a source of atmospheric CH$_4$ and the sensitivity of the soils to potential changes in climate require further research in the future.

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