Eddy covariance based methane flux in Sundarbans mangroves, India

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We report the initial results of the methane flux measured using eddy covariance method during summer months from the world's largest mangrove ecosystem, Sundarbans of India. Mangrove ecosystems are known sources for methane (CH_4) having very high global warming potential. In order to quantify the methane flux in mangroves, an eddy covariance flux tower was recently erected in the largest unpolluted and undisturbed mangrove ecosystem in Sundarbans (India). The tower is equipped with eddy covariance flux tower instruments to continuously measure methane fluxes besides the mass and energy fluxes. This paper presents the preliminary results of methane flux variations during summer months (i.e., April and May 2012) in Sundarbans mangrove ecosystem. The mean concentrations of CH_4 emission over the study period was 1682 ± 956 ppb. The measured CH_4 fluxes computed from eddy covariance technique showed that the study area acts as a net source for CH_4 with daily mean flux of 150.22 ± 248.87 mg m^{-2} day^{-1}. The methane emission as well as its flux showed very high variability diurnally. Though the environmental conditions controlling methane emission is not yet fully understood, an attempt has been made in the present study to analyse the relationships of methane efflux with tidal activity. This present study is part of Indian Space Research Organisation–Geosphere Biosphere Program (ISRO–GBP) initiative under 'National Carbon Project'.

1. Introduction

Methane is one of the most important greenhouse gases that account for global warming by absorbing infrared radiation and thereby contributing significantly to global climate change. According to IPCC (2007), methane (CH_4) is second in importance with a radiative forcing value of 0.48 Wm^{-2} compared to that of carbon dioxide's value of 1.66 Wm^{-2}. Also, global warming potential of methane for 100 years is 25, which indicates that it traps 25 times more heat than carbon dioxide in 100 years period. It has also been reported that there was a significant increase in the pre-industrial value of atmospheric methane concentration from about 715 to 1732 ppb in early 1990s, and was 1774 ppb in 2005. Due to the increasing trend of atmospheric methane concentration, it is important to quantify the potentials of various ecosystems for their contribution to the atmospheric methane in developing global scale models for greenhouse gas emissions (IPCC 2007).

Natural wetlands, rice paddies, landfills, ruminants and other biogenic sources have contributed more than 70% to the total annual methane emission (Kreuzwieser *et al.* 2003). Among the biogenic sources, methane is produced as an intermediate and end product in microbial processes in

anoxic conditions and mostly occurs in natural wetlands and thus contributes about 20%–39% of the global source strength (IPCC 2007). Mangroves, the most productive terrestrial ecosystem and natural renewable source, which occupy a large fraction of the tropical coastline, are considered to be potential sources of organic matter due to the high rate of nutrient turnover (Robertson *et al.* 1992). Methane release in mangrove systems is significant with the methanogenesis which occurs in anoxic conditions prevailing due to tidal flooding (Schutz *et al.* 1990). However, due to limited studies and lack of continuous datasets on CH_4 fluxes from tropical mangrove ecosystems, their potential as a source of methane is yet to be determined (Kreuzwieser *et al.* 2003).

Mangroves are among the most carbon rich forests in tropics, containing an average of 1023 mg C ha^{-1} (Daniel *et al.* 2011). They are complex ecosystems with various species of trees, shrubs, animals, and microbial lives (Lekphet *et al.* 2005). Due to these complex associations of several environmental factors over mangroves, methane emissions have been uncertain, and thus the reported values over different mangrove systems have a very wide range. From the mangroves along southwestern coast of Puerto Rico the methane emission of about 4–82 mg $m^{-2}d^{-1}$ was reported (Sotomayor *et al.* 1994). Methane emission rates in mangrove wetlands in Queensland, Australia range from about 20 to 350 μg m^{-2} hr^{-1} (Kreuzwieser *et al.* 2003). Methane values ranging from about 0 to 192 mg $m^{-2}d^{-1}$ are reported from the mangroves in Tanzania (Lyimo *et al.* 2002). So far limited studies have been carried out in Sundarbans mangrove ecosystem to study carbon fluxes. Purvaja and Ramesh (2001) state that coastal wetlands are potentially significant sources of atmospheric methane with reported methane emissions from different mangrove ecosystems of south India ranging from 47.23 to 324.48 mg $m^{-2}d^{-1}$.

Most of the studies of methane emission over mangroves measured the concentration of methane using closed chamber techniques which are not so accurate for measuring methane fluxes due to their large temporal and spatial variability (Lapitan *et al.* 1999; Wille *et al.* 2008). The present study measures the vertical turbulent CH_4 flux between atmosphere and canopy interaction using eddy covariance (EC) method at the ecosystem scale. The EC flux towers have the capability to measure fluxes *in-situ*, continuously, across several hectares of ecosystem and without artifacts. The major advantages of EC method over chambers technique are the following: chambers technique determines the spatial and temporal variability at relatively small areas (cm^{-2} to m^{-2}) whereas eddy covariance methods are used to characterize temporal variability in huge areas (hundreds of m^{-2} to km^{-2}). Also the spatial extent sampled by the chamber is relatively small when compared with the spatial variation of fluxes across the ecosystem (Pavelka *et al.* 2007). Compared with chambers, the strengths for EC method are especially important for ecosystems where methane transport occurs through bubbles (ebullition), diffusion through soils, and water columns (Baldocchi and Koteen 2012). Also, the concentrations in the chamber can build up to levels where they inhibit the normal emission rate and also closed chambers alter the atmospheric pressure fluctuations normally found at the soil surface (Lapitan *et al.* 1999).

A recent survey states that measuring continuous methane fluxes using eddy covariance flux towers are done in different ecosystems (namely tundra, wetlands, meadow, rice, mixed forests, grasslands, etc.), but no tower in mangroves has been reported (Baldocchi and Koteen 2012). The present EC flux tower at Sundarbans, India stands as one of the few towers established in mangrove ecosystems across the world, which has the ability to measure both methane and carbon dioxide fluxes continuously. The present study is carried out under the submodule of 'Soil and Vegetation-Atmosphere Fluxes' of 'National Carbon Project' initiated by 'Indian Space Research Organisation', the major goal of which is to assess the carbon pools, fluxes, and net carbon balance for the terrestrial biomes in India.

The main objective of this paper is to present the diurnal variations of methane flux and their relations with frictional velocity, tidal activity, and soil temperature during summer months (i.e., April and May 2012).

2. Study area and tower instrumentation

Sundarbans, also a world heritage site, is the largest mangrove biosphere reserve in the world, spread across West Bengal, India and Bangladesh. The Indian Sundarbans delta is a part of the Ganga–Brahmaputra–Meghna river basin which is geographically situated between 21°31′–22°30′N latitudes and 88°10′–89°51′E longitudes at a mean sea level of 7 m (figure 1). The Sundarbans cover an area about 9000 km^2 which is estimated at about 34% in Indian territory and 66% in Bangladesh (Naskar *et al.* 2009). The Sundarbans is generally very humid and receives a lot of precipitation (annual average of 1800 mm). It exhibits wide diversity with a variety of tree species, the most dominant tree being *Heritiera fomes* (locally '*sundari*'), from which name Sundarbans is derived. The islands have also been as natural habitats
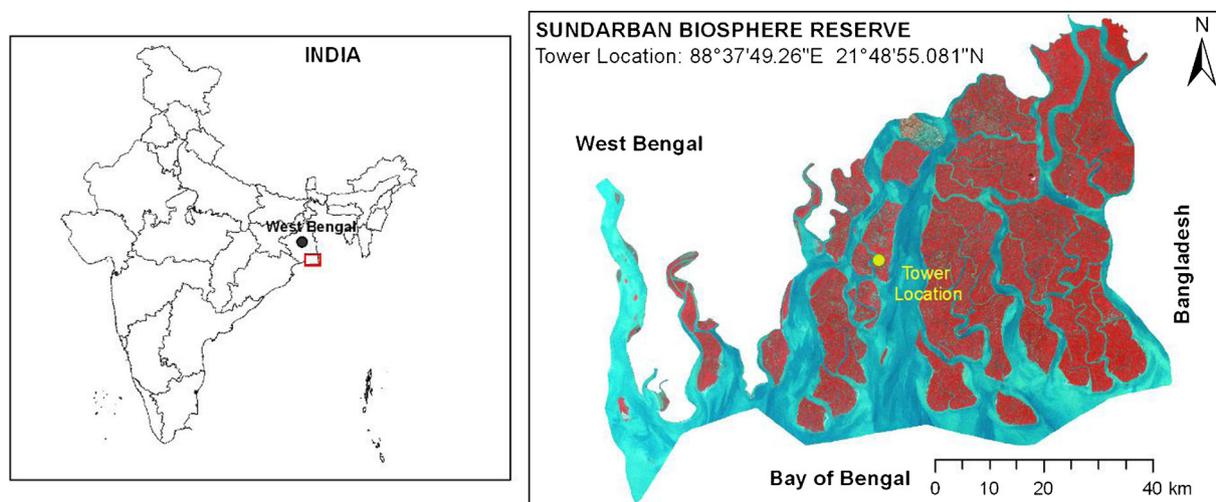
Figure 1. Location of the Sundarbans flux tower on the false colour composite (FCC) of IRS AWIFS data.

for many endangered species including the Royal Bengal tiger.

A tower of 15 m height has been established at $21°48'55''$N latitude and $88°37'49''$E longitude at a mean sea level of 3 m in an island of the Sundarbans biosphere reserve, India (figure 1). The study area is rich in a variety of mangrove species namely *Rhizophora, Avicennia alba* and *Bruguiera gymnorrhiza* with a mean height of 5 m.

Micrometeorological and trace gas (CH_4) measurements were made at a height of 10 m. A three-dimensional sonic anemometer, CSAT-3 (Campbell Sci., USA) was used to measure high frequency wind velocity components (i.e., u, v, w) and speed of sound. The concentrations of methane are measured by infrared gas analyser (IRGA) based on laser absorption spectroscopy at a frequency of 10 Hz. Open path IRGA, LI-7700 (LICOR, USA) is used for measuring concentration of methane. The Sundarbans flux tower site being an uninhabited marshy island with total dependence on solar power, LI-7700 was installed due to its low power demand and low maintenance (Peltola *et al.* 2012). The measurement range of LI-7700 is between 0 and 25 ppm with an accuracy of 5 ppb.

The slow response sensors are also installed on the tower. Wind sensors (Wind Monitor 05103, RM Young, USA) at different levels (2, 4 and 8 m) measure wind speed and wind direction. The micrometeorological parameters like temperature, relative humidity and also radiation components along with soil temperature, and soil heat flux are measured and logged on to the data logger CR3000 (Campbell Scientific Inc.) every 10 minutes.

3. Methodology

3.1 *Theoretical considerations for eddy covariance measurements*

Air flow can be imagined as a horizontal flow of numerous rotating eddies. Each eddy has 3D components, including vertical movement of air. Each air parcel has associated features such as temperature, concentration (i.e., CH_4, etc.). With the known direction of the movement of these features it can be determined whether the entity of interest is transported into or out of the pool. The basic principle of eddy covariance measurements is that the vertical flux can be calculated as covariance between concentration of the entity of interest (e.g., CH_4) and vertical wind speed in the eddies. Eddy covariance method assumes that the flow is turbulent and also the terrain is homogenous and flat (Burba and Anderson 2007). During calm and low turbulent nights the fluxes are likely to be underestimated.

3.2 *Flux data processing*

The measured concentrations of CH_4 along with high frequency wind velocity components (i.e., u, v, w) and air temperature (which is obtained from speed of sound) and also tower site bio-meteorological parameters are used to compute fluxes using Eddypro Express post processing software (version 4.1.0, LI-COR, USA, 2012).

The half-hourly processed fluxes are associated with the quality flag, according to the stationary tests and well developed turbulent based flux similarity as proposed by Mauder and Foken (2004). The quality flags 0, 1, and 2 represent data with

good, moderate and bad values, respectively. The poor quality data (quality flag = 2) and gaps are filled using mean diurnal variation (MDV) method. Though eddy covariance method is the best and most accurate way to measure ecosystem fluxes, 30–40% of the measurements are replaced with gap-filled values depending on site characteristics (Moffat *et al.* 2007; Baldocchi 2008). In the present study, about 40% of the data was filled using MDV method. MDV is a simple interpolation technique where the missing or low quality value is replaced with the averaged value of the adjacent days at exactly that time of day (Falge *et al.* 2001). The gap filled data is used and weekly average flux
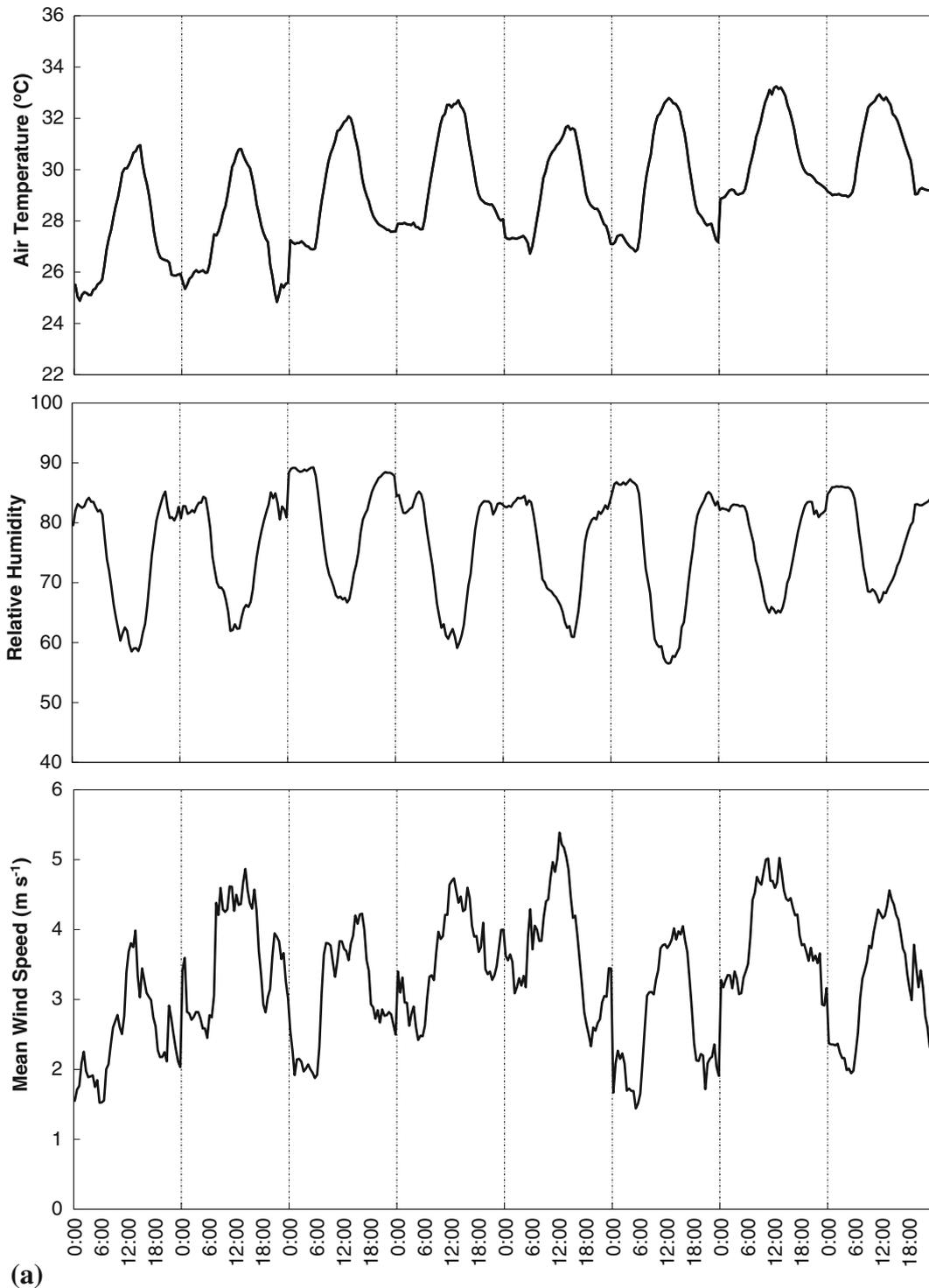

Figure 2. (**a**) The weekly average diurnal pattern of air temperature, relative humidity and wind speed during eight weeks of April and May 2012. (**b**) Predominant wind direction (south–west) during April–May 2012. Wind speed mostly ranged from 2–6 m/s^{-1}. Orange triangle represents north orientation of eddy flux tower.
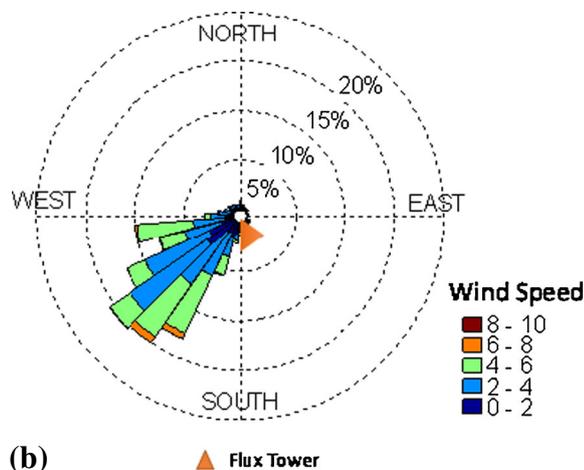
(b)

Figure 2. (*Continued.*)

curves are generated to understand the diurnal variation of methane fluxes.

The flux footprint described as an upwind area 'seen' by the instruments measuring vertical turbulent fluxes has also been estimated using the crosswind integrated footprint model using simple footprint parameterization model by Kljun *et al.* (2004).

4. Results and discussions

The footprint (or fetch) which contributes to the 90% of the total turbulent flux computations was about 240 m with a standard deviation of 20 m during the study period. The study site has recorded a daily average temperature of $29.47 \pm 1.5°C$ and

relative humidity of 76.47 ± 4.15. Figure 2(a) represents the weekly averaged diurnal pattern of air temperature, relative humidity, and wind speed at a height of 8 m from the ground. Figure 2(b) shows wind direction and wind speed plotted for the study period over the study site. The predominant wind direction is observed to be south–west during the study period, while the methane sensor (LI-7700) is orientated towards north, thus cancelling any possibility of wind distortion due to tower infrastructure.

Though mangroves are the most carbon rich ecosystems, the methane emissions significantly vary diurnally and their relations with the biophysical parameters are yet to be fully established. During the study period, the average daily methane flux was estimated at 150.22 ± 248.87 mg m^{-2} d^{-1}, showing high variability. These values imply that the study area is a source of methane with varying source strengths. The estimated methane fluxes at Sundarban mangroves are observed to be in range 47.23–324.48 mg $m^{-2}d^{-1}$ with the flux estimates at Pichavaram mangroves of south India (Purvaja and Ramesh 2001). The mean concentration of CH_4 during the study period was 1.18 mg m^{-3} (or 1682 ppb), similar to the range of the earlier reported methane concentrations (i.e., 0.903 ± 0.318 mg m^{-3}) using gas chromatography in some of the islands in Sundarbans (Mukhophadhya *et al.* 2001).

The summer months are important since we expect high methane releases due to high temperature and moisture contents. The weekly average diurnal values of methane fluxes varied from –0.5 to 1.5 µmol m^{-2} s^1 in the study period (figure 3).
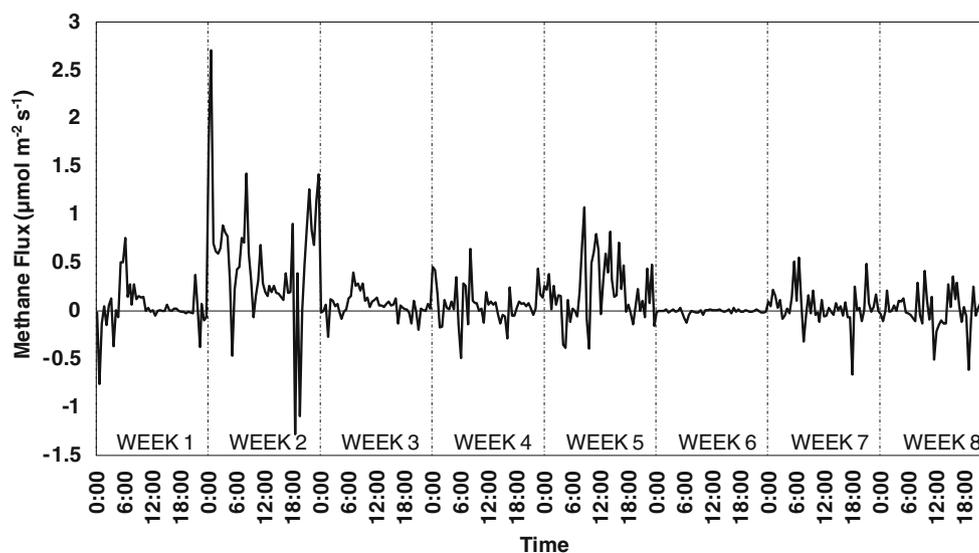

Figure 3. Weekly average diurnal pattern of methane flux observed during eight weeks of the study period. Weeks 1–4 represent April 2012 and weeks 5–8 represent May 2012.

Previous studies carried out across Sundarbans mangrove ecosystem measuring methane fluxes using micrometeorological method reported fluxes between 4.53 and 8.88 μg m^{-2}s^{-1} (Mukhopadhya *et al.* 2002).

The data analysis showed the presence of low quality flagged data points that might have resulted due to several environmental conditions not fulfilling the assumptions needed for eddy covariance procedure as mentioned above and for such datasets, gap filling using MDV was carried out. Figure 4 shows the gap filled methane fluxes for representative days (i.e., 17–19 April 2012). In order to model methane fluxes for regional estimate, relations with environmental variables are to be understood. The process of methane production, transport, oxidation, and emission are complex (Abril and Borges 2005) and are hardly established. However, an attempt has been made to understand the variability of methane flux with frictional velocity, soil temperature and tidal activity (Lekphet *et al.* 2005; Wille *et al.* 2008). Frictional velocity, the measure of turbulence over the surface which largely depends on wind velocity is found to be directly related to daily methane efflux though with some amount of scatter (figure 5). The methane flux increases with the frictional velocity during the study period.

The correlation of methane flux with tidal activity is not uniform and yet to be established (Lekphet *et al.* 2003, 2005). The studies carried out in eastern and southern coasts of Thailand showed different relations with high and low tides. The study at eastern coast reported that methane release during high tides was less in comparison with low tides since the process of CH_4 transportation from sediments to the atmosphere is hindered by water inundation (Lekphet *et al.* 2003). The study over Ranong Province, southern coast of Thailand reported that the methane release during low tides was low due to the oxidation state of soil affecting the burrows and cracks (Lekphet *et al.* 2005). Figure 6 shows methane fluxes with respect to tidal activity for the study area. The tidal charts for the nearest location of the tower (Sagar Island, India) were predicted using 'XTide Tide Prediction Server'. The preliminary results suggested that the integrated methane flux during high tides (5.73 g m^{-2}) was found to be about 80% more than the methane flux during low tides (3.18 g m^{-2}) for the study period. This suggests that high methane flux followed high tide. However, more seasonal datasets of methane fluxes over the study area are required to establish relations with tidal activity.

Figure 7 shows the relation between methane fluxes and the soil temperature. The methane
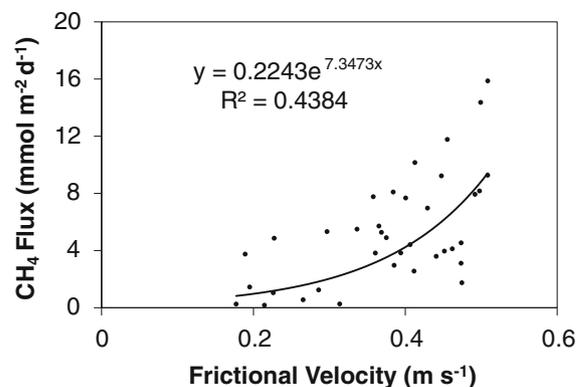
Figure 5. The exponential relation obtained between frictional velocities averaged per day *versus* the total methane flux per day during the study period.
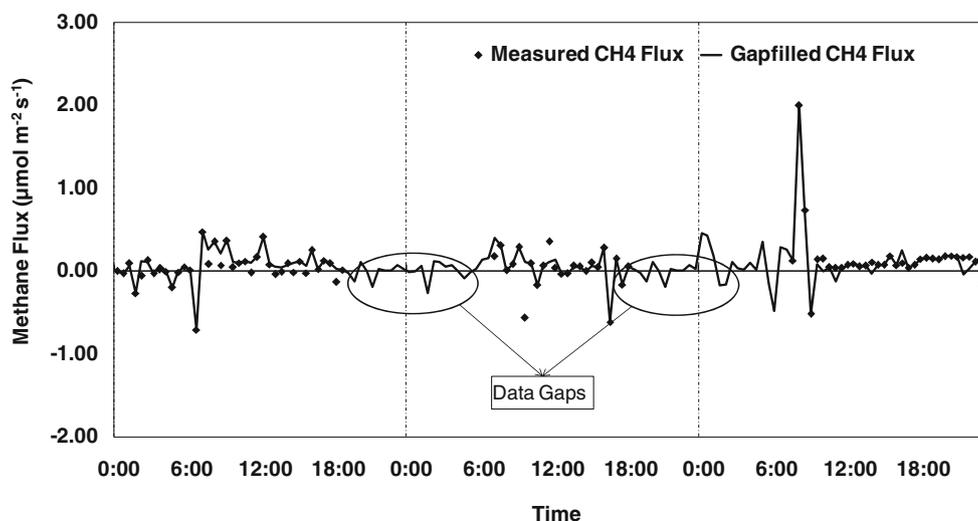
Figure 4. The measured methane flux during 20 to 22 April 2012. Points represent actual measurements. Data gaps are shown in circles. MDV method based gap filled methane flux is represented in line.
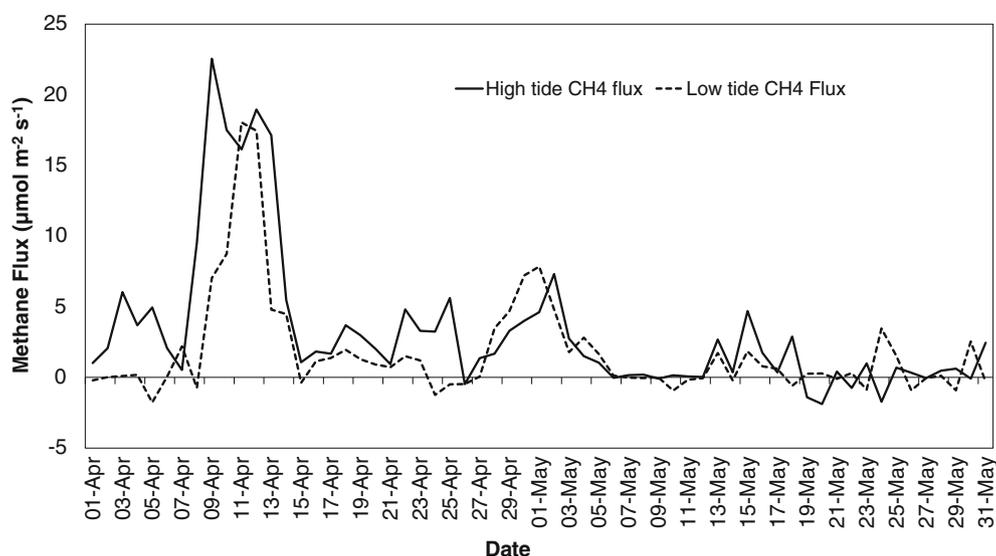
Figure 6. The daily methane flux partitioned into fluxes during high tide and low tide periods for the study period.
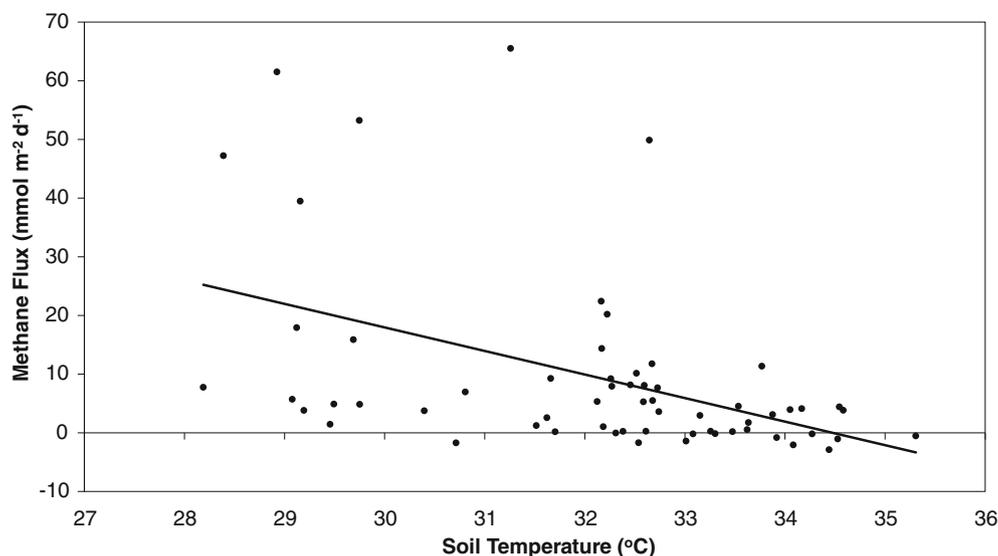

Figure 7. The relationship between total methane fluxes per day *versus* the averaged soil temperature per day during the study period.

fluxes decreased with increase in soil temperature during the study period with a low correlation coefficient ($r = 0.45$; $p < 0.001$).

5. Conclusion

The eddy covariance tower establishment in the marshy mangrove has been able to provide uninterrupted data on the environmental parameters as well as the half-hourly computed flux. Due to its high temporal resolution, the diurnal and seasonal variability of the parameters of interest could be quantified with high accuracy and reliability. Though it is known that there is large uncertainty in the methane emission due to the dynamic nature, range, and sources of methane, an attempt has been made to address the environmental control of methane emission with preliminary results from Sundarbans flux tower, which is one of the very few in mangroves across the world. However, long term datasets with continuous monitoring would provide better understanding of interrelationships between CH_4 emission with soil temperature and frictional velocity.

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