DOI: 10.1007/s002670010169

RESEARCH

Natural and Anthropogenic Methane Emission from Coastal Wetlands of South India

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ABSTRACT / For the first time, the methane emissions from diverse coastal wetlands of South India have been measured. Annual emission rates varied widely, ranging from 3.10 mg/m^2/hr (Bay of Bengal) to 21.56 mg/m^2/hr (Adyar River), based on nature of the perturbance to each of the ecosystems studied. Distinct seasonality in methane emission was noticed in an unpolluted ecosystem (mangrove: 7.38 mg/m^2/hr) and over a twofold increase was evident in the ecosystem that was disturbed by human activities (21.56 mg/m^2/hr). The wide ranges in estimate suggest that methanogenesis occurs by both natural and anthropogenic activities in these coastal wetlands. Several physical and chemical factors such as salinity, sulfate, oxygen, and organic matter content influenced methanogenesis to a large degree in each of these ecosystems in addition to individual responses to human-induced stress. For example, there was a clear negative correlation between oxygen availability (0.99), sulfate (0.98), and salinity (0.98) with CH_4 emission in the Adyar river ecosystem. Although similar results were obtained for the other wetland ecosystems, CH_4 emission was largely influenced by tidal fluctuations, resulting in a concomitant increase in methanogenesis with high sulfate concentrations. This study demonstrates that coastal wetlands are potentially significant sources of atmospheric methane and could be a greater source if anthropogenic perturbations continue at the current rate.

The past and current increase in the level of methane (CH_4) from both natural and anthropogenic sources and, more precisely, its likely effect on climate warming is a cause for concern. This concern has generated the need for quantifying the potential of individual ecosystems as sources or sinks for atmospheric methane. Because methanogenesis is obligately anaerobic, it generally occurs at high rates in systems that are continuously water-saturated and rich in organic matter, such as natural wetlands and rice paddies. Since wetlands are believed to be the single largest source of CH_4, extensive effort was made to quantify their emission rates to the atmosphere. The current estimate of CH_4 emission from natural wetlands is between 55 and 150 Tg CH_4/yr corresponding approximately to 20% of the total global CH_4 release (IPCC 1994). The uncertainty in the range of these estimates over the past few years has diminished only slightly. This is due to a number of difficulties that arise when sampling wetland areas. Although CH_4 production in wetlands occurs through strictly anaerobic bacteria, CH_4 oxidizing bacteria (aerobic) may partially oxidize the CH_4 formed in deeper soil layers as it passes through the soil to the atmosphere. In marine sediments and in some saline inland waters, there is evidence for anaerobic CH_4 oxidation (Iversen and Joergensen 1985, Iversen and others 1987). Both processes, and therefore the resulting CH_4 emissions, are very sensitive to a large number of parameters such as water table depth, soil temperature, and carbon content. Freshwater wetlands, including rice paddies have been studied intensively (Aselmann and Crützen 1989; Cicerone and Oremland 1988; Wassmann and others 1993) whereas studies on coastal wetlands, which are also significant sources of atmospheric CH_4, are rudimentary. On the other hand, we have only scant information available on natural wetlands and on tropical and saline wetlands in particular.

Studies by Atkinson and Hall (1976), King and Wiebe (1978) Bartlett and others (1985), 1987), DeLaune and others (1983), and Magenheimer and others (1996) indicate that methane emissions from various coastal salt marshes in the temperate zones vary with salinity and vegetation. Coastal wetlands, particularly the mangrove ecosystems in the tropics, by virtue of their higher temperature, high organic matter content, and biological productivity are also considerable CH_4 sources to the atmosphere. Individual emission rates ranging from 23.40 mg/m^2/day to 162.24 mg/m^2/day have been recorded from the Pichavaram mangroves of south India (Purvaja 1995). Although Harriss and others (1988) and Bartlett and others (1989) reported negligible fluxes from salt water mangroves,

KEY WORDS: Methane emissions, Coastal wetlands; Mangroves; Lagoon; River; Estuary; Pollution

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Barber and others (1988) estimated a diffusive flux of 82 mg/m^2/day in a brackish water mangrove pond in Florida. More recently, Sotomayor and others (1994) have reported values between 4 and 82 mg/m^2/day for the mangroves along the southwestern coast of Puerto Rico. Thus fluxes have been found to vary geographically, based on the localized variations in natural factors such as temperature, salinity, methane concentration gradient, and the organic carbon content of these wetlands (Dacey and others 1994, Howes and others 1985). Additionally, several human-induced factors, such as disposal of sewage and agricultural runoff into these ecosystems, further enhance CH_4 emissions to the atmosphere.

Methane emission from wetland sources is controlled by several physical processes, such as diffusion, ebullition and ventilation, and biological processes, such as microbial production and consumption. Being an anoxic environment, the methanogenic capability of the mangrove soils is enhanced to large extent. Furthermore, the specialized root system (pneumatophores) developed for gas diffusion into the anoxic zones may facilitate CH_4 transport from this soil. Dacey and Klug (1979) and Sebacher and others (1986) reported that wetland plants constitute an effective pathway between the sediment and the atmosphere as their aerenchyma serves as a conduit for the diffusion of gases such as O_2 and/or CH_4. While O_2 diffuses downward from the atmosphere to the soil layers, an upward transport of CH_4 takes place from the methane-rich soil layers to the atmosphere (Purvaja 1995). There may also be certain O_2-rich zones in the soil, due to a leak from the plant roots, resulting in oxidized conditions in the rhizosphere (Crowder and others 1987, Trolldenier 1988). Hence the net flux of CH_4 to the atmosphere is controlled by the amount of CH_4 oxidation–production balance (Giani and others 1996, Priemé 1994). In this study, we quantified CH_4 emissions from an unpolluted mangrove ecosystem, a polluted river, an estuary, a lagoon, a man-made canal, and the ocean (Bay of Bengal). Our objective was to understand the CH_4 emission capability of these under-represented ecosystems to natural and anthropogenic influences in a better way.

Materials and Methods

Field Site

Field measurements of CH_4 emission were undertaken at six major coastal ecosystems (Figure 1) in the southeastern coastal state of Tamil Nadu, India. The coastline of Tamil Nadu extends about 1000 km, with varied ecosystems such as mangroves, deltas, lagoons, rivers, estuaries, and coral reefs. The following six different coastal wetlands were identified for this study: rivers (Adyar River); estuaries (Adyar estuary); man-made canals (Buckingham Canal); mangroves (Pichavaram); lagoon (Ennore Creek); and ocean (Bay of Bengal).

The luxuriant mangroves along the Cauvery Delta (Pichavaram mangroves) represents the unpolluted site. Detailed flux measurements were carried out at the Pichavaram mangroves (latitude 11°27′N, longitude 79°47′E) covering an area of 1400 ha; the area is traversed by a large number of channels and creeks connecting two major rivers, the Coleroon in the south and the Vellar in the north. A total of 51 islets were identified in the mangrove area, which are separated by intricate waterways connecting the two river systems. About 40% of the total mangrove area is covered by waterways, 50% by forests and mudflats, while sandflats accounted for the remaining area. The Pichavaram mangrove is separated from the Bay of Bengal by a narrow sand bar during summer and is periodically flooded by the incoming tidal waters. The maximum depth of water in the mangrove area varies between 3 and 4 m near the main channel and the minimum depth ranges from 30 to 50 cm with a mean depth of 1.5 m. Semidiurnal tides flush this ecosystem with a fluctuating amplitude of 0.5–1 m. The muddy bottom sediments are exposed at extreme low tides during summer. Three different zones based on salinity gradient and species diversity were identified for this study: high salinity (>33‰), intermediate salinity (15–25‰), and low salinity (<15‰). This unimpacted "fringe" mangrove is a protected natural marine sanctuary and receives freshwater from the two riverine sources and through rainfall. Additionally, it receives negligible amounts of agricultural runoff from the adjacent paddy fields, the effects of which may impact the low-salinity zone.

The Ennore Creek, Adyar River, and the Buckingham Canal are located close to Madras city, thus representing ecosystems with immense human impact. The Bay of Bengal represents the site with the highest influence of salinity. Extensive field measurement of CH_4 flux was made at each of these wetlands and is described in detail below.

Methane Flux

Time varying fluxes of CH_4 were measured in all the coastal ecosystems at monthly intervals for one year, using the static chamber technique. The flux chambers were made of Perspex [53 × 37 × 71 cm, length/width/height), which was placed on the groves of an aluminum base (57 × 37 × 10 cm length/width/height). The metal

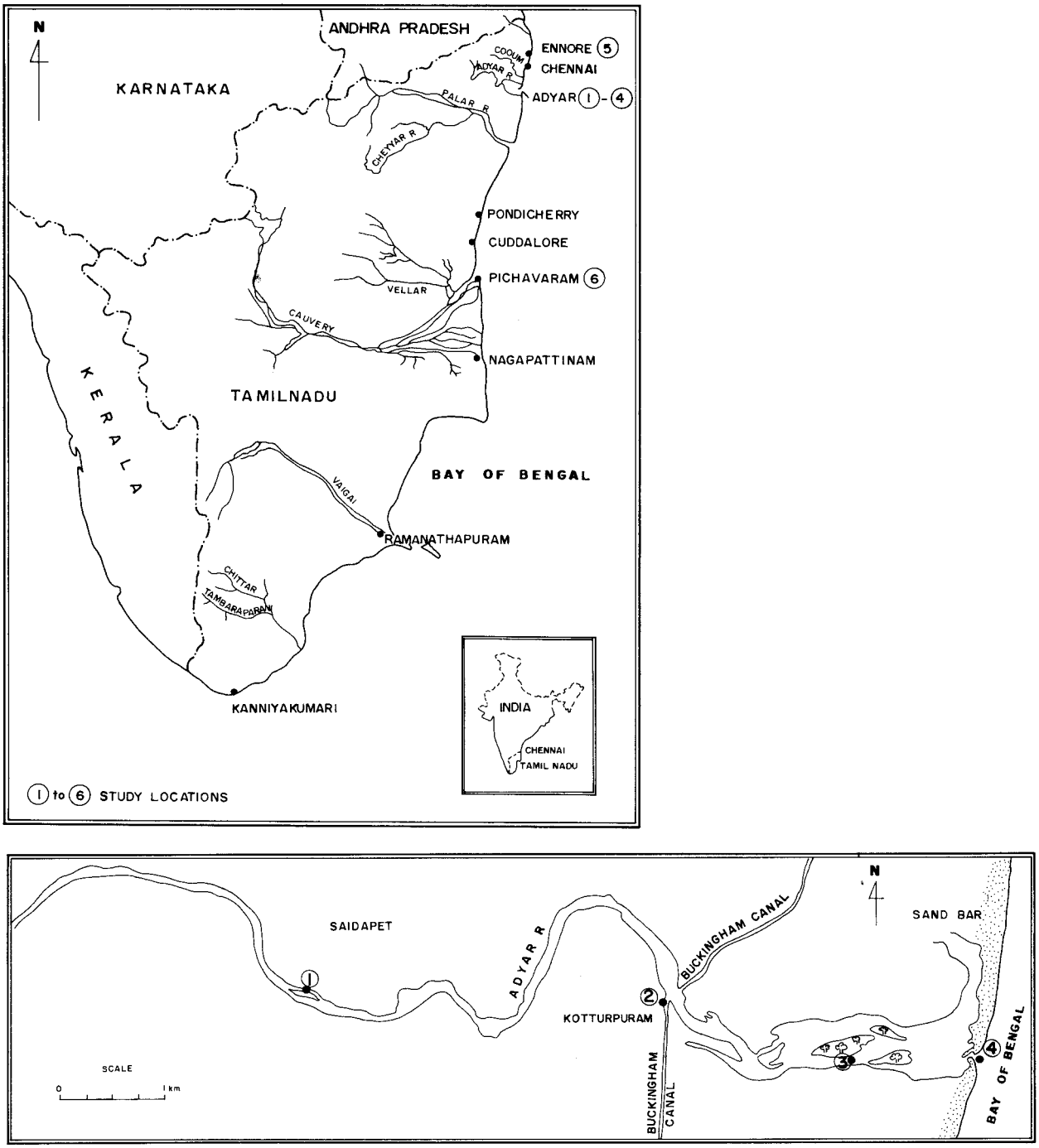

Figure 1. Map of Tamil Nadu with the sampling locations. 1: river (Adyar river); 2: estuary (Adyar estuary); 3: man-made canal (Buckingham Canal); 4: ocean (Bay of Bengal); 5: lagoon (Ennore Creek); 6: mangroves (Pichavaram).

base was inserted into the sediment column for about 10 cm, over which the chamber was placed to form a trap for the gases emanating from the sediment–water interface. The base was in place for at least 6 hr before the first gas sampling was made. In the mangrove site, the aluminum base was placed carefully between the intricate pneumatophores of *Avicennia marina*. The open end of the Perspex chamber was placed on the aluminum base and immersed in water so that the air inside the chamber was isolated from the outside atmosphere making the system

Table 1. Monthly methane efflux (mg/m^2/hr) from coastal wetlands of South India[a]

Month	Pichavaram Mangrove	Adyar Estuary	Adyar River	Ennore Creek Lagoon	Bay of Bengal	Buckingham Canal
January	3.96 ± 0.19	2.20 ± 0.11	22.27 ± 1.11	5.43 ± 0.27	1.92 ± 0.06	1.15 ± 0.05
February	9.13 ± 0.45	28.39 ± 1.41	22.94 ± 1.15	3.31 ± 0.16	1.97 ± 0.13	2.30 ± 0.12
March	3.60 ± 0.18	20.30 ± 1.01	33.60 ± 1.68	1.54 ± 0.07	3.75 ± 0.34	7.70 ± 0.46
April	4.60 ± 0.23	8.40 ± 0.42	38.90 ± 1.95	2.29 ± 0.11	7.10 ± 0.46	12.37 ± 0.59
May	11.34 ± 0.56	18.60 ± 0.93	42.56 ± 2.12	2.01 ± 0.10	8.59 ± 0.82	30.34 ± 1.30
June	9.02 ± 0.45	5.94 ± 0.29	18.42 ± 0.92	3.71 ± 0.18	2.12 ± 0.09	6.30 ± 0.39
July	8.67 ± 0.43	4.01 ± 0.20	21.20 ± 1.06	1.68 ± 0.08	0.58 ± 0.01	4.62 ± 0.28
August	13.52 ± 0.67	23.24 ± 1.16	22.12 ± 1.06	0.52 ± 0.02	0.47 ± 0.01	2.73 ± 0.14
September	7.98 ± 0.39	22.50 ± 1.11	23.24 ± 1.16	5.05 ± 0.25	2.70 ± 0.14	3.92 ± 0.16
October	11.35 ± 0.56	2.67 ± 0.13	7.02 ± 0.35	11.28 ± 0.56	3.98 ± 0.15	1.83 ± 0.09
November	1.97 ± 0.09	2.75 ± 0.13	1.91 ± 0.09	3.13 ± 0.15	1.98 ± 0.08	19.45 ± 1.50
December	3.37 ± 0.16	45.97 ± 2.29	4.50 ± 0.22	20.30 ± 1.01	2.04 ± 0.09	2.91 ± 0.12
Range	1.97–13.52	2.20–45.97	1.91–42.56	0.52–20.30	0.47–8.59	1.15–30.34
Average	7.38	15.41	21.56	5.02	3.10	7.98

[a]Refer Figure 1 for locations. The values are means ± SD of four replicates.

airtight. A battery-operated air circulation pump with a flow rate of 1.5 liters/min (obtained from M/S Aerovironment Inc., Monrovia, California, USA) was connected to mix the air inside the chamber and was also used to transfer the air sample from the chamber to the sampling bottle. The samples were collected in glass bottles fitted with a Teflon septum, at regular intervals of 15 min for an hour in the morning and in the afternoon. The glass bottles were initially filled with N_2 bubbled water after evacuation of other gaseous contaminants with N_2 gas. The gas samples were then collected into the sampling bottles using a pulse pump by displacing the water within the glass bottles and were sealed once all the water had been replaced by the air sample from within the chamber. We also monitored the air, water, and soil temperatures in situ. In addition, water level fluctuations within the chamber were continuously monitored. Gas samples were analyzed for CH_4 using a Hewlett Packard Gas Chromatograph 5890 fitted with a flame ionization detector and Porapak Q column (Ramesh and others 1997). Column, injector, and detector temperatures were 60°, 100° and 250°C, respectively, with N_2 gas as carrier, and a flow rate of 30 ml/min was maintained during analysis. The gas chromatograph was calibrated before and after each set of measurements using 1.77 parts per million by volume (ppmv) CH_4 in N_2 obtained from M/S Matheson Inc., as primary standard (±1%). The CH_4 efflux from individual sites was extrapolated to annual rates from the Indian coastal wetland areas by using the following equation:

$$CH_4(10^9\ g/yr) = \frac{CH_4\ efflux(mg/m^2/hr) \times 24\ h \times 365\ days \times area\ of\ wetlands\ (km^2)}{10^9}$$

Water samples were fixed with manganous sulfate and alkaline iodide to estimate the dissolved oxygen content (Winkler method). These samples were also analyzed for sulfate (using a turbidimetry method) and salinity (by Mohr's titration). A detailed methodology is given in Ramesh and Anbu (1996). For the estimation of organic matter, a known quantity of the sediment was oxidized with hydrogen peroxide (H_2O_2). The difference in weight before and after addition of H_2O_2 was used to determine the organic matter content (percentage) in these sediments. The soil moisture (grams H_2O per 100 gram fresh soil) was determined gravimetrically.

Results and Discussion

Monthly Variation of Methane from Natural Coastal Wetlands

At the mangrove site, the annual methane efflux (Table 1, Figure 2) varied from 1.97 to 13.52 mg/m^2/hr. A first peak (9.13 mg/m^2/hr) appeared after the monsoon (February), a second peak (11.34 mg/m^2/hr) in summer (May), while the annual maximum in CH_4 emission (13.52 mg/m^2/hr) was observed during

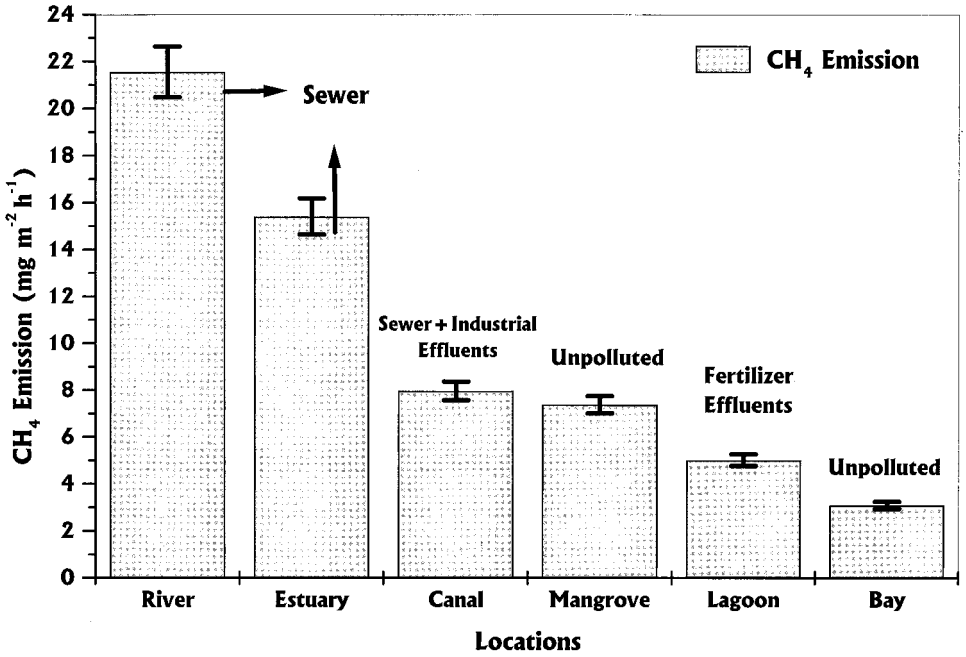

Figure 2. Average annual methane emission from the coastal wetlands of South India.

Table 2. Spatial and seasonal variation in organic matter (%) and CH_4 efflux (mg/m^2/hr) in Pichavaram mangroves[a]

	Intermediate salinity zone				Highly saline	
	Location 1		Location 2		Location 3	
Season	Org. matter	CH_4 efflux	Org. matter	CH_4 efflux	Org. matter	CH_4 efflux
Postmonsoon (January–March)	10.50 ± 0.53	7.80 ± 0.39	10.60 ± 0.53	5.61 ± 0.28	4.30 ± 0.22	4.32 ± 0.21
Summer (April–June)	12.80 ± 0.64	12.20 ± 0.61	12.90 ± 0.65	8.34 ± 0.41	5.10 ± 0.26	6.15 ± 0.31
Premonsoon (July–September)	13.60 ± 0.68	14.92 ± 0.75	14.20 ± 0.71	10.01 ± 0.5	5.80 ± 0.29	5.16 ± 0.26
Monsoon (October–December)	9.40 ± 0.47	5.97 ± 0.30	9.70 ± 0.49	5.39 ± 0.27	4.20 ± 0.21	4.68 ± 0.23

[a]The values are means ± SD of four replicates.

the premonsoon season (August). These peaks are a result of both a rise in soil temperature and the degradation of organic matter in this study area. Conrad (1989) proposed that if the supply of organic matter is not limiting, increasing temperatures generally stimulate CH_4 production in most methanogenic environments and the same was observed in this study. During the wet season (November–December), immediately following monsoon, the height of the flood waters (~1.0 m) may have restricted the transfer of methane from the subsurface to the atmosphere resulting in a decrease in CH_4 efflux rates. It was also observed that CH_4 emission was not appreciable until oxygen became limited (Purvaja 1995). Additionally, inputs from decaying foliage and debris provided a large amount of organic matter in the sediments of this zone. In general over 50% of the mangrove litter production is converted to soil organic matter in such undisturbed ecosystems (Purvaja 1995). This may have resulted in the high accumulation of organic matter (13.6%) in the mangrove area (Table 2). Furthermore, the high rate of decomposition of organic matter in summer creates oxygen stress, eventually resulting in the formation of CH_4 in the subsurface. A strong positive correlation ($r^2 = 0.96$) between soil organic matter and CH_4 efflux was observed for the Pichavaram mangroves (Table 2). During summer, organic matter degradation was enhanced by higher temperatures, leading to an increased emission of CH_4 from the subsurface to the atmosphere. In principle, CH_4 production and emission could be expected to be more or less proportional to the input of organic carbon.

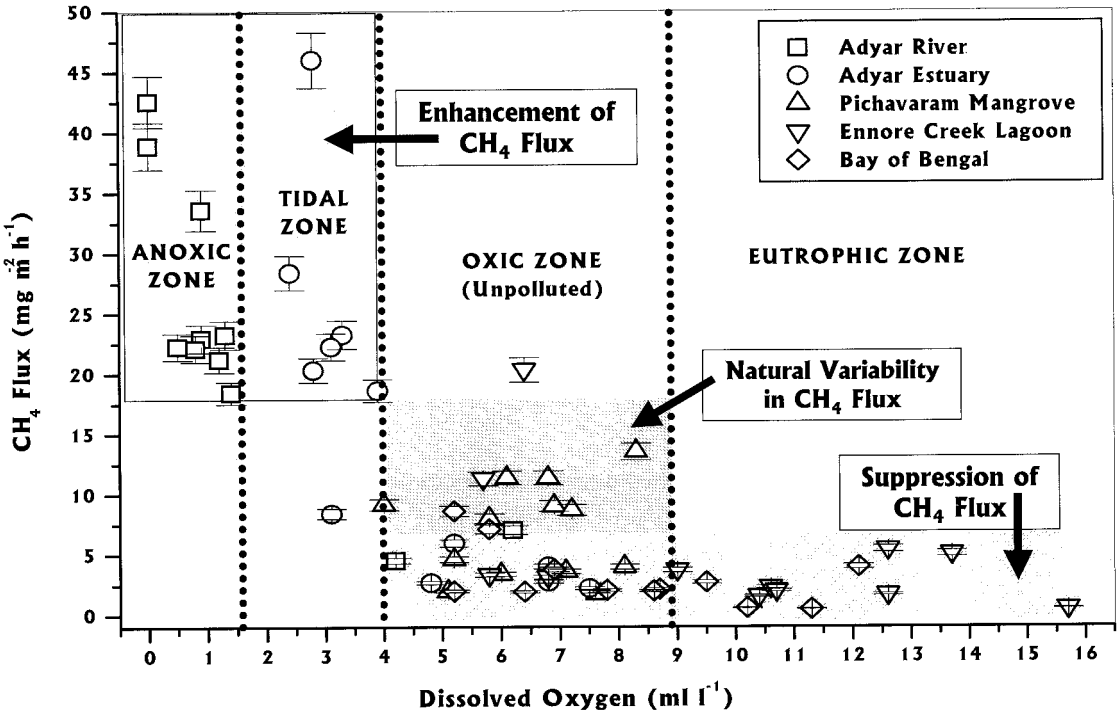

Figure 3. Effect of dissolved oxygen concentration on methane flux from the coastal wetlands of South India.

Monthly Variations of Methane from Anthropogenic Coastal Wetlands

Methanogenesis in the polluted wetlands of the present study was almost entirely governed by the magnitude of human perturbation in each of these wetlands. Erratic dumping of sullage, discharge of domestic sewage, and industrial effluents into the coastal ecosystems caused brief periods of enhanced CH_4 emission (Table 1, Figure 2).

Buckingham Canal, in particular, has a high loading of industrial contaminants such as phenols and tannery effluents due to discharge from the major industrial complexes. The Adyar River and estuary also receives large quantities of industrial effluents both directly and through the Buckingham Canal. The results obtained in the present study show a twofold difference in annual CH_4 emission between the unpolluted and polluted coastal wetlands. This suggests that anthropogenic additions of organic matter, in addition to increasing temperatures, can cause rapid formation of CH_4 in tropical coastal wetland ecosystems. New global figures for the emission of CH_4 from domestic sewage range from 15 to 80 Tg/yr with an average of 25 Tg/yr (IPCC 1994). Abrupt and unpredictable changes in emission characteristics were observed at the Adyar estuary (2.2–45.97 mg/m^2/hr) with several intermediate peaks (Table 1) as a result of anthropogenic disturbances to the ecosystem. Monthly fluxes also varied with the quantity and quality of domestic effluents discharged into the estuary as well as with tidal inundation. The concentration of industries and population (over 6 million) in the metropolitan area of Madras city has led to heavy pollution of the major waterways and the adjoining coastal waters, due to inadequate management of wastes. It has been estimated that about 8 million liters of domestic sewage is added to the Adyar river and its estuary every day. The biological oxygen demand (BOD) of the river and estuarine waters was always over 70 mg/liter suggesting very high organic pollution of the waterways (Ramesh and others 1997).

Thus, the emission of CH_4 to the atmosphere at the Adyar river and estuary is a result of anthropogenic discharge of domestic wastes into the waterways, leading to severe oxygen stress (Figure 3) and frequent anaerobic conditions. However, the influence of the tides (especially in the estuarine area) also led to the dilution and dispersion of sewage from the enclosed area, providing oxygen supply for brief periods. The result of this periodic dilution by tides, in addition to the continuous input of domestic wastes from land-based sources caused significant and abrupt changes in CH_4 emission to the atmosphere (Figure 3). Increasing population density on the coast has also resulted in physical, chemical, and biological alterations to coastal

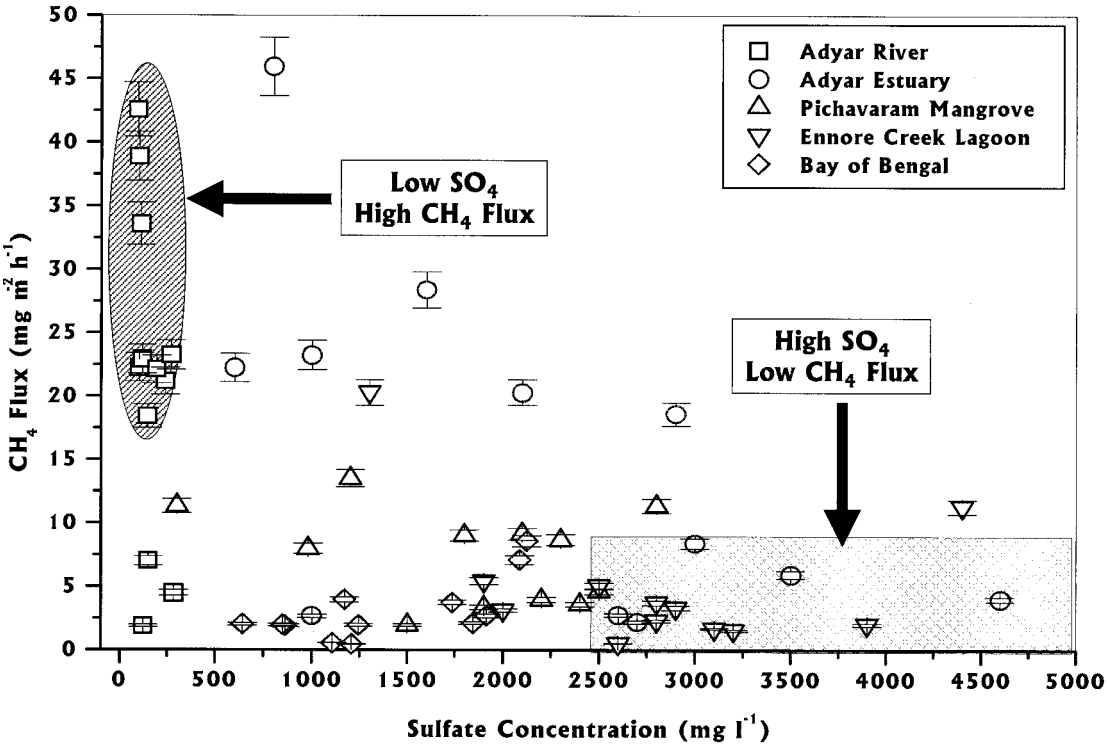

Figure 4. Influence of sulfate on methane flux from the coastal wetlands of South India.

environments that adversely affect the emission of CH_4 from the coastal ecosystems.

The subsurface to atmosphere exchange of CH_4 was less pronounced during most of the year (January–August) at the Ennore Creek lagoon (1.54–5.05 mg/m^2/hr) and larger peaks were observed during September (11.28 mg/m^2/hr) and December (20.3 mg/m/hr). We assume this feature is due to the continuous coating of crude oil effluents on the sediments of the Ennore Creek, which suppressed gaseous exchange with the atmosphere, resulting in low emission rates from this site. However, during monsoon, the topsoil containing crude oil effluents was washed away by surface runoff enabling free exchange of gases from the subsurface to the atmosphere, thereby accounting for peak emission rates during the later part of the year.

The surface–atmosphere exchange of CH_4 was less pronounced at the Bay of Bengal (0.47–8.59 mg/m^2/hr) probably due to the inhibiting influence of sea water, which has high salinity and sulfate content. The obvious decline in CH_4 concentration with increasing salinity and sulfate content can be seen from Figures 4 and 5, respectively. Marine wetlands such as mangroves and estuaries are not considered to be a major source of atmospheric CH_4 due to the inhibiting influence of high concentrations of SO_4 in seawater. Sulfate content in water was extremely high in all the wetland systems studied, ranging from <100 to >3000 mg/liter (Figure 5) and corresponding to tidal influence and seasonal precipitation. Much work has been done on the competitive interactions, especially with regard to methanogens and sulfur-reducing bacteria (Sansone and Martens 1981, Giani and others 1996). In such environments, sulfur reducers will out-compete methanogens for H_2 and acetate because these two substrates are the most important CH_4 precursors in many anaerobic environments. The removal of these competitive substrates by the sulfur reducers restricts their availability for the methanogens (Lovely and Klug 1983).

At the estuarine and mangrove sites, however, the emission of CH_4 was high, despite high sulfate content in the water and sediments (Figure 5). These sites are thus typical examples for the coexistence of methanogenesis as well as sulfate reducers, as observed by Oremland and King (1988). It is believed that several compounds such as methanol, methylated amines (trimethyl amine), and dimethyl sulfide (DMS), termed non-competitive substrates, exist for which sulfate reducers do not have strong affinity as they do for H_2 and acetate. These noncompetitive substrates are important CH_4 precursors in saline

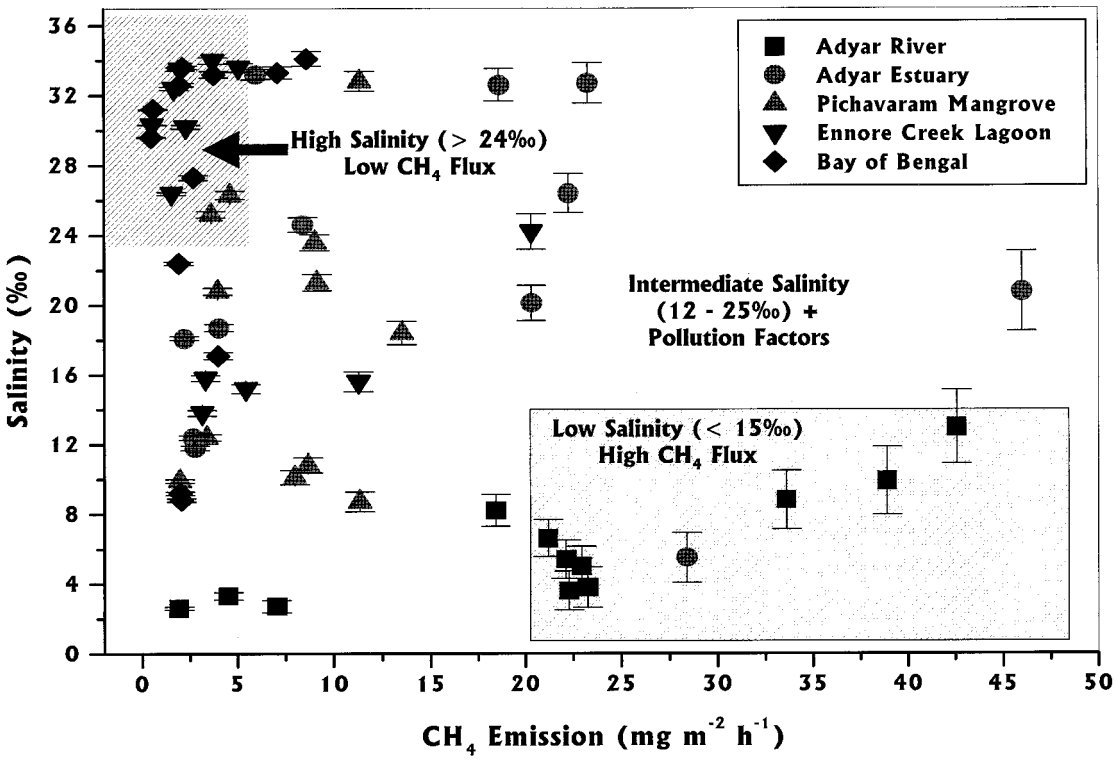

Figure 5. Effect of salinity on methane emission from the coastal wetlands of South India.

environments containing abundant plant material (King and others 1983) such as swamps and salt marshes. Thus, the CH_4 emission characteristics observed for the coastal wetlands in this study seem to be supported by a symbiotic coexistence rather than competitive inhibitions between the methanogens and the sulfur-reducing bacteria.

At Buckingham Canal, the average monthly flux ranged from 1.15 to 30.34 mg/m^2/hr in January and May respectively, with several intermediate peaks. A secondary peak in CH_4 emission (19.45 mg/m^2/hr) was recorded during monsoon (November) as observed at the Adyar estuarine and Ennore creek lagoon areas (Table 1). According to Roswall and others (1989), wetting of soils by rainfall stimulates heterotrophic activity, decreasing soil oxygen concentration, which is an important regulator of trace gas flux. Generally, coastal and marine wetlands are not considered to be major sources of atmospheric CH_4 due to the inhibiting influence of sulfate and salts in seawater (Schütz and others 1989). The results obtained for the Bay of Bengal confirm this finding. However in the Adyar estuary, erratic trends in annual CH_4 emission characteristics have been recorded due to constant input of domestic sewage into this wetland. The problem is further compounded by the formation of a sand bar, which further restricts water movement from the river to the ocean and vice versa.

Emission from Coastal Wetlands of India

The area under major wetland categories of the Indian coast, as given by the Space Applications Center (1992), was taken for computing the probable CH_4 emission from coastal wetlands (Table 3). The CH_4 emission observed at Pichavaram mangroves was used to predict the minimum and maximum range in CH_4 emission under unpolluted conditions for the coastal wetlands of India (Table 3). However, in order to highlight the intensity that human impacts could have on CH_4 emission, the minimum and maximum values obtained at the Adyar estuarine region have been taken to estimate anthropogenic CH_4 emission from these wetlands, using the following formula as given above in the Materials and Methods section.

Based on this, annual CH_4 emission ranging from 0.98 to 6.73 $\times$ 10^9 g/yr and from 1.09 to 22.87 $\times$ 10^9 g/yr is being emitted to the atmosphere under natural and anthropogenic conditions respectively, from the major coastal wetlands of India. It can be observed from our study (Table 3), that the coastal wetlands are potentially a major source of atmospheric CH_4. However, in comparison to freshwater wetlands, the emissions are

Table 3. Range in CH_4 (10^9 g/yr) efflux from coastal wetland ecosystems of India[a]

Wetland category	Area (km^2)	CH_4 flux with natural variability		CH_4 flux under anthropogenic stress	
		Minimum	Maximum	Minimum	Maximum
Mudflat	22961	0.40	2.72	0.44	9.25
Mudflat with vegetation	6125	0.11	0.73	0.12	2.47
Beach	1465	0.03	0.17	0.03	0.59
Beach vegetation	290	0.01	0.03	0.01	0.12
Shoal	93	0.00	0.01	0.00	0.04
Coral reef	1270	0.02	0.15	0.02	0.51
Mangroves	3979	0.07	0.47	0.08	1.60
Marsh vegetation	370	0.01	0.04	0.01	0.15
Lagoon	2132	0.04	0.25	0.04	0.86
Flood-prone areas	3437	0.06	0.41	0.07	1.38
Coastal dunes	2509	0.04	0.30	0.05	1.01
Reclaimed area	1212	0.02	0.14	0.02	0.49
Palaeo beach	434	0.01	0.05	0.01	0.17
Palaeo mudflats	6821	0.12	0.81	0.13	2.75
Strand plain	1378	0.02	0.16	0.03	0.55
Salt-affected areas	697	0.01	0.08	0.01	0.28
Salt pans	1617	0.03	0.19	0.03	0.65
Total	56790	0.98	6.73	1.09	22.87

[a]Minimum and maximum values for natural variability have been taken from the CH_4 flux values for Pichavaram mangroves. Minimum: 1.97 $mg/m^2/hr$; maximum: 13.52 $mg/m^2/hr$. Minimum and maximum values for anthropogenic stress are values obtained for the Adyar estuary. Minimum: 2.20 $mg/m^2/hr$; maximum: 45.97 $mg/m^2/hr$. Calculations: CH_4 (10^9 g/yr) = CH_4 flux (mg m^2/hr) $\times$ 24 $\times$ 365 $\times$ area of wetland (km^2)/10^9.

lower due to the inhibiting influence of sulfate and salinity. On the other hand, if anthropogenic additions increase at the current pace, these ecosystems could also become major sources for the future. More observations in other areas, such as mud flats, coral reefs, flood plains, etc., will help to refine this database further.

Conclusions

The present study provided the first insight into the quantification of CH_4 flux from unpolluted and polluted coastal wetland ecosystems of India. Our results clearly show that a significant amount of CH_4 is produced in coastal sediments and bears a strong inverse relationship with salinity and sulfate concentration in the unpolluted coastal wetlands. However, a concurrent increase in CH_4 emission at high sulfate levels suggests that either the natural environmental forcing factors, such as high sulfate and salinity, cease to have an effect on CH_4 production and emission or other noncompetitive substrates exist in these wetlands promoting the coexistence of the methanogens and the sulfate reducers. In addition, the polluted coastal wetlands are influenced by human pressures locally; some act as major sources (Adyar River and estuary) while others (e.g., lagoons) are negligible sources of methane to the atmosphere. A first-order estimate of CH_4 emission from the coastal wetlands of India range between 0.98–6.73 and 1.09–22.87 $\times$ 10^9 g/yr under natural and anthropogenic conditions, respectively. The results suggest that even though production and emission of CH_4 are natural processes in these wetlands, any anthropogenic intervention will alter the natural balance and the global CH_4 budget in the future.

Acknowledgments

The authors thank Dr. Peter Frenzel, Max-Planck-Institute for Terrestrial Microbiology, Marburg, Germany, for critically reviewing the manuscript. The authors thank Prof. B. H. Subbaraya and Dr. S. Rajaratnam, ISRO, Department of Space, Government of India for their advice and the ISRO-GBP for its financial support. The authors thank Prof. Dr. David Alexander, Editor-in-Chief of this journal, Dr. Kocasoy, and the other anonymous reviewer for their critical review and constructive suggestions in substantially improving the quality of this manuscript.

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