Human impacts on methane emission from mangrove ecosystems in India

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Abstract This study deals with the emission of methane in relation to changing environmental conditions and human impact, in three mangrove ecosystems of south India. Time-varying fluxes of methane adopting the close chamber technique were used to estimate CH_4 emission from an unpolluted site (Pichavaram mangroves) and two polluted sites viz. (1) Ennore Creek mangroves (affected by fertilizer effluents and crude oil discharges) and (2) Adyar estuary mangroves (affected by the discharges of organic and industrial wastes), covering monthly and seasonal variations. The results indicate annual average CH_4 emissions of 7.4, 5.02 and 15.4 mg m^{-2} h^{-1} from the sediment–water interface of the Pichavaram, Ennore Creek and Adyar estuary respectively. Emission characteristics obtained at Pichavaram mangroves represent a natural variability with changing physico-chemical factors, whereas the emission characteristics at Ennore Creek and Adyar estuary mangroves show anthropogenic influence. Several environmental factors such as oxygen availability, organic matter, soil physical and chemical properties, in addition to human-mediated interventions have been identified as influencing emission rates in the mangrove ecosystems. Preliminary CH_4 emission estimates for the mangrove ecosystems along the Indian subcontinent and the tropical and subtropical coastline of the world by linear extrapolation based on surface area range from 0.05 to 0.37 and 2.8 to 19.25 Tg CH_4 $year^{-1}$ respectively. Our results also highlight the impact of human activities on future emission of methane from the mangrove ecosystems.

Key words Mangroves · Methane efflux · Anthropogenic alterations · Emission inventory for mangroves

Introduction

Methane (CH_4), one of the trace gases that causes concern regarding global warming, occurs both naturally and as a product of human activities. Atmospheric concentrations of CH_4 have increased dramatically over the last century and the rise has continued at a rate of approximately 1% per year until recently (Blake and Rowland 1988). The rate of increase in atmospheric CH_4 concentration has slowed down in recent years (Steele et al. 1992; Dlugokencky et al. 1994; IPCC 1994). Because of its absorption of infrared radiation, CH_4 is an effective greenhouse gas. Biogenic CH_4 formation results from complex biochemical reactions involving bacteria during the decomposition of organic matter (Cicerone and Oremland 1988). Due to the strictly anaerobic nature of methanogenic bacteria, CH_4 production and emission into the atmosphere is restricted to habitats where anoxic conditions prevail. For this reason, waterlogged soils and sediments are prime sites of CH_4 production.

Tropical coastal ecosystems are dominated by the forested intertidal zones known as mangroves which are influenced by the neritic waters of the tropical coastal oceans and freshwater input from major riverine systems. Jagtap et al. (1993) estimate that India has 3150 km^2 of mangroves, over 80% of which occurs along its east coast. While significant studies have been carried out on CH_4 emission from coastal environments (Atkinson and Hall 1976; King and Wiebe 1978; Bartlett et al. 1987), only a few deal particularly with mangrove ecosystems (Sotomayor et al. 1994; Purvaja 1995). Bartlett et al. (1989) and Harriss et al. (1988) observed negligible CH_4 fluxes from saltwater mangroves, while Barber et al. (1988) estimated a diffusive flux of 82 mg CH_4 m^{-2} day^{-1} in a brackish-water pond in Florida. More recently, Sotomayor et al. (1994) quantified CH_4 emission from mangrove sediments along the coast of Puerto Rico. In this paper we focus primarily on methane efflux and the factors controlling the emission rates in mangrove ecosystems of south India. The extensive spatial and temporal variation in flux measurements carried out in this study provides a first estimate of CH_4 emission from this ecosystem and highlights effects of human impacts on emission rates.

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Methodology

Field sites

Three diverse mangrove ecosystems along the south-east coast of India were identified for this study (Fig. 1a). The Pichavaram mangroves along the Cauvery delta represent an unpolluted biotope. The mangroves along the Ennore Creek and the Adyar estuary close to Madras city represent ecosystems with immense human impact. The Pichavaram mangroves are located 225 km south of Madras city on the south-east coast of India (Fig. 1b). The mangrove forests of Pichavaram (11°27′N, 79°47′E) cover an area of about 1400 ha and are traversed by large numbers of channels and creeks which connect the Coleroon estuary in the south and the Vellar estuary in the north. A total of approximately 51 islets were identified (Muniyandi 1985) and were found to be separated by intricate waterways connecting the two estuaries.

The Pichavaram mangrove area is separated from the Bay of Bengal by a narrow sand bar. The maximum and minimum water depth in the mangrove region varies between 3 and 4 m and 30 and 50 cm respectively, with a mean depth of 1.56 m. Semidiurnal tides flush this ecosystem with an amplitude of 0.5–1 m. During extremely low tides in summer, the muddy bottom sediments are exposed. Neritic waters from the Bay of Bengal flush the mangrove area during most of the year, through three openings in the sand bar. Freshwater enters the mangrove area primarily through the main drainage channel joining the Coleroon river and the Khan Sahib Canal which drains agricultural wastewater.

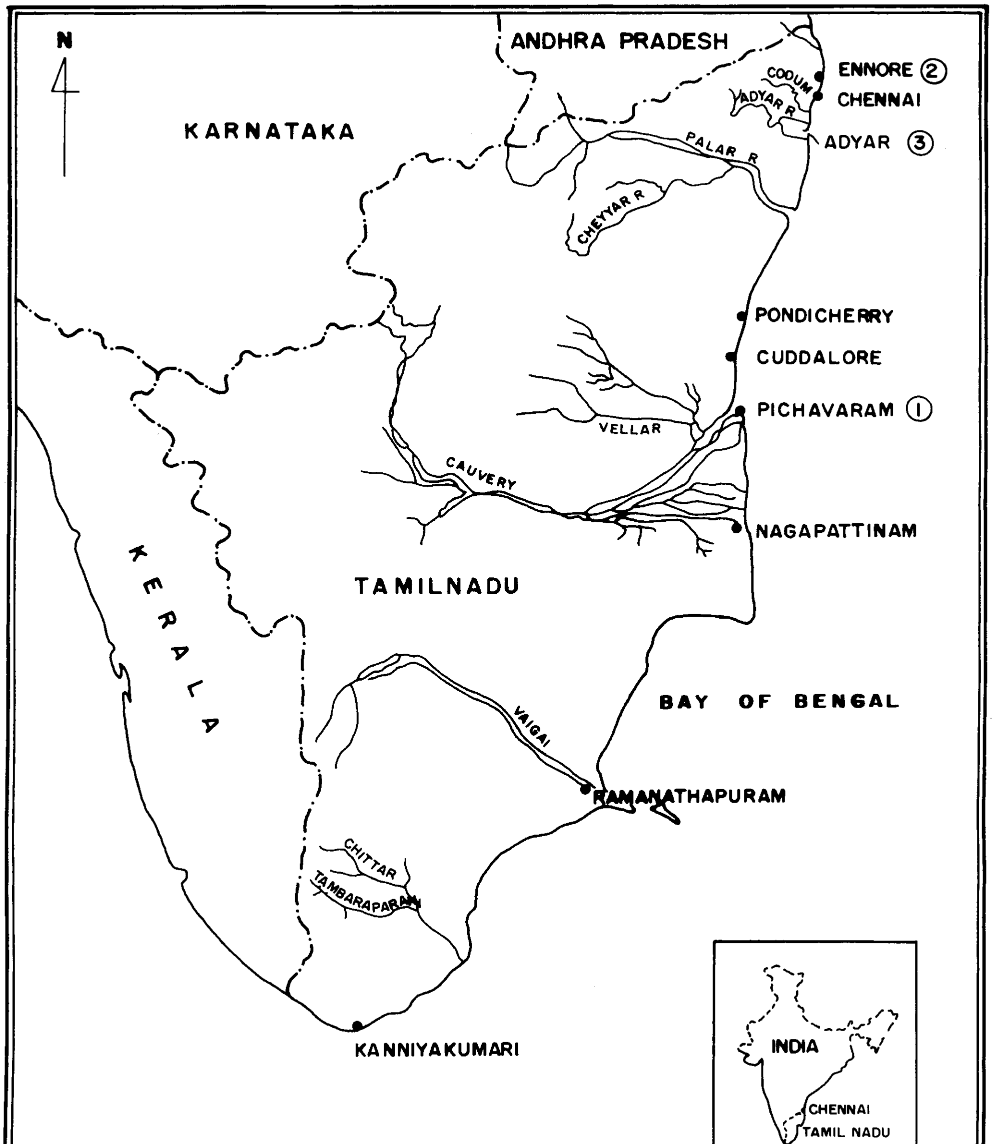
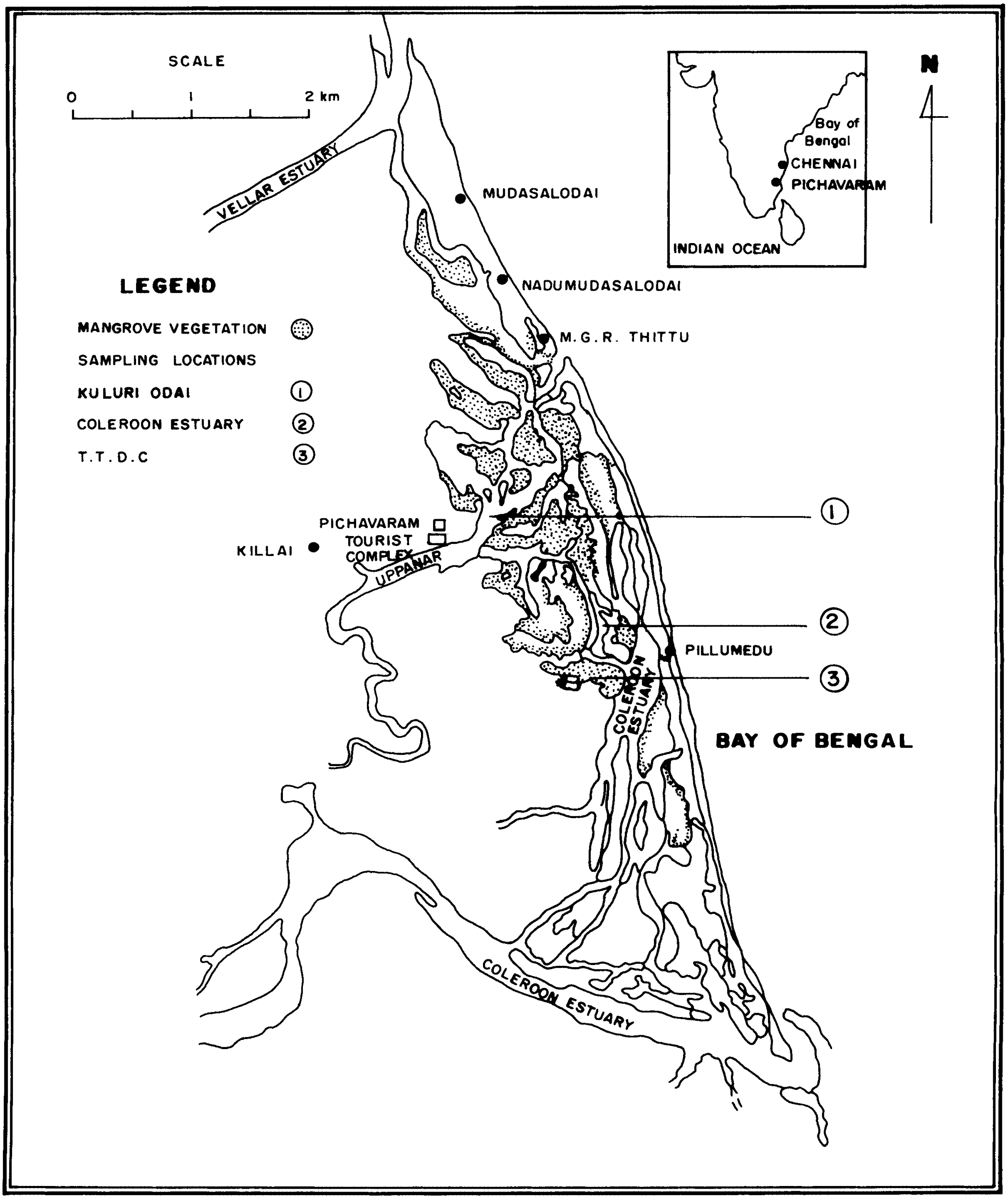


Fig. 1
a Sampling locations in mangroves of south India **b** Sampling sites within Pichavaram mangroves

Lugo and Snedaker (1974) classified the Pichavaram mangroves as the "fringe type". The floodwaters enter all the islets and wash away most of the fallen litter and decomposing organic matter. The mangrove vegetation is made up mainly of species of *Rhizophora*, *Avicennia*, *Bruguiera*, *Ceriops*, *Salicornia* and *Excoecaria*.

The intertidal margins of the Ennore Creek (13°30′N, 80°15′E) and the Adyar estuary (13°N, 80°15′E) (Fig. 1a) have small patches of mangrove vegetation covering 70 ha (Ennore Creek) and 48 ha (Adyar estuary). The mangrove vegetation at both Ennore Creek and the Adyar estuary is dominated by *Avicennia marina*. Absence of species like *Rhizophora* which is very common among other mangrove stands may indicate that these mangroves are under stress. The average height of *Avicennia marina* is over 21 m at the Adyar estuary, while that at Ennore is only 1.2 m (Selvam et al. 1993). A size fraction of the bed sediment samples was separated by standard sieving methods using American Society of Testing Materials (ASTM) Standard Sieves. Based on our observations, the soil texture in both the Ennore Creek and Adyar estuary mangroves is of the sandy-silt type (54%) in contrast to the silty-clay (37%)



b

nature at Pichavaram, with acidic to neutral pH (5.2–6.8), using 0.1 N KCl as the reference.

Methane flux measurements

At each mangrove area three permanent sampling locations were identified covering an area of 30 × 30 m in the zone dominated by *Avicennia marina.* Three different zones based on surface salinity gradient and species diversity were identified for this study: (1) the high salinity (>33l), (2) intermediate salinity (between 15 and 25l) and (3) low salinity (<15l) zones. The intermediate salinity zone prevails over a large extent of the mangrove area (>60%) and a freshwater zone can be clearly demarcated only during the monsoon. The maximum depth of water in the Pichavaram mangrove area varies between 3 and 4 m near the main channel and the minimum range is between 30 and 50 cm, with a mean depth of 1.5 m. Semidiurnal tides flush this ecosystem, with a fluctuating amplitude of 0.5–1 m. At each site, four replicate samples of gas, water and soil were collected and the water level from the sediment surface at the time of sampling was noted. Sampling was carried out at monthly intervals in these three zones, covering seasonal variations. Measurements were made at exactly the same location in each of the sites to record subtle changes in seasonal variations. Besides collection of gas samples from the sediment–water interface, atmospheric temperature, water temperature (just overlying the sediment surface) and soil temperature (at a depth of 10 cm) were monitored *in situ*. Dissolved oxygen (Winkler method), pH and EC were also measured *in situ* in the surface water using a portable Mettler field laboratory kit. Water samples of 1 l were also collected in polyethylene bottles and stored at 4 °C for the analysis of salinity nutrients and sulfate and these were analyzed within 24 h of sampling. Additionally, bulk bed sediment samples were collected up to a depth of 5 cm from the surface for the analysis of salinity, sulfate, water content and organic matter using standard procedures (Ramesh and Anbu 1996). For the analysis of organic matter, bulk sediment samples up to a depth of 5 cm were collected using a scoop from at least eight different locations in a particular salinity zone. These were then dried and pooled for the organic matter analysis.

Gas flux from the soil using closed chambers was determined by periodically collecting the gas samples from the chamber and measuring the change in concentration with time. The flux chambers are simple inverted containers made of Perspex glass. An aluminum base (57 cm long, 37 cm wide and 10 cm high) was inserted into the sediment column over which the chamber was placed, to trap gases emanating from below. The base was installed at the measuring sites well in advance (at least 12 h before sampling), to minimize effects of disturbance. Our flux chambers enclosed the pneumatophores of *A. marina* and care was taken not to disturb the root structure while inserting the aluminum base into the sediment surface. In all the study areas, the flux chambers were enclosed with about 10–15 pneumatophores and the monthly sampling was restricted to this particular site. The number of pneumatophores enclosed in the flux chambers remained constant during each sampling and in all the mangrove ecosystems throughout the study period.

The temperature and water level fluctuations within the Perspex chamber were also monitored during the period of sampling. A Perspex chamber (53 × 37 × 71 cm long/wide/high) was placed into grooves of the aluminum base, which were filled with water to make the system air-tight. The air inside the chamber was circulated using a battery-operated pulse pump. The samples were collected in gas-tight glass sampling bottles at fixed intervals of 15 min during early morning, and in the afternoon. Ambient air samples were also collected in gas sampling bottles filled with water using the displacement method. Quality control checks revealed that the glass bottles were appreciably leak-proof for over a week, but the samples were always analyzed within 24 h of sampling.

Gas samples were analyzed for CH_4 using a gas chromatograph (model HP 5890) fitted with a Flame Ionization Detector and a Porapak Column. Column, injector and detector temperatures were maintained at 60, 100 and 250 °C respectively with a flow rate of 35 ml min^{-1} of high-purity nitrogen as carrier gas. The gas chromatograph was calibrated before and after each set of measurements using 1 ppmv CH_4 in N_2 obtained from M/s Mathesons, USA, as a primary standard and 2.87 and 10.9 ppmv CH_4 in N_2 were used for intercalibration. Detailed methods are described elsewhere (Ramesh et al. 1997). The four replicate samples collected from each salinity zone were analyzed and the mean standard deviation was calculated, incorporating pressure and water level corrections; details are given elsewhere (Purvaja 1995). Extrapolations were made for CH_4 emission from an unpolluted mangrove site, the Pichavaram mangrove, to the other mangrove areas of the Indian subcontinent. These were based on the basic similarities in climatological, physical and chemical properties of the water and soil and the presence of the characteristic mangrove vegetation (*Avicennia marina*).

Results and discussion

Ambient methane concentration in the study areas

The ambient CH_4 concentration averaged 1.70 ppmv in all the study areas. Fluctuations were minimal, ranging from 1.68 to 1.72 ppmv at Pichavaram and Ennore Creek mangroves. At the Adyar estuary mangroves, ambient CH_4 concentrations as high as 3.1 ppmv probably reflected production of CH_4 from additions of domestic sewage.

Seasonal methane budget from the mangroves

CH_4 emission showed distinct seasonal trends at Pichavaram and Ennore Creek, and less so in the Adyar estuary (Tables 1–4, Fig. 2). In general, CH_4 emission increased with increasing soil temperature and soil organic matter and decreased as salinity and the concentrations of oxygen and sulfate increased. Although the magnitude of flux varied during each sampling, four distinct peaks were noticed during the sampling period (January to December) in all the study areas. In order to delineate natural CH_4

Table 1
Factors influencing methane emission from Pichavaram mangroves (refer to Fig. 1b for sampling location). Values are means ± SD of four replicates. Rainfall data collected from India Meteorological Department, Madras. *DO* Dissolved oxygen; *OM* organic matter; *Tr* trace amount

Date (1996)	CH_4 efflux ($mg\ m^{-2}\ h^{-1}$)	pH	DO ($ml\ l^{-1}$)	Salinity (‰)	Soil temperature (°C)	Water depth[a] (cm)	NO_3 ($mg\ l^{-1}$)	SO_4 ($mg\ l^{-1}$)	OM (%)	Rainfall (mm)
21 January	3.96 ± 0.01	7.90 ± 0.39	8.10 ± 0.40	20.80 ± 1.04	26.80 ± 1.34	4.20	6.00 ± 0.3	2200 ± 11.00	8.20 ± 0.41	Tr
23 February	9.13 ± 0.04	6.80 ± 0.34	4.00 ± 0.20	21.30 ± 1.06	29.80 ± 1.49	5.60	3.40 ± 0.17	2100 ± 10.50	8.80 ± 0.44	41.80
20 March	3.60 ± 0.02	7.60 ± 0.38	7.10 ± 0.35	25.20 ± 1.26	28.20 ± 1.41	5.80	8.40 ± 0.42	2400 ± 12.00	8.70 ± 0.43	Tr
19 April	4.60 ± 0.03	8.40 ± 0.42	5.20 ± 0.26	26.30 ± 1.31	30.20 ± 1.51	3.40	0.70 ± 0.03	2500 ± 12.50	8.30 ± 0.41	Nil
17 May	11.34 ± 0.06	7.40 ± 0.37	6.80 ± 0.34	32.80 ± 1.64	31.50 ± 1.57	4.50	5.80 ± 0.29	2800 ± 14.00	9.20 ± 0.69	27.80
15 June	9.02 ± 0.04	6.90 ± 0.34	6.90 ± 0.34	23.60 ± 1.18	27.50 ± 1.37	5.10	2.90 ± 0.14	1800 ± 9.00	13.90 ± 0.46	92.90
15 July	8.67 ± 0.02	7.30 ± 0.36	7.20 ± 0.36	10.80 ± 0.54	25.60 ± 1.28	9.50	13.60 ± 0.68	230 ± 11.50	12.30 ± 0.61	83.40
20 August	13.52 ± 0.08	7.40 ± 0.37	5.80 ± 0.29	18.40 ± 0.92	26.00 ± 1.39	4.20	23.10 ± 1.15	1200 ± 6.00	10.50 ± 0.6	65.10
21 September	7.98 ± 0.02	7.60 ± 0.38	8.30 ± 0.42	10.10 ± 0.50	25.30 ± 1.26	8.50	32.60 ± 1.63	980 ± 4.90	12.70 ± 0.63	82.80
19 October	11.35 ± 0.05	8.20 ± 0.36	6.10 ± 0.31	8.70 ± 0.43	24.20 ± 1.21	9.20	38.60 ± 1.93	300 ± 1.50	12.00 ± 0.52	320.20
18 November	1.97 ± 0.01	7.10 ± 0.35	5.10 ± 0.25	9.90 ± 0.49	25.00 ± 1.25	10.30	41.10 ± 1.05	1500 ± 7.50	6.10 ± 0.30	312.00
20 December	3.37 ± 0.02	7.20 ± 0.36	6.00 ± 0.30	12.40 ± 0.62	25.50 ± 1.27	11.20	20.40 ± 1.02	1900 ± 9.50	5.20 ± 0.26	132.70
Average	7.38	7.50	6.40	18.40	27.10	6.90	16.40	1832.00	9.70	96.60

[a] Observed from soil surface

Table 2
Factors influencing methane emission from Ennore Creek mangroves (refer to Fig. 1a for sampling location). Values are means ± SD of four replicates. Rainfall data collected from India Meteorological Department, Madras. *DO* Dissolved oxygen; *OM* organic matter

Month	CH_4 efflux ($mg\ m^{-2}\ h^{-1}$)	pH	DO ($ml\ l^{-1}$)	Salinity (‰)	Soil temperature (°C)	Soil moisture (%)	NH_4 ($mg\ l^{-1}$)	NO_3 ($mg\ l^{-1}$)	PO_4 ($mg\ l^{-1}$)	SO_4 ($mg\ l^{-1}$)	OM (%)	Rainfall[µ] (mm)
January	5.43 ± 0.01	7.50 ± 0.37	12.60 ± 0.63	15.20 ± 0.76	25.60 ± 1.28	35.40 ± 1.77	1.40 ± 0.07	0.90 ± 0.04	1.70 ± 0.08	1900 ± 9.5	1.80 ± 0.09	Nil
February	3.31 ± 0.01	7.20 ± 0.36	6.40 ± 0.32	15.80 ± 0.79	26.80 ± 1.34	42.8 ± 2.14	1.19 ± 0.05	1.20 ± 0.06	1.70 ± 0.08	2900 ± 14.5	3.10 ± 0.15	Nil
March	1.54 ± 0.14	7.40 ± 0.37	10.40 ± 0.52	26.40 ± 1.32	28.40 ± 1.42	43.20 ± 2.16	2.56 ± 0.12	0.80 ± 0.04	0.60 ± 0.03	3200 ± 16.0	2.80 ± 0.14	2.00
April	2.29 ± 0.15	8.30 ± 0.41	10.60 ± 0.53	30.20 ± 1.51	29.70 ± 1.48	36.8 ± 1.84	1.90 ± 0.09	1.80 ± 0.09	1.20 ± 0.06	2800 ± 14.0	2.40 ± 0.12	Nil
May	2.01 ± 0.08	7.30 ± 0.36	10.70 ± 0.53	33.50 ± 1.67	30.50 ± 1.52	37.60 ± 1.88	3.45 ± 0.17	3.80 ± 0.19	2.70 ± 0.13	3900 ± 19.5	2.90 ± 0.14	57.90
June	3.71 ± 0.09	6.40 ± 0.32	9.00 ± 0.45	34.00 ± 1.7	26.80 ± 1.34	25.10 ± 1.25	1.39 ± 0.06	2.20 ± 0.11	3.10 ± 0.15	2800 ± 14.0	4.80 ± 0.24	49.40
July	1.68 ± 0.06	7.20 ± 0.36	12.60 ± 0.63	32.40 ± 1.62	25.60 ± 1.28	27.40 ± 1.37	1.28 ± 0.06	1.20 ± 0.06	3.20 ± 0.16	3100 ± 15.5	2.60 ± 0.13	72.20
August	5.05 ± 0.13	7.40 ± 0.37	15.70 ± 0.78	30.30 ± 1.51	25.20 ± 1.26	29.20 ± 1.46	2.35 ± 0.11	2.30 ± 0.11	2.80 ± 0.14	2600 ± 13.0	3.90 ± 0.19	112.10
September	11.28 ± 0.34	7.40 ± 0.37	13.70 ± 0.68	33.60 ± 1.68	26.30 ± 1.31	18.60 ± 0.93	2.37 ± 0.11	3.40 ± 0.17	0.50 ± 0.02	2500 ± 12.5	4.10 ± 0.20	52.90
October	0.52 ± 0.46	7.50 ± 0.37	5.70 ± 0.28	15.60 ± 0.78	25.00 ± 1.25	28.40 ± 1.42	1.42 ± 0.07	4.40 ± 0.22	1.90 ± 0.09	4400 ± 22.0	2.90 ± 0.14	258.10
November	3.13 ± 0.82	7.20 ± 0.36	6.80 ± 0.34	13.80 ± 0.69	23.60 ± 1.18	33.00 ± 1.65	0.54 ± 0.02	2.70 ± 0.13	3.30 ± 0.16	2000 ± 10.0	3.10 ± 0.15	355.10
December	20.30 ± 0.09	6.80 ± 0.34	5.60 ± 0.28	24.20 ± 1.21	24.80 ± 1.24	13.00 ± 0.65	2.31 ± 0.11	2.90 ± 0.14	1.60 ± 0.08	1300 ± 6.5	4.30 ± 0.21	283.70
Average	5.02	7.20	9.98	25.40	26.50	30.88	1.85	2.30	2.03	2784.00	3.20	103.60

Table 3
Factors influencing methane emission from Adyar Estuary mangroves (refer to Fig. 1a for sampling location). Values are means ± SD of four replicates. Rainfall data collected from India Meteorological Department, Madras. *DO* Dissolved oxygen; *OM* organic matter

Month	CH_4 efflux (mg m^{-2} h^{-1})	pH	DO (ml l^{-1})	Salinity (‰)	Soil temperature (°C)	Soil moisture (%)	NH_4 (mg l^{-1})	NO_3 (mg l^{-1})	PO_4 (mg l^{-1})	SO_4 (mg l^{-1})	OM (%)	Rainfall$^{\mu}$ (mm)
January	2.20 ± 0.03	7.20 ± 0.36	7.50 ± 0.37	18.10 ± 0.90	24.60 ± 1.23	36.80 ± 1.84	12.36 ± 0.61	2.80 ± 0.14	0.90 ± 0.04	2700 ± 13.5	5.50 ± 0.27	Nil
February	28.39 ± 0.70	7.70 ± 0.38	2.40 ± 0.12	5.50 ± 0.27	23.80 ± 1.19	18.80 ± 0.94	15.00 ± 0.75	1.60 ± 0.08	1.40 ± 0.07	1600 ± 8.0	8.90 ± 0.44	Nil
March	20.30 ± 0.19	7.50 ± 0.37	2.80 ± 0.14	20.10 ± 1.00	25.80 ± 1.29	22.10 ± 1.10	16.40 ± 0.82	0.70 ± 0.03	5.20 ± 0.26	2100 ± 10.5	6.80 ± 0.34	2.00
April	8.40 ± 0.27	7.30 ± 0.36	3.10 ± 0.15	24.60 ± 1.23	29.00 ± 1.45	33.80 ± 1.69	17.30 ± 0.86	2.10 ± 0.10	4.50 ± 0.22	3000 ± 15.0	3.10 ± 0.15	Nil
May	18.60 ± 0.47	7.50 ± 0.37	3.90 ± 0.19	32.60 ± 1.63	30.60 ± 1.53	12.90 ± 0.64	18.45 ± 0.92	3.20 ± 0.16	3.60 ± 0.18	2900 ± 14.5	7.20 ± 0.36	57.90
June	5.94 ± 0.55	6.90 ± 0.34	5.20 ± 0.26	33.20 ± 1.66	26.40 ± 1.32	33.70 ± 1.68	23.82 ± 1.19	2.80 ± 0.14	4.80 ± 0.24	3500 ± 17.5	8.40 ± 0.42	49.40
July	4.01 ± 0.10	7.10 ± 0.35	6.80 ± 0.34	18.70 ± 0.93	25.00 ± 1.25	34.40 ± 1.72	14.06 ± 0.70	4.60 ± 0.23	6.80 ± 0.34	4600 ± 23.0	7.80 ± 0.39	72.20
August	23.24 ± 0.40	7.10 ± 0.35	3.30 ± 0.16	32.70 ± 1.63	24.80 ± 1.24	29.00 ± 1.45	16.03 ± 0.80	1.50 ± 0.07	2.50 ± 0.12	1000 ± 5.0	5.90 ± 0.29	112.10
September	22.25 ± 0.81	6.90 ± 0.35	3.10 ± 0.15	26.40 ± 1.32	27.30 ± 1.36	16.80 ± 0.84	17.42 ± 0.87	4.20 ± 0.21	3.40 ± 0.17	600 ± 3.0	7.90 ± 0.39	52.90
October	2.67 ± 0.09	6.80 ± 0.34	4.80 ± 0.24	12.40 ± 0.62	24.60 ± 1.23	34.60 ± 1.73	9.45 ± 0.47	4.60 ± 0.23	4.10 ± 0.20	1000 ± 5.0	8.10 ± 0.40	258.10
November	2.75 ± 0.05	6.70 ± 0.35	6.80 ± 0.34	11.80 ± 0.59	24.20 ± 1.21	53.60 ± 2.68	10.45 ± 0.52	5.20 ± 0.26	7.60 ± 0.38	2600 ± 13.0	6.00 ± 0.30	355.10
December	45.97 ± 0.54	7.30 ± 0.36	5.80 ± 0.29	20.80 ± 1.04	21.40 ± 1.07	12.50 ± 0.62	12.10 ± 0.60	2.30 ± 0.11	3.40 ± 0.17	800 ± 4.0	9.20 ± 0.46	283.70
Average	15.40	7.20	6.30	21.40	25.60	28.25	15.60	2.90	4.01	2200.00	7.10	103.60

fluxes from the anthropogenic effects, the results for polluted and unpolluted mangroves are discussed separately.

Methane emission from unpolluted mangroves

At Pichavaram, the annual flux varied from 1.97 to 13.52 mg m^{-2} h^{-1}. A first peak (9.13 mg m^{-2} h^{-1}) appeared after the monsoon (February), a second peak (11.34 mg m^{-2} h^{-1}) in summer (May), while the annual maximum in CH_4 emission (13.52 mg m^{-2} h^{-1}) was observed during the pre-monsoon season (August). These peaks are a result of a rise in both 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 has been observed in this study. During the wet season (Nov–Dec), immediately following the monsoon, the height of the floodwaters (~0.5 m) restricted the transfer of methane from the subsurface to the atmosphere, resulting in a decrease in CH_4 efflux rates. It is also evident from the results that CH_4 emission was not appreciable until oxygen became limited.

Methane emission from polluted mangroves

The exchange of CH_4 was less pronounced for a major part of the year at the Ennore Creek mangroves (0.52–5.05 mg m^{-2} h^{-1}) and thereafter larger peaks were observed in September (11.28 mg m^{-2} h^{-1}) and December (20.3 mg m^{-2} h^{-1}). During the dry season, the sediment surface and the pneumatophores of the mangrove plant *Avicennia marina* were covered with crude oil effluents, which presumably suppressed gaseous transfer between the soil and the atmosphere. *Avicennia* sp. rely on their pneumatophores for respiration and exchange of gases. When coated with oil, the pneumatophores become sealed and the plant eventually suffocates and dies. This was also reflected in the degenerated growth of *A. marina* in this study area. Due to suppressed gas exchange, CH_4 concentrations presumably built up in the subsurface layers. After the retreat of the monsoon in late December, the soil surface fell dry and cracked, resulting in a release of the accumulated CH_4, which contributed significantly to the season total.

The freshwater inflow to the Adyar estuary occurs mainly during the monsoon (Oct–Nov) in addition to receiving domestic effluent discharges and tidal incursion every day. However, the effluent discharges do not regularly reach the Bay of Bengal due to the presence of a bar mouth, causing irregular stagnation in the estuarine and mangrove area. The removal of domestic effluents from the mangrove area occurs mainly during the highest of high tide. In summer, due to high ambient temperature (>40 °C), the evaporation rate is equally high, resulting in acute dry spells. As a consequence of this alternate stagnation, tidal dilution and dryness, abrupt changes in CH_4 emission characteristics (2.2–45.97 mg m^{-2} h^{-1}) were observed. Although the daily variations in sewage input were not directly quantified, it is reported that on average about 6.81 million l day^{-1} is discharged into the enclosed mangrove area (Table 5). This results in the stagnation of wastewater in the man-

Table 4
Seasonal variation in methane emission (mg m^{-2} h^{-1}) from mangroves of the study area

Season	Location Pichavaram	Ennore Creek	Adyar Estuary
Post-monsoon (Jan–Mar)	5.56 ± 0.28	3.43 ± 0.17	16.96 ± 0.83
Summer (Apr–Jun)	8.32 ± 0.42	2.67 ± 0.13	10.98 ± 0.55
Pre-monsoon (Jul–Sep)	10.06 ± 0.50	6.00 ± 0.30	16.50 ± 0.83
Monsoon (Oct–Dec)	5.56 ± 0.28	7.98 ± 0.39	17.13 ± 0.86

grove area, frequently causing anoxic conditions. Several intermediate peaks in CH_4 emission were observed correlating with the quantity of domestic effluents as well as tidal incursion into the mangrove area. Low emissions were recorded only during the monsoon and high tide regimes.

Abiotic and biotic controls of methane emission

Methane emission from the mangrove ecosystem is affected by a range of abiotic and biotic variables including (1) soil temperature, (2) dissolved oxygen, (3) soil moisture, (4) the availability of the decomposing organic substrate, (5) inhibitors of CH_4 formation (such as sulfate and salinity), and (6) anthropogenic factors, which are discussed in detail below.

Soil temperature

The soil temperature ranged from 21 to 32 °C in all the study areas during the entire period of sampling, coinciding with the dry and wet seasons respectively. Methane fluxes were generally high during summer and pre-monsoon at both Pichavaram and Adyar (Tables 1 and 3), indicating that soil temperature controlled the efflux rates, except under stressed conditions when anthropogenic influence dominates emission characteristics. The formation of CH_4 is positively correlated with soil temperature (>0.8). Aselmann and Crutzen (1989) reported that the production of CH_4 in a wetland ecosystem shows a seasonal cycle that is correlated with temperature. It is also evident from our results that the seasonality of CH_4 production is attributable to changes in sediment temperature in the wet and dry seasons in Pichavaram mangroves. In general, CH_4 production rates from wetlands have been shown to increase with increased temperature (Bachoon and Jones 1992). King and Wiebe (1978) also found that CH_4 emission from the marsh sediment to the atmosphere was seasonal, with higher values during summer than in winter, which is also supported by DeLaune et al. 1986.

Dissolved oxygen

Oxygen is a critical factor controlling methanogenesis in mangrove ecosystems. The results presented for the Pichavaram mangroves (Table 1) show in the majority of our observations that the emission of CH_4 is inversely proportional to oxygen concentrations. However, higher oxygen levels were observed during the monsoon than in summer, basically due to precipitation and high wave action. Moreover, plants like *Avicennia marina* which inhabit permanently such seasonally inundated areas possess pneumatophores which bring oxygen to their roots. These structures and associated active and passive transport mechanisms were found to serve as efficient conduits for CH_4 emissions to the atmosphere (Sotomayor et al. 1994). At Ennore Creek, an enrichment of O_2 in the overlying waters was recorded due to constant tidal flushing in the mangrove area. The low CH_4 values observed here have resulted from an increased oxygen dif-

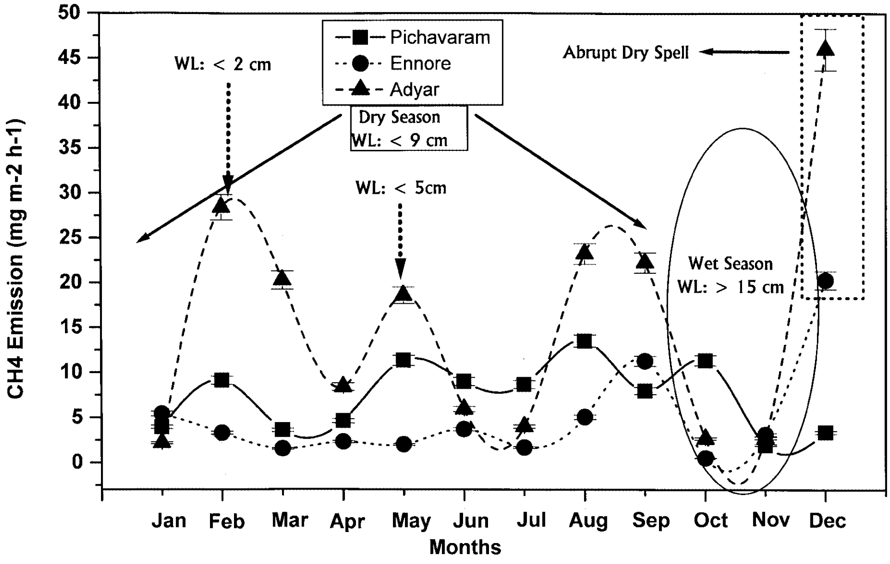


Fig. 2
Monthly methane emission from mangroves of south India

Table 5
Effluent discharges into mangrove areas of south India. *mld* Million liters per day

Location	Area of mangrove (ha)	Industrial effluents (mld)[b]	Domestic effluents (mld)[b]	Emission rate (mg m^{-2} h^{-1})		Annual methane emission (10^9 g $year^{-1}$)		
				Min.	Max.	Min.	Max.	Total
Pichavaram[a]	1400	Nil	Negligible	1.97 ± 0.09	13.52 ± 0.67	0.24 ± 0.01	1.60 ± 0.08	10.85
Ennore Creek	70	0.45	3.40	0.52 ± 0.02	20.30 ± 1.01	0.06 ± 0.003	0.12 ± 0.006	0.37
Adyar Estuary	48	0.78	6.81	2.20 ± 0.11	46.00 ± 2.29	0.01 ± 0.0002	0.19 ± 0.009	7.70
Total	1518	–	–	–	–	0.31	1.91	18.92

[a] Unpolluted reference site
[b] Data taken from Ramesh et al. (1997)

fusion into the sediment from the oxygen-rich surface waters of the Ennore Creek. Because of this phenomenon, even a small production of CH_4 in the subsurface would have been oxidized on its way to the atmosphere.
In contrast to the other two sites, anoxic conditions prevailed for a major part of the year, with a low dissolved oxygen content of 2.4 ml l^{-1} at the Adyar estuary except when monsoon showers elevate the oxygen content of the overlying waters. The addition of sewage waters causes stagnant conditions in the enclosed mangrove area. The decomposition of organic matter results in the utilization of large amounts of O_2 from the soil, leading to anaerobic conditions. The top few millimeters of the soil are oxygenated, the main source of O_2 being that dissolved in the overlying water. Beneath this is the reduced layer which contains reduced products such as ammonia and sulfides. Continuous stagnation of the wastewater cuts off the O_2 from the atmosphere, causing anaerobic fermentation of organic matter in soil and CH_4 is the major end product of this process.

Soil moisture

Soil moisture is one of the primary factors affecting transport of CH_4 from the subsurface to the atmosphere. We observed large fluctuations in soil moisture content at Adyar estuary mangroves (16.8–53.6%), due to alternating dry and wet spells in this location. The insufficient tidal influx coupled with the fluctuating quantities in effluent discharge into the enclosed mangrove area resulted in alternate drying and submergence of the soil as mentioned above. The soil water content remained relatively constant, showing seasonal trends (30.2–59%) at Pichavaram mangroves. We attribute two principal factors for this low fluctuation in soil moisture: (1) continuous tidal and freshwater influx and (2) the silty-clay (20–30%) nature of the soil retained considerable soil moisture in the interstices. A similar observation has been made for the Ennore Creek mangroves.

Influence of soil organic matter

The effect of organic matter on CH_4 emission is shown in Fig. 3 for the Pichavaram, Ennore and Adyar estuary mangroves. Mangroves and their associated sediments are rich in organic matter, and hence understanding their contribution to CH_4 production and emission assumes special significance. Submergence is often equated with retarded decomposition and accumulation of organic matter in wetlands. Among the three mangrove biotopes studied, Pichavaram mangroves were found to accumulate organic matter in high concentrations (5.2–13.9%), followed by the Adyar estuary (3.1–9.2%) and Ennore Creek (1.8–4.8%). Distinct spatial variation in soil organic matter content between the intermediate and highly saline zones was observed at the Pichavaram mangroves. The data obtained for all these locations have been averaged to arrive at a monthly mean for the Pichavaram mangrove area. Nevertheless, we did not observe large site-specific temporal variations (Table 6) within each of these locations. Owing to a combined effect of weak circulation and high organic inputs mainly from decaying foliage and debris, there is a large amount of organic matter in the sediments of this zone. In general, >50% of the mangrove litter production is converted to organic matter in such undisturbed ecosystems (Purvaja 1995). This results in the high accumulation of organic matter in the soil during the summer and premonsoon seasons. Further, the high rate of decomposition of organic matter creates oxygen stress, eventually resulting in the formation of CH_4 in the subsurface. A strong positive correlation (0.76) between soil organic matter and CH_4 efflux has been observed for Pichavaram and is significant (>0.60) for the Ennore and Adyar mangroves. Organic matter accumulation has been found to be consistent with increased soil temperature, salinity and pH. In the Adyar mangroves continuous input of organic matter in the form of domestic sewage enhanced CH_4 emission irrespective of competition for the substrates by sulfur reducers. Owing to the considerably high methanogenesis at this location despite its high sulfate content, we are compelled to believe that this may be due to higher amounts of non-competitive substrates (methylated amines, DMS, etc.) in these ecosystems, as reported by King (1984). Thus, methanogenesis may be the last step in organic matter decomposition in such low-O_2 environments.

Sulfate and salinity

Generally, marine wetlands such as mangroves are not considered to be a major source of atmospheric CH_4 due to the inhibiting influence of high concentrations of sulfate in seawater (Schütz and Seiler 1989; DeLaune et al. 1990). Sulfate content in surface water was extremely high in all

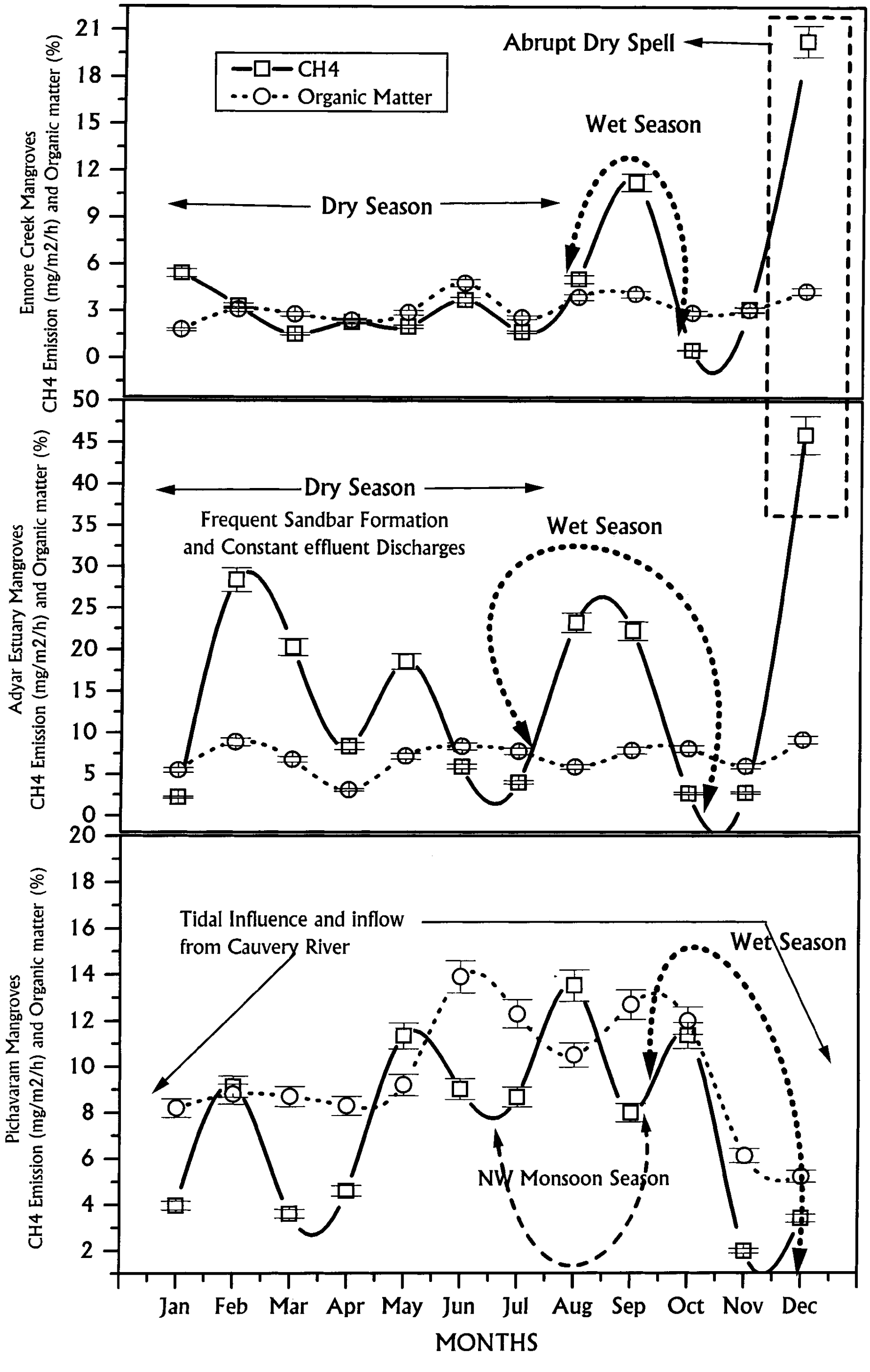


Fig. 3
Effect of organic matter on methane emission

the study areas, ranging from 300 to 2800 mg l^{-1} at Pichavaram, 1300 to 4400 mg l^{-1} at Ennore and 600 to 4600 mg l^{-1} at Adyar, corresponding to local precipitation and tidal inundation. Methane flux showed negative correlation with sulfate in all three mangrove biotopes, but was most significant (−0.71) in the Ennore Creek area. Although the inhibition of sulfate and salinity on methane emission was obvious in the mangrove ecosystems studied, particularly at Ennore, our data reveal a secondary peak in CH_4 emission during the summer, when the concentrations of sulfate, salinity, pH and soil temperatures were also at a maximum due to the availability of non-competitive substrates, as mentioned earlier.

Anthropogenic factors

It is clear that methane is formed and released to the atmosphere both by natural and anthropogenic means, but nearly every source can be affected by human activities. The mangroves along the Adyar estuary receive approximately 6.81 million l day^{-1} (mld) of sewage (Table 5), making the entire mangrove area anoxic. The problem is further aggravated by stagnation of domestic sewage in these enclosed areas, except during high tide and in the monsoon season. Our results show a twofold increase in mean CH_4 flux at Adyar estuary (15.58 mg m^{-2} h^{-1}) in comparison to the Pichavaram mangroves (7.38 mg m^{-2} h^{-1}). New global figures for emission of CH_4 from domestic sewage range

Table 6
Spatial and seasonal variation in organic matter (%) and CH_4 efflux (mg m^{-2} h^{-1}) in Pichavaram mangroves. Values are means ± SD ($n = 5$) for each site

Season	Intermediate salinity zone (15–25‰)				High salinity zone (>33‰)	
	Location 1		Location 2		Location 3	
	Organic matter	CH_4 efflux	Organic matter	CH_4 efflux	Organic matter	CH_4 efflux
Post-monsoon (Jan–Mar)	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 (Apr–Jun)	12.80 ± 0.64	12.20 ± 0.61	12.90 ± 0.65	8.34 ± 0.41	5.10 ± 0.26	6.15 ± 0.31
Pre-monsoon (Jul–Sep)	13.60 ± 0.68	14.92 ± 0.75	14.20 ± 0.71	10.01 ± 0.50	5.80 ± 0.29	5.16 ± 0.26
Monsoon (Oct–Dec)	9.40 ± 0.47	5.97 ± 0.30	9.70 ± 0.49	5.39 ± 0.27	4.20 ± 0.21	4.68 ± 0.23

from 15 to 80 Tg $year^{-1}$, with an average of 25 Tg $year^{-1}$ (IPCC 1990). This suggests that an important amount of CH_4 is generated from the domestic effluents and that the emission is directly proportional to the quantity and quality of effluents discharged (Ramesh et al. 1997). Conversely, a decline in CH_4 emission has been recorded at the Ennore Creek mangroves, where the addition of terminal acceptors, such as nitrogenous fertilizer effluents, has decreased CH_4 fluxes and at the same time increased the primary productivity rates appreciably.

Methane efflux from the study area

It is quite clear from the data presented in Table 7 that anthropogenic interference in the Adyar estuary mangroves contributes significantly to the atmospheric concentration of CH_4. The total annual emission from this mangrove is calculated to be ~7.7 × 10^9 g $year^{-1}$, which is highly significant considering the small extent it covers and large emissivity characteristics. Individual values up to 58.9 mg m^{-2} h^{-1} have been recorded from this location, with average values in the range of 45.97 mg m^{-2} h^{-1}, clearly highlighting the intensity of man-made pollution in this area. According to Schütz and Seiler (1989), higher CH_4 emission rates other than from boreal peatlands are found in swamps and ponds of subtropical and tropical regions, reaching individual values of up to 216 mg m^{-2} h^{-1} and average values up to 51 mg m^{-2} h^{-1}. Human additions of fertilizer and crude oil effluents into the Ennore Creek have significantly reduced annual CH_4 emissions (0.37 × 10^9 g $year^{-1}$) to the atmosphere. On the contrary, the annual CH_4 emission from Pichavaram mangroves was ~10.85 × 10^9 g $year^{-1}$, varying naturally with environmental factors. These results suggest that human perturbation of the ecosystem, as observed for the Adyar estuary mangroves, enhances emission rates rapidly and therefore could have significant environmental consequences. It is this increasing input of CH_4 from anthropogenic sources into the atmosphere, combined with a possible decrease in the tropospheric OH radical, that is considered to yield the observed increase in atmospheric CH_4 (Dlugokencky et al. 1994).

Aselmann and Crutzen (1989) estimated a CH_4 emission rate of 57–112 mg m^{-2} day^{-1} from the global swamps. However, our results for the Pichavaram mangroves yield a range between 47.3 and 324.5 mg m^{-2} day^{-1}, which best represents a tropical mangrove ecosystem. The observed maximum of 324 mg m^{-2} day^{-1} is more than twofold higher than that reported by Aselmann and Crutzen (1989). This discrepancy has resulted from the high temperature regimes observed in the tropics, which is conducive for methanogenesis and hence higher annual emissions.

Probable methane emission from mangroves of the Indian subcontinent

The Indian coastline extending to about 5100 km and falls within the bounds of the tropics. The east coast is dominated by the gigantic deltas of the Ganges-Brahmaputra, Krishna-Godavari and Cauvery, which harbor rich mangrove vegetation, accounting for nearly 2% of the global mangrove area. The total extent of the Indian mangroves is estimated to be 315,100 ha (Jagtap et al. 1993), of which nearly 85% is confined to West Bengal (Sundarbans) and the islands of the Bay of Bengal. The coastal climate of the

Table 7
Annual methane emission from mangroves of the study area

Location[a]	Area of mangrove (ha)	Emission rate (mg m^{-2} h^{-1})			Range observed (10^9 g $year^{-1}$)		
		Min.	Max.	Total	Min.	Max.	Total
Pichavaram[b]	1400	1.97 ± 0.09	13.52 ± 0.67	88.51	0.24 ± 0.01	1.60 ± 0.08	10.85
Ennore Creek	70	0.52 ± 0.02	20.30 ± 1.01	60.25	0.06 ± 0.003	0.12 ± 0.006	0.37
Adyar Estuary	48	2.20 ± 0.11	45.97 ± 2.29	184.74	0.01 ± 0.0005	0.19 ± 0.009	7.70
Total	1518	–	–	333.50	3.10	1.91	18.99

[a] For sampling locations refer to Fig. 1
[b] Unpolluted site

Indian subcontinent is generally uniform, although some variation in soil composition has been reported (Untawale 1987). The Gangetic Sundarbans (the largest mangrove stands in India) has deposition of alluvial soil, brought in by the river flow. The soil from the Cauvery delta is equally rich in alluvium and is classified under saline hydromorphic soils, with little humus, while that in Pichavaram mangroves consists of rich alluvium with fine and coarse sand. The soil organic matter content of the Indian mangroves ranges from 1.1 to >20% (Untawale 1987). Moreover, Blasco (1975) reports that a more or less complete zonation in vegetal composition and floristic distribution is seen in the Pichavaram mangroves, typical of a tropical mangrove ecosystem.

Because of this homogeneity in climatological, physical and chemical properties of the water, soil and vegetation of the mangroves, extrapolation of the data from a year-round survey in Pichavaram mangroves was attempted, to predict the probable emission rates from the mangroves of the Indian region. The seasonal oscillations in CH_4 efflux, in tune with the environmental forcing factors, further strengthens the choice of this ecosystem for regional and global extrapolation. A standard classification based on a combination of vegetation and soil types, hydrology and physico-chemical variability, in addition to the areal extent of the mangroves, has been used for extrapolation studies in this paper. The probable range in CH_4 emission from the mangroves along the Indian subcontinent ranges from 0.05 to 0.37 Tg year^{-1}. However, the predicted range of values is only based on the assumption that the mangrove ecosystem along the Indian subcontinent is unpolluted. This is only a first-order approximation, requiring a more detailed site-specific study of CH_4 emission and its local controlling factors.

Aselmann and Crutzen (1989, 1990) grouped the natural wetlands into six categories: bogs, fens, swamps, marshes, floodplain and shallow lakes. The mangroves are classified under marine swamps, based on their nature of occurrence in the tropics and subtropics. The total annual CH_4 emission from various sources has been estimated to be 540 Tg CH_4 year^{-1}, of which natural wetlands dominate as the single largest source, with an average emission of 115 Tg CH_4 year^{-1} (Cicerone and Oremland 1988; Steudler et al. 1989). The studies of Matthews and Fung (1987) suggest that the tropical and subtropical peat-poor swamps ranging from 20° N to 30° S represent about $\sim$30% of the global wetland area and produce $\sim$25% (i.e. 135 Tg CH_4 year^{-1}) of the total CH_4 emission. From the present data set, computed for the mangrove ecosystems occurring globally (16,257,341 ha), an annual average of 11.03 Tg CH_4 year^{-1} is emitted, accounting for $\sim$8% of the total emission from swamps. Of this, the contribution from the mangroves along the Indian subcontinent is $\sim$4% of the total mangrove emission (11.03 Tg CH_4 year^{-1}). In this study, we have computed the annual CH_4 emission from the mangrove ecosystems worldwide to range from 2.80 to 19.25 Tg CH_4 year^{-1} which is well within the estimates made by Bolle et al. (1989) (31 to 37 Tg CH_4 year^{-1}) for the global swamps. Sotomayor et al. (1994) reported an annual CH_4 emission from the mangroves of the Caribbean and Central America ranging from 0.012 to 0.036 Tg year^{-1}.

Conclusions

The preliminary estimates made in our study for CH_4 emission from the Indian (0.05–0.37 Tg year^{-1}) and global (2.8–19.25 Tg year^{-1}) mangroves indicate that mangroves are important potential sources of atmospheric CH_4. There is a doubling in CH_4 emission rates between the unpolluted (117.12 mg m^{-2} day^{-1}) and polluted (369.6 mg m^{-2} day^{-1}) mangrove soils, highlighting the effect of human intervention on natural fluxes. We have also quantified and discussed the factors controlling CH_4 emission, including temperature, salinity, sulfate, water content and organic matter availability in these ecosystems. At Pichavaram mangroves, there has been a gradual change in emission rate with the changing physico-chemical and environmental factors. While there was a decline in CH_4 emission rate at Ennore Creek mangrove due to fertilizer and crude oil discharges, sewage effluents increased emission rates at the Adyar estuarine mangroves. The fact that mangroves are now being used as primary and secondary sewage disposal sites poses a great threat to the ecosystem in general and to the future of this trace gas balance in particular.

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