JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. D6, PAGES 6169–6179, APRIL 30, 1992

SOURCES AND SINKS OF METHANE AND CARBON DIOXIDE EXCHANGES IN MOUNTAIN FOREST IN EQUATORIAL AFRICA

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Abstract. Sources and sinks of methane were studied in the Mayombe forest, a tropical evergreen forest located in a mountainous region in central Africa. Important methane emissions, reaching 6×10^{13} molecules/cm^2/s, were measured in flooded lowlands where soil characteristics: pH and redox potential, favor the growth of methanogenic bacteria. However, basically, soils of this region constitute a sink of atmospheric methane with uptake rates ranging from 10^{10} to 10^{11} molecules/cm^2/s. Methane emission from termite nests was also studied; it appeared to be a minor component of the methane budget. CH_4 concentrations were measured inside the forest and in the surrounding atmosphere, CO_2 being used as a qualitative tracer of air exchanges. In spite of intense but scattered and size-limited sources this environment seems to be a net sink of atmospheric methane.

1. Introduction

Soils of tropical forests have long been recognized as an important factor in the global budget of many trace gases which have a direct effect on the radiative budget of the Earth, i.e., N_2O, CH_4, and CO_2. These soils can act as sources or sinks of methane depending on their degree of anoxy. Methane fluxes from soils are the result of two antagonistic processes: CH_4 production by methanogenic bacteria and CH_4 oxidation by methylotrophic bacteria. Methane-oxidizing bacteria are ubiquitous components of soil and water microflora [Haber et al 1983], in oxic soils where the development of methanogens is inhibited, atmospheric CH_4 is consumed. It is the case in most tropical soils [Keller et al., 1983, 1986]; [Seiler et al., 1984] and notably in dry forest soils. On the other hand it has been demonstrated that flooded forest and floodplains in the tropics are major sources of methane [Bartlett et al., 1988; Devol et al., 1988; Crill et al., 1988]. Permanently or seasonally flooded forests constitute a small part of tropical rain forests [Matthews and Fung, 1987]. However in non flooded tropical forests annual rainfall is generally higher than 1500 mm and anoxic zones do exist in these ecosystems. They constitute scattered sources of methane. Additional sources are provided by termite nests which can be of great density. Can methane emissions from these scattered sources compensate for uniform consumption in dry soil? Does flooded tropical forest act as a net source or sink of atmospheric methane ? The present paper tries to answer these questions through a study of methane sources and sinks in the Mayombe forest, a tropical evergreen forest located in a mountainous region in the southern Congo. CO_2 is used as a tracer of air exchanges between the forest and the atmosphere in order to give a global view of the behavior of atmospheric methane in this medium at regional scale.

2. Experimental Site and Techniques

The Mayombe, located in southwestern Congo, is a mountainous region which forms a band along the Atlantic coast, some 60 to 80 km wide and 1000 km long, from Angola to Gabon and presents an Appalachian-type relief. The mountain chain is a succession of watersheds separated by rather deep main valleys inside which small peaks separate secondary valleys. The altitude of the summits increases progressively from west to east and reaches 900 m, 100 km inland. A very dense hydrographic network is

Paper number 90JD02575.
0148-0227/92/90JD-02575$05.00

associated with this relief, with small rivers inside the main valleys and a great number of seasonal or permanent tributaries running in shallows which are partly flooded after heavy rainfalls. The vegetation is predominantly evergreen tropical rain forest. The top of the densest vegetation stratum is about 30 m high, while the upper part of the canopy attains 50 m, with some emergent trees rising to about 60 m above the forest floor. The vegetation is very dense; only 10% of the incident solar radiation flux reaches the soil surface which remains moist during the greater part of the year except at the end of the dry season (September). Soils are classified as ferralitic cambisoils [Food and Agriculture Organization, 1976]. Under a litter layer generally rather thin, the carbon content inside the organo- mineral horizon (5 - 10 cm) ranges from 6 to 20%. Annual litter falls are about 5 T dry matter per year (D. Schwartz, 1989, personal communication).

In the lower layers of the atmosphere (0 - 2000 m) the air flow originates from the Atlantic ocean. The Mayombe region is under an equatorial-type climate, however, during the austral winter from June to October a seasonal coastal upwelling (Benguela current) induces cooling of the lower atmosphere which considerably limits the convective activity. This period corresponds to the dry season. Precipitations are very low, less than 20 mm per month and limited to stratiform rains; however orographic effects often lead to the formation of fog which maintains high humidity. The annual rainfall is about 1500 mm. The heaviest rains generally occur in November and April [Clairac et al., 1989]. Experiments were conducted in the vicinity of the Dimonika Research Station (4°30'S, 10°30'E). The main sampling site was located in a valley 10 km from the station. A 45-m-high metallic tower, built through the vegetation and reaching the top of the canopy, allowed sampling at different levels. Measurements of CH_4 and CO_2 were also performed at the research station itself. The sampling point was located on the top of a hill which rises about 150 m above the bottom of the Dimonika valley. These second series of measurements can be considered representative of atmospheric layers just above the forest canopy.

Methane and CO_2 were measured by gas chromatography. Analytical techniques are described in another paper [Tathy et al., this issue]. Two types of measurement were performed: direct flux measurements using closed static chambers and concentration measurements in the atmosphere. Samples of air were taken inside the chambers through a septum with 15-ml glass syringes which were wrapped in polyethylene bags after sampling. Samples of air for concentration measurements in the atmosphere were taken in 0.71 aluminum containers under a pressure of 3 bars using a small compressor, energy being supplied by a 12-V battery. At the laboratory of the Dimonika Research Station air samples were taken 3 m above ground using 1-cm-diameter Teflon tubing. The same type of tubing was also used to take samples at different levels inside the forest. Gas chromatography analysis was performed in our laboratory at Brazzaville within a few days after sampling. Uncertainties on concentration measurements were 0.5% for methane and 1% for carbon dioxide while detection limits for flux measurements were 10^9 and 10^{11} molecules/cm^2/s. respectively.

Flux measurement by the static chamber method was accompanied by measurement of pH, water content, and redox potential of the soil. Methanogenic and homoacetogenic bacteria were measured on the main types of sampled soils. CH_4 emissions from different termite nests were also studied by the static chamber method. In this case the chamber was constituted of a light wooden frame built up over the termite mound and covered with a Teflon film. The volume of air trapped inside the Teflon enclosure was calculated from its own volume and by assessment of the volume of the mound. Air samples were taken inside the enclosure in aluminium containers filled up every 10 mn, up to 40 mn after covering the nest. CO_2 and CH_4 were analyzed in the same samples.

Methane and CO_2 were measured at the Dimonika Research Station in order to follow the daily evolution of their concentrations in the surrounding atmosphere of the forest. Inside the forest, samples of air were taken at different levels up to 40 m high throughout the day to follow daily evolutions of vertical gradients. CH_4 gradients were also measured in flooded shallows using a Teflon line hoist up to 10 or 15 m by a pulley attached to tree branches.

Data presented in this paper were obtained during four research campaigns in April 1988, January 1989, and April 1989 during the rainy season and in June 1988 in the early dry season. During these campaigns all the measurements previously described, i.e., study of daily patterns of concentrations outside the forest and concentration gradients inside the forest, flux measurements by static chambers over soils and termite mounds were carried out over 6-to-8 day periods. Results obtained were characterized by a good reproducibility for comparable weather conditions; most of the variations observed were similar. We will present in the sections below, especially in figures, only the most representative of the eight daily variations of vertical gradients measured inside the forest.

3. Methane and CO_2 Flux From Static Chamber Measurements

3.1. Soils

Methane and carbon dioxide were measured on different types of soil. Mean values are given in Table 1. Soils are divided into four categories: mountain slopes, non flooded soils in valleys, seasonally flooded shallows and permanent swamps. Basically, dry soils on both mountains and valleys exhibit positive values of redox potential (+230, +400 mV) and negative flux showing consumption of atmospheric methane with an uptake rate of the order of 10^{10} molecules/cm^2/s in the wettest zones of the valleys and reaching 10^{11} molec./cm^2/s on the upper parts of hillsides on well-aerated organic soils. These soils, like most tropical forest soils, have acidic pH, generally lower than 4.

In flooded shallows during the rainy season, where soils present strongly negative redox potential (-180 mV) and are made up of organic and reducing mud, methane emission is very high, reaching $6x10^{13}$ molec./cm^2/s . These fluxes are 10 to 20 times higher than those measured in the flooded forest zone of the northern Congo [Tathy et al., this issue). These values are comparable with the highest fluxes recorded in the Amazon floodplain [Devol et al., 1988; Bartlett et al., 1988]. As substrate quality is nearly the same in the northern Congo and Mayombe forests, with soil carbon contents generally higher than 10%, the difference in methane flux could be linked to the difference in the pH of the two media. Basically, tropical forest soils are acidic; in floodplain permanently or seasonally flooded by the rising of the water table, acidity is still higher (pH is equal to 3.1-3.3 in the Northern Congo forest). During the rainy season in flooded shallows of the Mayombe forest, pH is around neutral value. This is probably due to the washout of cations by running waters along mountain slopes. In shallows where running water is collected, soil characteristics become favorable to the development of methanogenic bacteria; pH around 7 and Eh around -200 mV are values close to optimal growing conditions of methanogen populations.

Methane emissions from these anoxic zones undergo drastic seasonal changes. In April 1988 methane flux was measured on waterlogged soils with pH of 6.6 and Eh of -180 mV. The average flux was very high: $2.58x10^{13}$ molecules/cm^2/s. Five weeks later at the beginning of the dry season, new measurements were carried out at the same place. During that period, owing to the absence of rain, soils had dried up, pH decreased from 6.6 to 4.8, Eh increased up to +220 mV and methane flux was still positive but 400 times lower than 5 weeks earlier, i.e., $6.3x10^{10}$ molecules/cm^2/s. Measurements were not performed at the end of the dry season, but it is very likely that at that period methane consumption in soils occurs everywhere, even in shallows.

Contrary to methane flux, that of carbon dioxide is quite constant for any type of soils. It does not seem to be strongly linked to the the soil moisture;

Table 1. CH_4 and CO_2 Fluxes From Different Soil Types Measured by the Static Chamber Method in the Mayombe Forest

Type of soil	nb.of meas.	Soil characteristics			CH_4 flux	CO_2 flux
		Water content %	pH	Eh (mV)	molecules. $cm^{-2}.s^{-1}$	molecules $cm^{-2}.s^{-1}$
Hillside	6	28 (25-32)	3.5 (3.4-3.6)	+375 (350-400)	$-8.3x10^{10}$ (-3.1,-12.3)	$1.83x10^{14}$ (1.41-2.2)
Valley	8	29 (21-40)	3.8 (3.5-4)	+275 (230 -340)	$-1.4x10^{10}$ (+4.3,-5.3)	$1.18x10^{14}$ (0.9-1.35)
Flooded shallow	6	saturated	6.9 (6.6-7)	-180 (-120,-200)	$8.4x10^{12}$ (25.8-0.12)	$1.19x10^{14}$ (0.5-1.42)
Permanent swamp	4	saturated	6.6	-162 (-150,-190)	$5.79x10^{13}$ (4.02-6.20)	-

Soil characteristics: Water content, pH, and oxido reduction potential Eh. Numbers in parentheses denote the range of measurements.

however, it seems to be higher on the driest soils, on hillsides (1.83×10^{14} molecules/cm^2/s) than on hydromorphic soils in valleys and flooded shallows (1.18×10^{14} molecules/cm^2/s). The average value obtained for the Mayombe forest soils: 1.4×10^{14} molecules/cm^2/s is similar to those obtained in Amazonia: 1.5×10^{14} molec./cm^2/s [Keller et al., 1986], 2.54×10^{14} molecules/cm^2/s [Wofsy et al., 1988]. In the Mayombe forest annual litter falls are weak: 4.8 to 5.2 T dm/ha (D. Schwartz, personal communication, 1989). Assuming a carbon content of 45% in the dead organic material, this corresponds to an input of 2.25 T(C)/ha/yr which represents only 25% of the carbon emitted as CO_2 from soil. Thus litter decomposition accounts for only one quarter of the CO_2 emission from soil; the remaining three quarters are due to respiration and decomposition of soil microfauna and microflora. This result agrees with many other studies in tropical forest [Medina et al., 1980; Wofsy et al., 1988].

3.2. Termite Mounds

Until recently, methane production by termites was considered as one of the most important sources of atmospheric methane. Global emission estimates were as high as 150×10^{12} g/yr [Zimmerman et al., 1982] or 50×10^{12} g/yr [Khalil and Rasmunssen, 1983]. Such estimates were based on laboratory experiments and used potential CH_4 production rates of several species of termites. More recently, field experiments on termite mounds in South Africa [Seiler et al., 1984] showed that the previous figure of global CH_4 production by termites was strongly overestimated. A recent paper by Khalil et al. [1990] agrees with this last conclusion with a global estimate of methane production by termites of only 12 Tg per year.

In the area of the Mayombe forest under study, the number of termite mounds per surface unit is known for the dominant species thanks to several studies undertaken to determine the role of termites in the dynamics of tropical forest soils [Sillam-Garnier, 1987; Rouland, 1986]. Around the main measuring point in the forest, near the metallic tower, termite mound density reaches 290 mounds per ha. Termites are divided into three categories: soil feeding termites (246 mounds per ha), fungus growing termites (16 mounds per ha) and wood feeding termites (28 mounds per ha) (Table 2). The average density of termites in the Mayombe region is estimated at between 1200 and 2700 insects/m^2 of soil, their role in soil ecology is considerable, especially that of fungus growing termites (*Macrotermes muelleri*); they consume and recycle at least half of the dead organic material brought down by litter falls. Some termite species are known to produce high amounts of methane, especially soil-feeding termites, up to 22 µl CH_4/termite/h [Brauman, 1989; Brauman et al., 1990].

Two approaches were used to study the role of termites in methane exchanges in the forest ecosystem, i.e., direct measurements over termite mounds and CH_4 vertical profiles inside the forest in a zone where the termite mound density was known. A strong source of methane assumed to be linked to termite activity would lead to a typical evolution in methane concentration inside the forest due to daily variations of air stability under the canopy as observed in the flooded forest of the Northern Congo, owing to important emission from waterlogged soils [Tathy et al., this issue]. Among the 10

Table 2. Termite Mound Repartition Close to the Measuring Site in the Mayombe Forest

Families	Species	Number of nests/ha Above Ground
Soil-feeding termites	*Thoracotermes*	72
	Noditermes	38
	Procubitermes	26
	Cubitermes	56
	Crenetermes	48
	Anoplotermes	6
Fungus-growing termites	*Macrotermes mülleri*	16
Wood-feeding termites	*Nasutitermes*	22
	Cephalotermes	1
	Macrotermes	5

From Sillam-Garnier [1987].

termite species identified in the sampling area, the three most abundant were studied by direct flux measurement: <u>Macrotermes</u> <u>muelleri</u>, <u>Thoracotermes</u> <u>macrothorax</u> and <u>Cubitermes</u> <u>speciosus</u>. The results obtained are presented in Table 3. They are given in molecules per cm^2 termite mounds per s corresponding to the enclosure area in order to be compared to soil emissions. All the mounds studied produce methane and carbon dioxide. CH$_4$ emission is lower than that of hydromorphic waterlogged soils, 2.3x10^{11} molecules/cm^2/s for <u>Macrotermes</u>, 3.8x10^{11} molecules/cm^2/s for <u>Thoracotermes</u> and in the same order of magnitude 10^{13} molecules/cm^2/s for <u>Cubitermes</u>. <u>Cubitermes</u> seem to be the main methane producers; however, <u>Cubitermes</u> mounds are generally rather small. CO$_2$ emission from termite mounds is 3 to 30 times higher than that of soils. The highest emissions registered were from <u>M.</u> <u>muelleri</u> mounds.

The rather low emission of methane in comparison with potential CH$_4$ production by termites could be due to methane-oxidizing bacteria which have been recognized for many decades, and can be present in the termite mound itself, consuming most of the methane produced. These bacteria are strictly aerobic and use methane as a carbon source. All methane oxidizers appear to require carbon dioxide for growth [Whittenbury and Dalton, 1981], therefore the termite mound constitutes certainly an environment which favors the growth of these bacteria. Nevertheless, an in vivo comparison in closed boxes, between the potential CH$_4$ production by termites and the potential consumption by methanotrophs from soil or termite mound fragments, is technically hard to realize. So it is difficult to appreciate the respective role of these two bacterial communities in the net methane production by termites in natural environment.

Absolute fluxes can hardly be compared with previous results [Fraser et al., 1983, Seiler et al 1984) because units are not the same and moreover emission from a given mound depends on its size, however flux ratios F(C-CH$_4$)/F(C-CO$_2$) are similar. Taking into account the above-mentioned distribution of termite mound in the region under study and the mean size of mounds of the different species we can estimate the total area of above ground termite mounds at 50 to 350 m^2 per ha (0.5 - 3.5%). With an average emission from a mound of 5x10^{11} molecules/cm^2/s this figure would lead to a methane emission from termites of 5x10^9 molecules/cm^2/s or 0.11 mg(CH$_4$) /m2/d for the Mayombe forest. Considering a termite density of 1200 /m^2, the mean CH$_4$ production rate would be 0.045 - 0.32 g (CH$_4$)/termite/d which is lower than the production rates given by Zimmerman et al. [1982]. Uncertainty linked with such calculation is certainly very large, and the role of termites which leave their nest during the night is not considered; however the order of magnitude obtained indicates clearly that termites do not constitute a major source of atmospheric methane. This source could be lower than the sink associated with methane uptake in dry soils as already found in tropical savanna [Seiler et al., 1984]. This will be verified in the section 4 through the results of variations of methane profiles within the forest.

4. Methane and Carbon Dioxide Variations: Relative Importance of CH$_4$ Sources and Sinks

Previous results show that flux measured by static chambers is, in most cases, representative of the enclosure surface only. The methane emission observed, ranges from 10^{10} to 5x10^{13} molecules /cm^2/s on soils, from 10^{11} to 10^{13} on termite mounds, while methane uptake by dry soils seems to be more homogeneous: 10^{10} to 10^{11} molecules/ cm^2/s. CH$_4$ sinks are widespread but weak, CH$_4$ sources are intense but scattered,

Table 3. Methane and Carbon Dioxide fluxes From Termite Mounds of the Three Most Abundant Species of the Mayombe Region Measured With a Teflon Enclosure

Termite Species	Number	CH4 Flux molecules/ cm^2/s	CO2 Flux cm^2/s	Flux C-CH4 / Flux C-CO2
<u>Macrotermes</u>	5	2.33x10^{11} (1.05-3.56)	1.8x10^{15} (0.62-3.53)	1.3x10^{-4}
<u>Thoracotermes</u>	4	3.76x10^{11} (1.3-6.23)	2.69x10^{14} (1.97-3.41)	1.4x10^{-3}
<u>Cubitermes</u>	3	10.2x10^{12} (6.3-12.2)	7.1x10^{14} (4.7-9.2)	1.4x10^{-2}

and their global area is probably small. Variations of intensity of more than 3 orders of magnitude and unknown distribution of sources do not allow any conclusion as to their effective role on the methane budget in this ecosystem. Previous studies of methane emissions in the flooded forest of the northern Congo have shown that in the presence of a strong widespread source of methane, concentration inside the forest and in the surrounding atmosphere presents a typical pattern linked to vertical exchange and correlates with CO_2 variations [Tathy et al., this issue]. The same type of analysis is applied to the Mayombe forest.

4.1. CO_2 Exchanges

CO_2 exchanges were studied during two experiments in June 1988 and April 1989. During the first experiment, air samples were taken throughout the day at 1, 3, 6, and 20 m above ground level, and during the second experiment at 1.5, 21, and 42 m, the densest vegetation stratum being at about 20 m above the forest floor. At the same time, air samples were taken every 2 hours at the Dimonika Research Station in order to follow CO_2 and CH_4 variations in the surrounding atmosphere of the forest.

CO_2 vertical profiles measured in June 1988 (Figure 1a) and April 1989 (Figure 1b) present dissimilar patterns. In both cases, CO_2 emission from soil leads to systematic increase in concentration within the first meters above the forest floor. On Figure 1a the evolution of CO_2 profiles during the daytime from 0900 to 1430 shows an accumulation of this gas close to the ground with concentrations exceeding 410 ppm in the afternoon. It has been previously shown [Clairac et al., 1988] that daytime exchanges are regulated by a temperature inversion between the ground and the lower part of the canopy; this phenomenon is comparable to that observed in the northern Congo forest. On a sunny day, around noon, this inversion can reach 5°C between 0 and 30 m leading to strong air stability close to the ground. This was the case on June 1, 1988, while in 1989, cloudy weather did not allow such stability to develop; CO_2 profiles always decrease from the surface to the canopy, but we did not observe accumulation of CO_2 in the surface layer (Figure 1b). In both cases the concentration in the densest part of the vegetation, around 20 m high, decreases during the daytime as a consequence of photosynthesis. In the upper part of the canopy, concentrations present only slight variations. In both cases we observe an accumulation of CO_2 during the night, until the early morning in the whole forest atmosphere. Concentrations are nearly uniform from the ground to the top of the canopy showing a well-mixed atmosphere during that period, then the forest acts as a source of CO_2 owing to nocturnal respiration and continuous soil emission. During daytime, most of the CO_2 emitted from the soil is absorbed by the vegetation. Strong stability conditions observed on June 1, 1988 allow calculation of the CO_2 flux from the soil, from integration, between 0 and 10 m of vertical profiles obtained at 0930

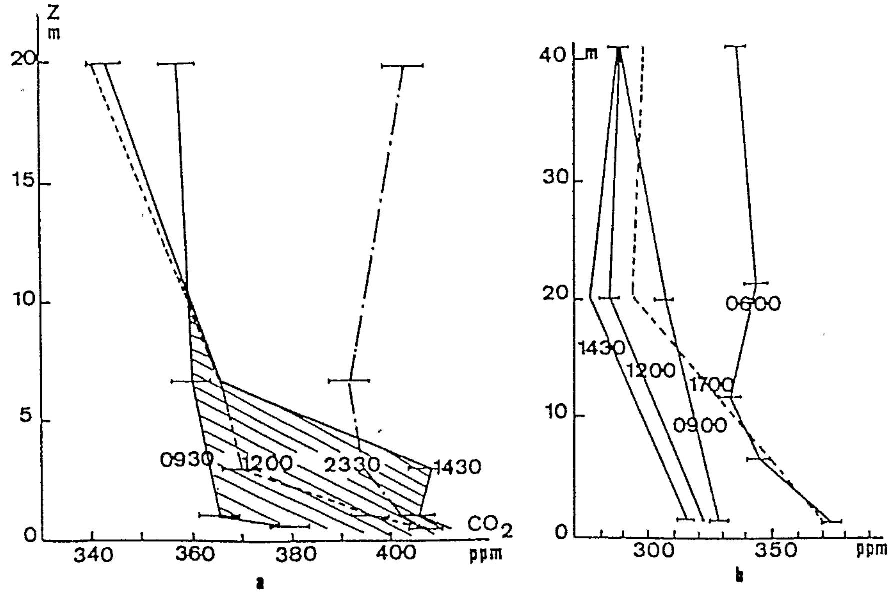

Fig. 1. (a) Vertical profiles of CO_2 between 0 and 20m height measured at the forest site using the metallic tower on June 13, 1988. (b) Vertical profiles of CO_2 on the same site on April 24, 1989.

and 1430. This flux is 2.84×10^{13} molecules/cm^2/s which represents less than a quarter of the average flux measured by static chambers. This discrepancy must be explored, in the Mayombe and in other tropical forest sites, in order to verify the generality of the phenomenon. June 1, 1988, was the only day, over the four campaigns, with diurnal stability conditions allowing this type of calculation. In the Mayombe region, days with clear sky are very scarce; on a yearly average sunshine is less than 2 hours a day.

At the Dimonika Research Station, considered as representative of the atmosphere above forest canopy, CO$_2$ evolutions are in accordance with this daily pattern. Maximum CO$_2$ concentrations are observed at the end of the night, they decrease in the morning to reach minimal values around noon and then increase in the late afternoon (Figure 2a and 2b). The amplitude of this daily wave reaches 45 parts per million by volume in June 1988 and 35 ppmv in April 1989. It certainly depends on the intensity of vertical exchanges between the forest and adjacent atmospheric layers and on the importance of temperature inversion under the canopy. It must also be noticed that the average CO$_2$ concentration is quite different during the two experiments: 373 ppmv in June 1988 and 344 ppmv in April 1989. The highest concentrations observed in June 1988 could be due to smaller exchanges between the forest environment and the atmospheric boundary layer.

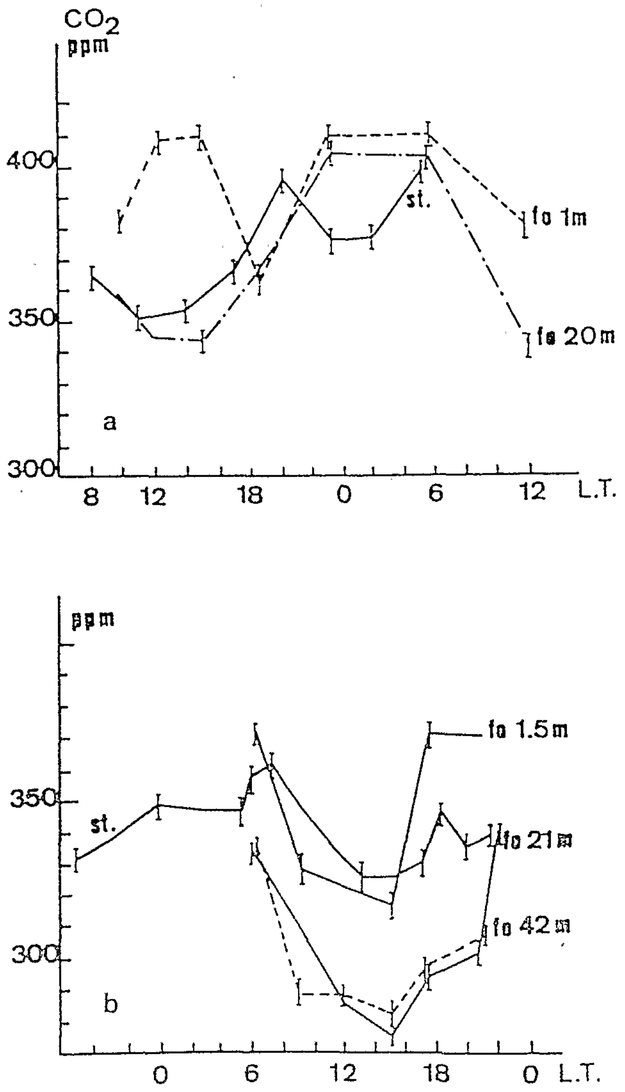

Fig. 2. Daily variations of CO$_2$ at different levels inside the forest and at the Dimonika Research Station on (a) June 3/4, 1988, and (b) April 23/24, 1989.

4.2. CH$_4$ Variations Within the Forest

As mentioned earlier methane concentrations were measured at different levels inside the forest over dry and waterlogged soils.

Flooded zones. In flooded shallows where a large flux was measured with static chambers, vertical profiles are generally characteristic of a methane source at ground surface. Profiles reported on Figure 3a were obtained on January 24, 1989, in shallows partly flooded with running water, a result of abundant rainfalls. At 1600 when vertical diffusion is minimal, a gradient of 0.1 ppmv is observed between the ground and 10 m high. In the other example (Figure 3b) obtained in June 1989 after the rainy season in a lowland, in the course of drying up, methane concentration decreases from the ground to 15 m high, but concentration profiles are somewhat incoherent. This is probably due to horizontal advection which brings air coming from more or less CH$_4$ productive zones. Similar measurements carried out during the other campaigns always showed the same result, i.e., a slight increase in methane concentration close to the flooded soil. We never found large increases in concentration like those observed in the northern Congo forest where concentrations of 4 ppmv were recorded in the afternoon. Flooded soils are generally situated on either side of small tributaries of the main rivers, these zones do not exceed a few meters wide; horizontal mixing of air prevent important increases in CH$_4$ concentration above these limited swampy zones.

Dry soils with a large density of termite nests. CH$_4$ profiles were measured over dry soils with water content ranging from 20 to 30% in the vicinity of the metallic tower, samples were taken at different levels up to 42 m high along the tower, with a teflon tubing. Termite mound distribution has been determined in this area (see Table

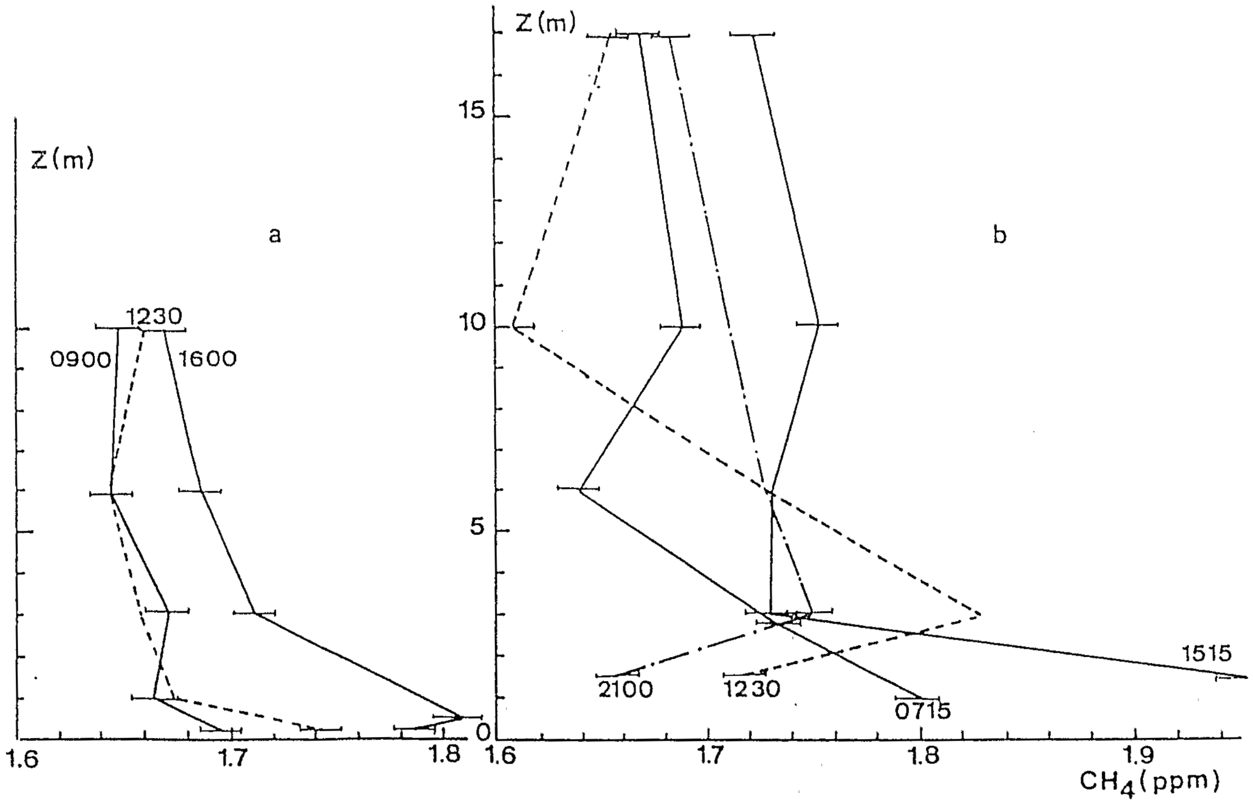

Fig. 3. Examples of vertical gradients of methane measured in flooded shallows on (a) January 13, 1989, and (b) April 24, 1989.

1). Several experiments were conducted on this site. The results of two are given in Figures 4 and 5. Methane profiles between 0 and 25 m high were measured in April 1988 during the wet season (Figure 4). Whatever the sampling level methane variations are small with a maximum amplitude of 0.1 ppmv. CH_4 and CO_2 profiles appear to be anticorrelated in the surface layer below 10 m high. The profile shape indicates a downward flux of CH_4, close to the ground, which could be linked to methane uptake by the soil. As a consequence this sink would be dominant toward the source constituted by termites whose density reaches 1200 /m^2

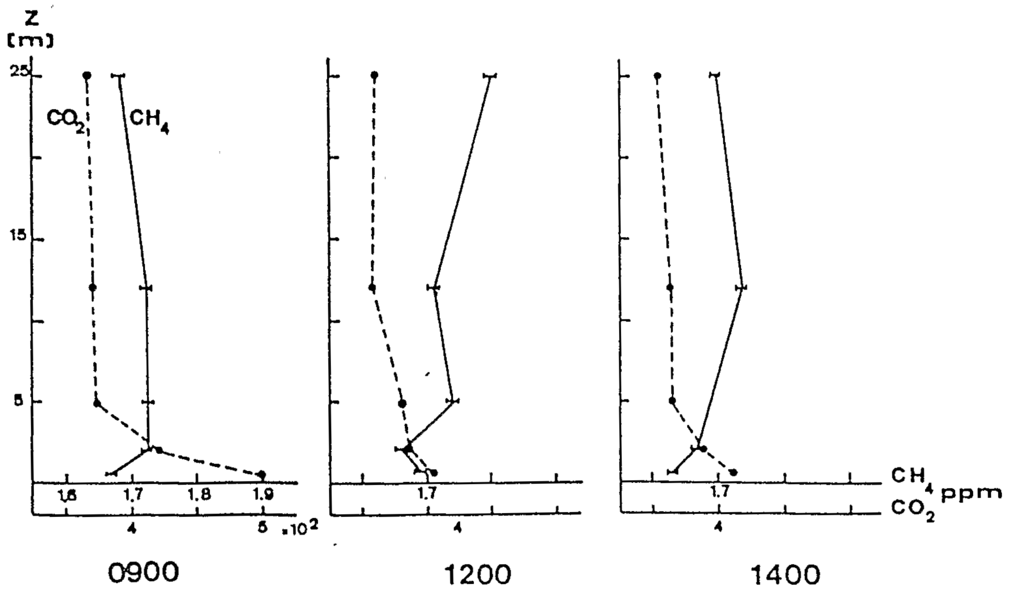

Fig. 4. Methane and CO_2 profiles over dry soils in a zone with high density of termite nests. Samples being taken on the metallic tower, April 27, 1989.

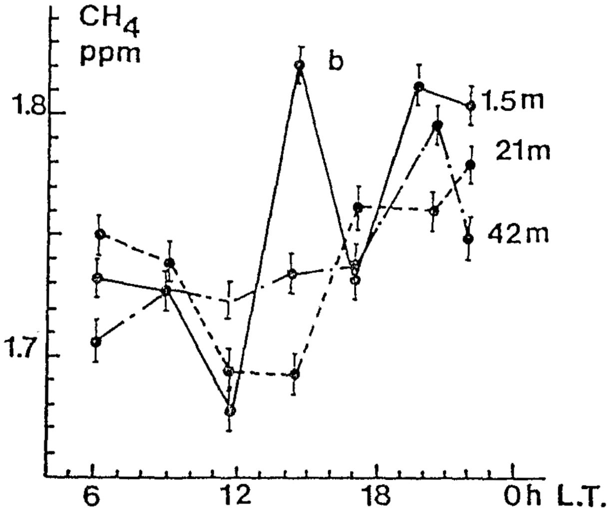

Fig. 5. Daily variations of methane concentrations at the three levels of 1.5, 21 and 42 m inside the forest on April 24, 1989.

in this zone. This is in accordance with the previous calculation based on the measurement of termite nest emission and of soil uptake rate.

Daily variations of CH_4 concentration were then studied at three levels (1.5, 21, and 42 m) on April 25, 1989 (Figure 5). No clear tendency appears in vertical gradients between the forest floor and the canopy; they are alternately positive or negative. As in the previous case CH_4 variations are of the order of 0.1 ppmv. Fluctuations at the same level are higher close to the ground (0.15 ppmv) than at upper levels (0.08 ppmv at 21 m, 0.05 ppmv at 42 m). This is certainly due to the presence of scattered sources: the termite mounds, combined with non organized air circulation close to the surface. Concentration seems to increase in the evening when the atmosphere under the canopy is well mixed, as shown by CO_2 profiles, outside air being transported within the forest as demonstrated through previous measurements of submicron particules and radon [Clairac et al., 1986; Clairac et al., 1988]. During daytime, when vertical exchanges are reduced, the average concentration under the canopy seems to be lower than that of the boundary layer. This tends to indicate that the forest globally acts as a sink for atmospheric methane.

4.3. CH_4 and CO_2 Evolution Outside the Forest

Methane and Carbon dioxide concentrations were measured at the Dimonika Research Station on June 2/3, 1988, and April 25/26, 1989 (Figure 6a and 6b). As shown in the previous section, CO_2 concentration outside the forest presents a daily wave associated with the photosynthetic cycle and air exchanges between forest and the outside atmosphere. CO_2 increases during the night when both soil and vegetation act as a source and decreases in the morning when atmospheric CO_2 is absorbed by the vegetation and CO_2 emitted by soils is

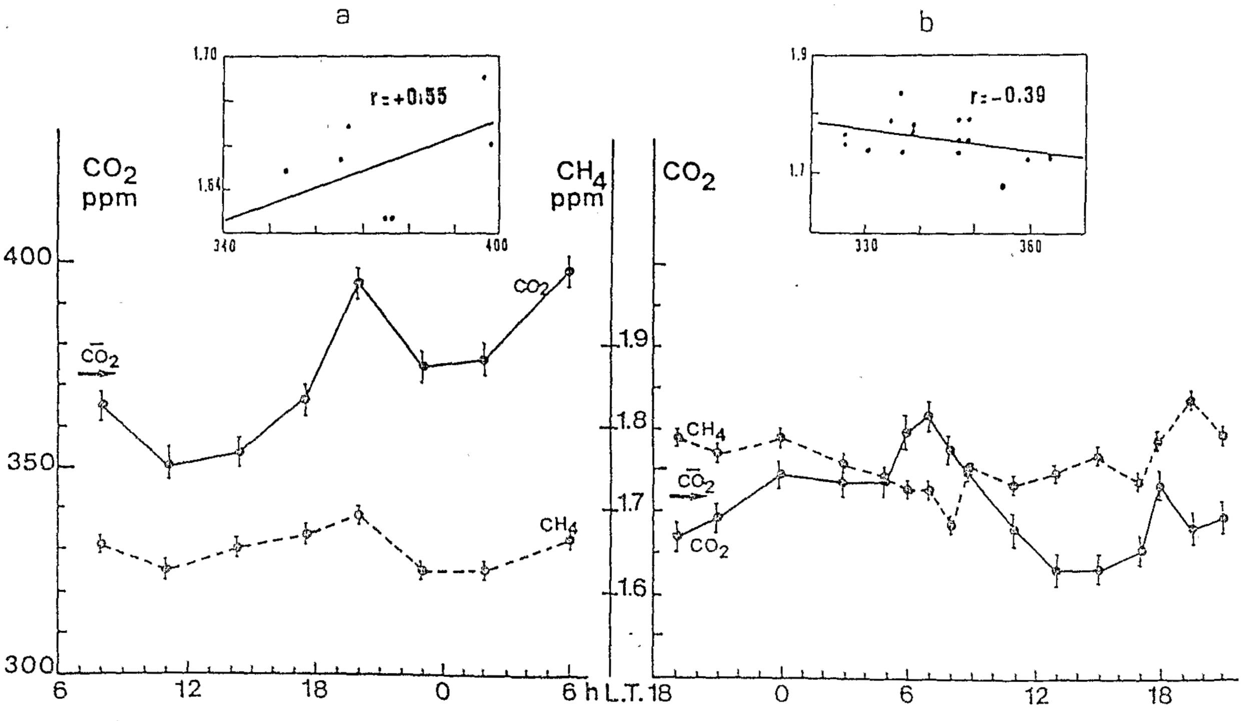

Fig. 6. CH_4 and CO_2 evolutions at the Dimonika Research Station on (a) June 3/4, 1988, and (b) April 23/24, 1989.

trapped within the forest atmosphere by temperature inversion below the canopy. Methane concentration outside the forest does not show any typical daily variations, they do not correlate with CO_2, the correlation cofficient being +0.55 in June 1988 and -0.39 in April 1989 (Figure 6a and 6b). An important CH_4 source inside the forest would have led to a diurnal pattern similar to that of CO_2 as observed in a clearing of the northern Congo flooded forest [Tathy et al., this issue]. It can just be noticed that mean values of CO_2 and methane, observed during the two campaigns in the surrounding atmosphere of the forest, present opposite behaviors. In june 1988 CO_2 is higher (375 ppmv) and methane low (1.65 ppmv) in comparison with average atmospheric concentrations. In April 1989 the reverse phenomenon occurs: CO_2 is lower (345 ppmv) while methane is high (1.75 ppmv). If we assume that global CO_2 exchanges between vegetation and ambient air were the same, the difference in CO_2 concentrations can be explained by global differences in air exchanges between the forest environment and the free atmosphere. Low methane concentrations correspond to reduced vertical exchanges; this observation, along with the former one (section 4.2), tends to indicate that globally this type of forest acts as a net sink for atmospheric methane.

5. Conclusion

Recent studies, only based on static chamber measurements of methane emission, have shown that dry forest soils absorb atmospheric methane leading to the conclusion that the tropical forest acts as a sink for this constituent. We tried to check this assertion in an African equatorial forest by studying individually potential sources and sinks and the behavior of atmospheric methane in this environment using CO_2 as a qualitative tracer of air exchanges. We have identified strong sources of methane in flooded shallows. The high flux recorded, up to $5x10^{13}$ molecules $/cm^2/s$ was attributed to soil conditions: neutral pH and strongly negative oxido reduction potential, favorable to the growth of methanogen populations. One of the most interesting results of this study concerns CH_4 emission by termites. It appears as a minor source. It was suggested by direct flux measurement over termite nests and then confirmed by a study of methane variation in ambient air under the canopy in a zone where termite mound density was known. This could be due to the methane-oxidizing bacteria living inside the termite mound which would act as a biofilter absorbing the methane produced by termites.

In spite of high emission rates the total area of the sources is too low to compensate for methane consumption by dry soils which present uptake rates ranging from 10^{10} to 10^{11} molecules/ cm^2/s. As a result this type of forest appears as a net sink for atmospheric methane. This is also confirmed by concentration measurement in the atmosphere within and above the forest canopy and is in accordance with previous studies in similar environment [Keller et al., 1986].

Aknowledgments. We would like to thank the Congolese Administration of the Scientific and Technical Research (DGRST), the manager, and the staff of the Dimonika Research Station for their help. This work was supported by the PIREN-CNRS, the French Ministry of Cooperation (CAMPUS PROGRAMME), and by the Division of Ecological Sciences of UNESCO.

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(Received April 27, 1990;
revised November 23, 1990;
accepted November 23, 1990.)