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Atmospheric balance of sulphur above an equatorial forest

By R. DELMAS, *Département de Physique, Faculté des Sciences d'Abidjan, 04 BP 322, Abidjan 04, Ivory Coast* and J. SERVANT, *Laboratoire de Physique des Aérosols et Echanges Atmosphériques, Université Paul Sabatier, 118 Route de Narbonne, 31062 Toulouse Cedex, France*

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ABSTRACT

The atmospheric sulphur balance over the humid tropical forest of the Ivory Coast is studied over a 1-year period. A box model limited by the monsoon layer between the coast of the Gulf of Guinea and the savannah is used. The height of the box is between 1 and 3 km, its length 120 km, and its width 0.001 km. The sulphur compounds considered are gaseous H_2S and SO_2 and particulate $SO_4^=$. Chemical criteria are used to differentiate the $SO_4^=$ of atmospheric, oceanic, soil-derived and plant origins. The sulphur compounds are measured in the air and in the rain-water at 2 stations, one at the box entry (Adiopodoumé) and the second at the exit (Lamto). The sulphur balance of the box (inflow minus outflow) indicates that the mean annual emission by the soils of the forests is 1.5 g S m^{-2} yr^{-1}. This emission is modulated by the rainfall. It is shown that the mean emission of the wet season is 6 times that of the dry season. If such a sulphur emission takes place in all other humid tropical forests, 25×10^6 metric tons of sulphur per year would be injected into the atmosphere, about $\frac{1}{4}$ of the present anthropogenic emissions. The tropical forests would then be one of the most important natural sources of atmospheric sulphur.

1. Introduction

Many balances of the global sulphur cycle have been established (Eriksson, 1960; Junge, 1960; Robinson and Robbins, 1972; Kellog *et al.*, 1972; Friend, 1973; Granat *et al.*, 1976). At present the intensity of the anthropogenic emission is estimated at $100 \pm 20 \times 10^6$ metric tons of sulphur per year, while that of the natural sources (continental and oceanic biomasses and volcanism) is still unknown. In all the different cycles, the natural emissions have been calculated in order to balance deposits. However, data for sulphur deposition is incomplete. No data are available for the oceans, and some measurements for the continents are erroneous due to, for example, the contribution of unevaluated sources such as the sulphate input from plant fragments. Therefore, the calculation of the emissions only gives the approximative order of magnitude of the intensity of the real emissions. Current research is directed towards the measurement of the fluxes of the natural sulphur compounds into the atmosphere. This work presents several difficulties. The first difficulty is that some gaseous sulphur compounds such as dimethyl sulphide (DMS) and methyl mercaptan (MeSH) are oxidized very quickly in the atmosphere (in about 1 or 2 h) and their ambient concentrations may be too low to be measured directly. It has been proposed (Bonsang, 1980) that the rate of generation of the oxidation product of these substances, sulphur dioxide (SO_2), be measured since its residence time in the atmosphere, which is of the order of 1 day, is better known (Nguyen *et al.*, 1975; Bonsang *et al.*, 1980). However, the techniques used for measurements at low levels, where the concentrations are about 30 p.p.t. over the oceans, do not yet have the required sensitivity to yield reliable values. The measurements of particulate (mainly sulphates (SO_4)) at levels comparable to those of SO_2 are less difficult because sulphate can be concentrated on a filter. A second difficulty appears with the necessity to determine the origins of the $SO_4^=$ collected. Indeed, even above a fixed

source through long-range transport, there are $SO_4^=$ contributions from various anthropogenic sources and natural inputs (continental, oceanic and volcanic). In general in the measurements carried out until now, the required criteria to discriminate and calculate the different $SO_4^=$ fractions in a given sample have not been investigated. From this point of view, the conclusions drawn from these studies are not totally convincing.

To demonstrate the importance of the natural sources, a study of the sulphur budget over the humid tropical forests will be presented. We have tried to solve the difficulties mentioned above. The climatic conditions in these forests promote the formation of hydrogen sulphide (H_2S) in the soils. These forests represent a potentially important source, as their total biomass is about 50% of that of the continental biomass. Delmas *et al.* (1978) showed that more than 70% of the $SO_4^=$ particles in the atmosphere are of biogenic origin in the forested zone of the Ivory Coast. The essential source is sulphate reduction of organic matter by bacterias in the forest soils leading to the formation of H_2S. This observation is in disagreement with that accepted until now, that the H_2S formed in the soils reduces the iron oxides, and that the emission into the atmosphere is very low. The intensity of this source was, however, not homogeneous. It varied highly with the hydrous state of the soils. For example the H_2S flux above hydromorphic soils was 10 to 30 times that above dry soils (Delmas *et al.*, 1980). It was therefore difficult to estimate the global emission of sulphur from measurements over small areas. In order to obtain a representative value of the mean emission of sulphur, one must multiply the number of measurement points. This is the reason we chose a more global approach, utilizing a simple model to represent the atmosphere above the forested zone. The monsoon layer is considered as a box in steady-state. The balance of the fluxes through this box allows us to evaluate the mean emission of sulphur from the soils of the forest. This model also allows calculation of the mean oxidation rate of sulphur compounds to $SO_4^=$, in the atmosphere.

2. Sulphur compounds

2.1. *Criteria of origins*

The sulphur compounds which were measured are gaseous H_2S and SO_2 and particulate $SO_4^=$. The techniques used were fluorescence, colorimetry and atomic absorption spectrometry (Delmas *et al.*, 1978; Slatt *et al.*, 1978; Delmas, 1980; Delmas *et al.*, 1980).

In the $SO_4^=$ analysis, the soil-derived and marine fractions were estimated by measuring the Ca^{++} and Cl^- contents and taking the ratios $(SO_4^=)/(Ca^{++}) = 1.16$ (soil-derived aerosol) and $(SO_4^=)/(Cl^-) = 0.14$ (marine aerosol). The value of the $(SO_4^=)/(Ca^{++})$ ratio was determined from 25 aerosol samples in Ouadagoudou, a station located 750 km north of Lamto and under the influence of the harmattan. This ratio is 7 times higher than the mean world ratio of the soil (Bowen, 1966). The sea-water value of the $(SO_4^=)/(Cl^-)$ ratio is questionable, as the Cl^- concentration is not an invariable property of the marine aerosols. It can decrease with the escape of Cl from the aerosol under the action of an acid stronger than HCl, such as H_2SO_4 or HNO_3. Na^+, usually a typical marine element, is also present in great abundance in the soil-derived aerosol in the atmosphere of the forested zone. Therefore Cl^- remains the best reference element for marine origin. To determine the input of $SO_4^=$ from plant debris, the ratio $[(K^+) + (Ca^{++})]/[(Na^+) + (Mg^{++})]$ was determined in the aerosols and rain-water collected from the forested zone. Crozat (1978) showed that this ratio varies from 7.6 in plants to 1.3 in soil-derived aerosols and 0.1 in marine aerosols. In general, the values of this ratio in our samples were between 0.2 and 0.5, which shows that the contribution from plant debris, 2 to 5%, is negligible.

2.2. *Emission of H_2S*

The emission rate of H_2S was measured in the Taï forest by accumulation of H_2S under the canopy during the night. During the dry season above a well-drained soil it was 12.5 μg S m^{-2} h^{-1} and above a flooded soil 300 μg S m^{-2} h^{-1}. By aircraft measurement and by the determination of the concentration profiles in the advection of air above the continent, the emission rate near Abidjan was estimated to be 40 μg S m^{-2} h^{-1} during the dry season.

2.3. *Atmospheric sulphur concentrations*

At ground level, the atmospheric $SO_4^=$ content was measured permanently at Adiopodoumé near the ocean and at Lamto in the savannah. The atmospheric $SO_4^=$ concentrations varied from 2.0 to

0.2 $\mu g\ m^{-3}$ near the ocean and 1.5 to 0.2 $\mu g\ m^{-3}$ near the savannah. The data have been reported previously (Delmas *et al.*, 1978; Delmas, 1980). The H_2S and SO_2 levels in the air were measured from time to time in these two stations and in the forested zone. From about 600 measurements, the H_2S, SO_2, $SO_4^=$ concentrations were 0.60, 0.65 and 1.54 $\mu g\ m^{-3}$.

The measured concentration profiles of $SO_4^=$ in January 1979 near Abidjan showed an increase of 74% between the ground and 150 m height, and a decrease by a factor of 2 between 150 m and the top of the monsoon layer. Measurements of H_2S in January and March 1979 near Abidjan revealed that the mean concentration in the monsoon layer was about $\frac{1}{3}$ of the ground concentration.

2.4 *Sulphur deposition*

The sum of the dry and wet depositions of $SO_4^=$ were measured monthly with 2 pluviometers at Adiopodoumé and Lamto and 9 others in the forested zones of the Ivory Coast. All these pluviometers were located at meteorological stations which met international standards. The mean $SO_4^=$ concentration was 0·43 mg l^{-1} and the mean deposition 673 $\pm \frac{376}{193}$ mg S $m^{-2}\ yr^{-1}$. The deposition was higher in the western part of the country where the rainfall is higher. At Adiopodoumé and at Lamto, the deposition was 682 mg S $m^{-2}\ yr^{-1}$ which is close to the mean. H_2S and SO_2 deposition was calculated with a deposition speed of 0.8 cm s^{-1}, a value given by several authors. This value gives a deposition rate of 145 mg S $m^{-2}\ yr^{-1}$. The dry deposition of atmospheric $SO_4^=$ particles with a diameter less than 1 μ was calculated using a deposition speed of 1 cm s^{-1}. The total dry deposition was 52 mg S $m^{-2}\ yr^{-1}$.

3. The box model

The mean distribution of the winds in January and July in the lower layers over West Africa is shown in Fig. 1. It is seen that the forested zone of

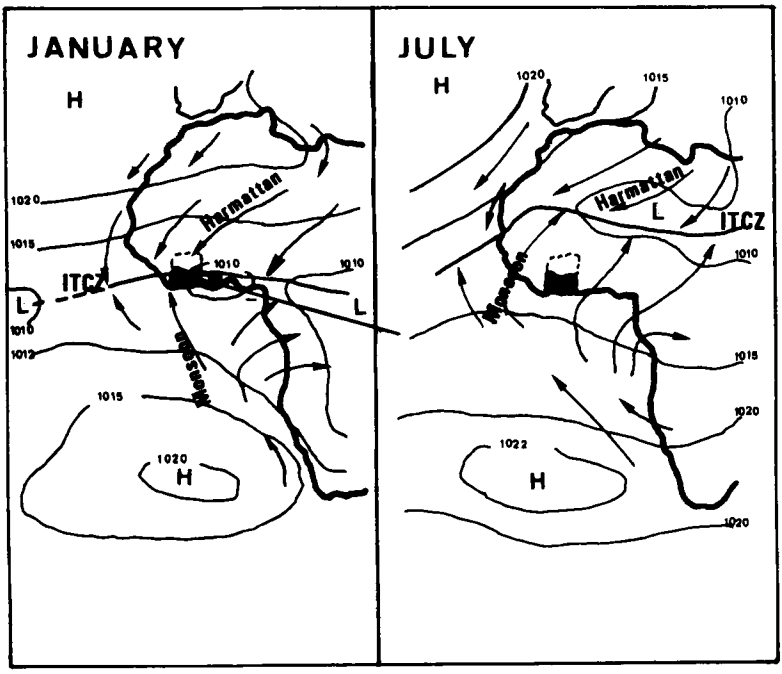

Fig. 1. Position of the main centres in the atmosphere and the circulation in the lower layers in January and July (from "Climatologie de l'Afrique" Air France—Paris 1963.) The Ivory Coast is indicated with a dashed line; the forested zone is black.

the Ivory Coast is under the influence of the monsoon throughout the year. On some occasions during the dry season, the hot continental air (harmattan) loaded with soil-derived dust penetrates towards the south and invades the forested zone. The tropical forest is therefore within the monsoon layer most of the time, with south-west winds up to between 900 and 3000 m. Above the monsoon layer, the harmattan blows from the north-east. At the ground, the separation between these two air masses, the intertropical convergence zone (ITCZ), is easily seen on meteorological maps. It is possible to evaluate the exchanges of sulphur compounds by simulating the forested zone as a box, limited to the south by the coastal zone (Adiopodoumé), and to the north by the savannah (Lamto). The upper limit is the top of the monsoon layer. The length and the width of the box under consideration are 120 and 0.001 km, respectively.

Four seasons are noted in the forests of the Ivory Coast:

—the great dry season (December–February)
—the great wet season (March–Mid-July)
—the small dry season (Mid-July–Mid-September)
—the small wet season (Mid-September–November)

The quantities of sulphur exchanged in the box are given in Fig. 2, where

Qi = sulphur input
Qo = sulphur output
Qe = sulphur emission
Qd = sulphur deposition
Qi,s = sulphur input at the summit
Qo,s = sulphur output at the summit

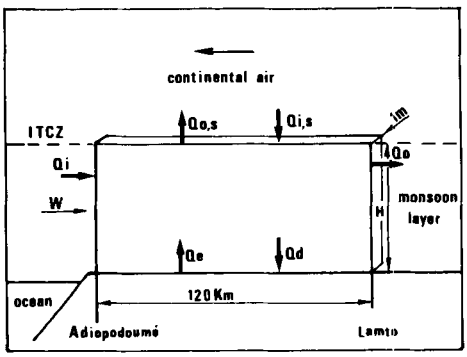

Fig. 2. The box model used for the study of sulphur exchanges over tropical forests.

Considering the stability of the climatic conditions, the time scale has been chosen as 1 month. As the concentrations do not increase within this time scale, a steady state may be assumed such that the difference between the input and output quantities is zero:

$$O = Qi + Qe + Qi,s - (Qo + Qd + Qo,s).$$

The parameters we will consider are the sulphur concentration in the air entering and leaving the box, the dry and wet depositions of sulphur (see Section 2) and the volume of air advected by the wind in the monsoon layer.

In the monsoon layer, the weight of the air advected by the wind is equal to the product of the air density, the layer width, the height of the layer and the mean horizontal wind speed. The height of the monsoon layer at Abidjan was estimated from daily radio-soundings. The top of the monsoon layer stands out very clearly as the wind turns from south-west to north-east. The height varied during the year from about 900 m in January to 3000 m in May. The mean surface wind speed was calculated from measurements at ground level, 300 per month. Upper level winds were obtained from four daily radio-soundings at 0 h, 5 h, 11 h and 17 h (local time) and wind observations at 600, 900, 1500 and 2100 m at Abidjan airport. In general the wind speed was lower near the ground than higher up and it was nearly constant between 600 and 2100 m. The values ranged from 3.1 m s^{-1} in January to 4.9 m s^{-1}, in July.

4. Results

4.1. *Flow of sulphur caused by the monsoon*

We used the box model described in Section 3 to calculate the main quantities which determine the annual sulphur balance.

The inflow of sulphur (Qi) and the outflow (Qo) caused by the monsoon are shown in Fig. 3. They are nearly identical (of the order of 5 kg S $month^{-1}$) throughout the dry season (January–May). Between June and October, a source is needed in the box to balance the deposition. During the wet season, the intensity of this source increases since Qo is at least twice as high as Qi, and also because of the increasing intensity of the depositions. The maximum value of Qo is about 40 kg S $month^{-1}$.

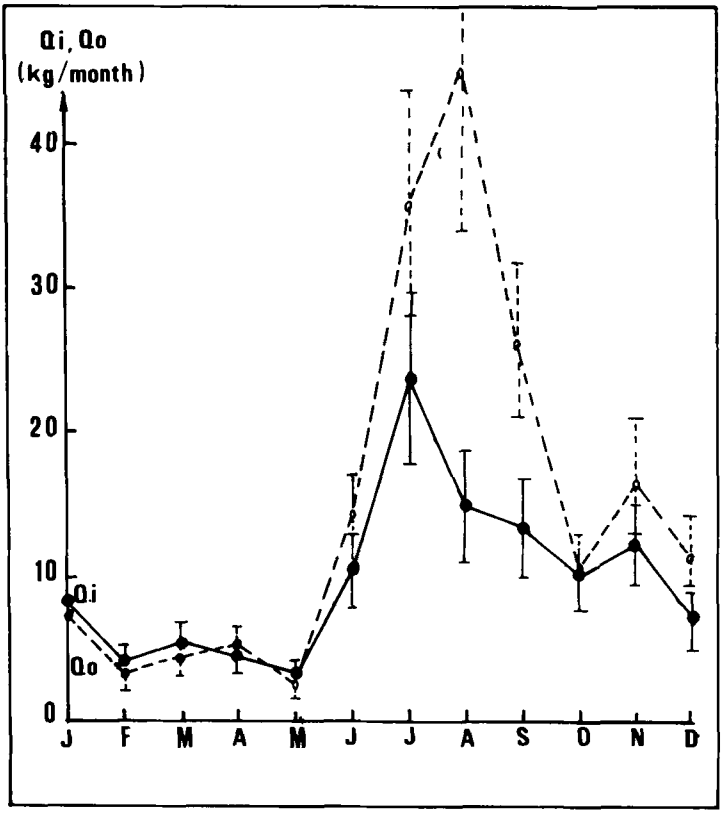

Fig. 3. Sulphur flux per month in the monsoon layer at the inflow (Adiopodoumé, Qi) and the outflow (Lamto, Qo) of the box.

4.2. *Sulphur deposition*

The total deposition Qd represents $SO_4^=$, which is measured, and gases (H_2S + SO_2), which are calculated (Delmas, 1980). The deposition of the gases is about 10% of that of $SO_4^=$. In fact, the wet removal of $SO_4^=$ is the most efficient, about 90% of the total. The results given in Fig. 4 illustrate this phenomenon. During the dry season, the total deposition is about 5 kg S $month^{-1}$, and during the wet season about 20 kg S $month^{-1}$.

4.3. *Sulphur exchange at the top of the box*

It was not possible to measure the sulphur exchange at the top of the box owing to experimental difficulties and the cost of such an experiment. Therefore the two terms of this exchange were estimated as follows. The quantity Qi,s enters the box and the quantity Qo,s is removed from it. The first term was calculated from the input of soil-derived particulates from the harmattan into the monsoon layer and the second term from the input of oceanic particulate into the harmattan from the monsoon layer (Fig. 5). The difference between the two terms (Qi,s–Qo,s) represents the net sulphur flux at the summit of the box. It is positive during the dry season and negative during the wet season. On the average, over the year, it is negligible compared to both the input by the monsoon and the deposition. Therefore its rôle in the balance is small.

4.4. *Sulphur emission*

From the balance equation in Section 3 we see that the sulphur emission Qe is given as:

$$Qe = Qo + Qd + Qo,s - Qi - Qi,s.$$

The mean monthly values of the sulphur emissions are given in Fig. 6. Typical variations are observed over the seasons. There is a minimum from January to May and a maximum from June to

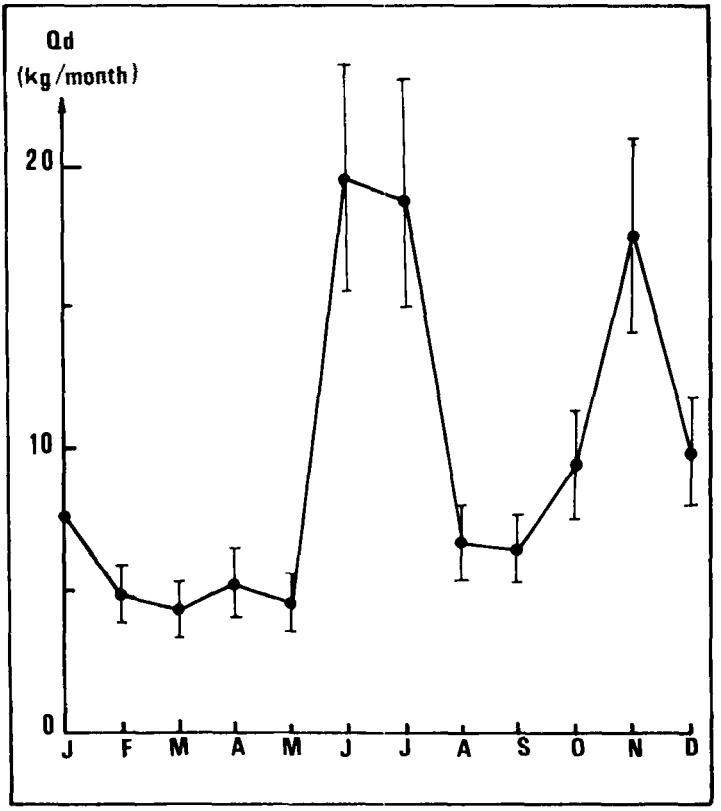

Fig. 4. Theoretical estimation of the monthly variations of sulphur deposition on the ground (area = 0.12 km²).

September. During the dry season, the fall of the foliage brings a large quantity of fresh plant material to the soil. With the heavy rains during the wet season, the redox potential decreases. It becomes negative over a 10-day period. The sulphur compounds of the plant material are reduced and H_2S release becomes possible. This is also confirmed by direct measurements of the emission of H_2S which are higher over wet soils than over dry. The values obtained through the balance are of the same order as those found experimentally. The mean calculated value during the dry season 55 μg S m^{-2} h^{-1}, is comparable with the measurements of 12.5 μg S m^{-2} h^{-1} in the Taï forest and 40 μg S m^{-2} h^{-1} near Abidjan. The mean value during the wet season, 270 μg S m^{-2} h^{-1}, is close to that measured over a flooded soil in the Taï forest, 300 μg S m^{-2} h^{-1}.

From these results we can calculate the mean emission of sulphur from the forested zone. It is equal to 170 μg S m^{-2} h^{-1}, or 1.5 g S m^{-2} yr^{-1}. This value is clearly greater than that determined from soils in temperate zones, which is about 0.06 g S m^{-2} yr^{-1} (Adams *et al.*, 1979; Aneja and Aneja, 1979; Aneja *et al.*, 1979; Delmas *et al.*, 1980). Thus, the equatorial forests are important sources of atmospheric sulphur.

4.5. *Oxidation rate of sulphur compounds to* $SO_4^=$

A fraction of the H_2S molecules emitted in the box are oxidized to $SO_4^=$ molecules. In a volume unit, the quantity of $SO_4^=$ generated in the box is the difference between the $SO_4^=$ concentration at the outflow of the box and that at the inflow corrected for the dry deposition and scavenging.

If C_1 and C_2 are the concentrations of $SO_4^=$ at the inflow and the outflow of the box, then the concentration of $SO_4^=$ formed in the box is the difference between that at the outflow C_2 and that at the inflow C_1 which is not deposited on the soil.

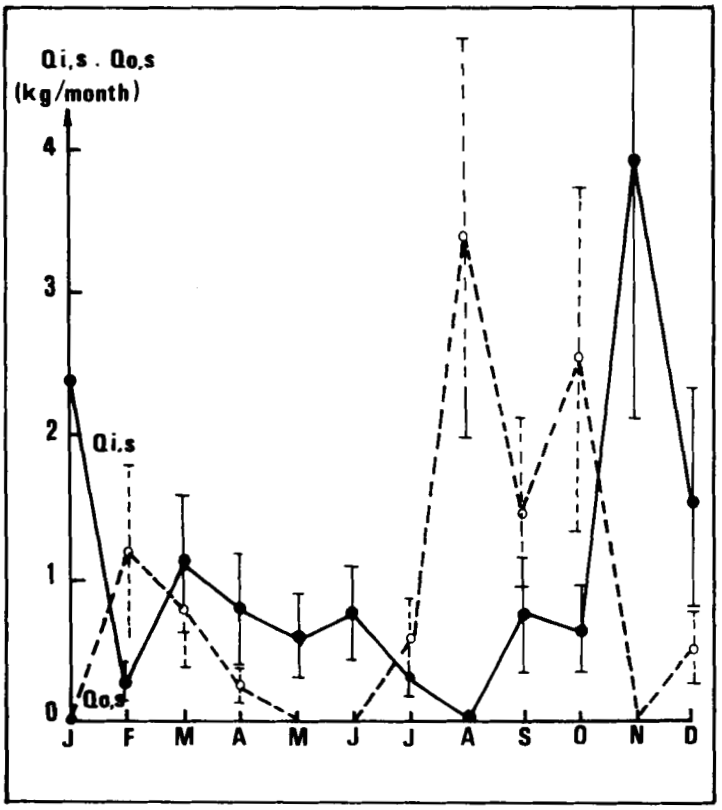

Fig. 5. Monthly sulphur flux, input to (Qi,s) and output from (Qo,s) the box at the summit.

The deposition rate per unit of time is the sum of two terms v_d/H for the dry deposition and Λ_1 for the rain scavenging; C_1 varies according to the exponential law $dC_1/dt = -(v_d/H + \Lambda_1)C_1$; after a transit time t in the box, C_1 is reduced by the factor $\exp[-(v_d/H + \Lambda_1)]t$. The concentration of $SO_4^=$ formed in the box is

$$C_2 - C_1 \exp\left[-\left(\frac{v_d}{H} + \Lambda_1\right)\right]t,$$

where

v_d = deposition speed of the atmospheric $SO_4^=$ (0.1 cm s^{-1}),
H = height of the box (900 to 3000 m),
Λ_1 = scavenging coefficient (0.54 to 6.60 d^{-1}),
t = transit time of the air in the box (7.6 to 10.4 h).

Assuming the $SO_4^=$ concentration to be homogeneous over a cross-section of the box, the flux of oxidized sulphur is

$$\Delta_{Qo} = \left(C_2 - C_1 \exp\left[-\left(\frac{v_d}{H} + \Lambda_1\right)t\right]\right)HV,$$

V = mean air speed.

The mean rate of oxidation per unit of time is:

$$\Delta T_0 = \frac{\Delta_{Qo}}{\Phi_R (S_g)} \frac{l}{\tau},$$

l = length of the box (1.2×10^5 m),
$\Phi_R (S_g)$ = flux of gaseous sulphur into the box (1.24 to 12.55 mg s^{-1}),
τ = mean residence-time of the sulphur in the box (3.68 to 5.54 h).

In the first 3 months of the year (January to March), $\Delta_{Qo} = 0$. In reality, sulphur oxidation exists, but it was not possible to evaluate Δ_{Qo} from

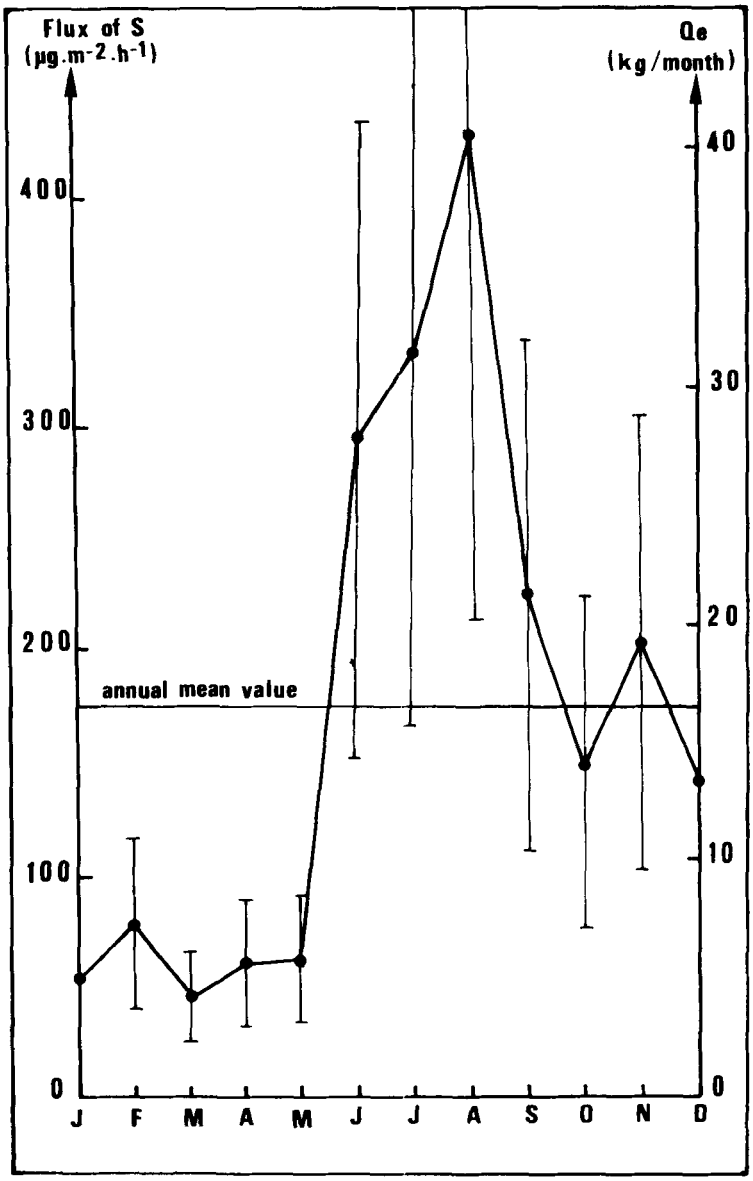

Fig. 6. Monthly variations of the mean emission of the soils of the forested zone.

the experimental data. During the 9 other months (April–December) the quantity of sulphur compounds oxidized to $SO_4^=$ per unit time (Δ_{Qo}) varied between 0.32 and 4.82 mg s^{-1}, the mean being 1.44 mg s^{-1}. The flux of H_2S ($\Phi_R(S_g)$) was 4.21 mg s^{-1} and the residence time of H_2S molecules in the box (τ) was 4.10 h. The mean value of the rate of oxidation per unit time is therefore:

$$\frac{1.44 \text{ mg s}^{-1}}{4.21 \text{ mg s}^{-1}} \times \frac{1}{4.10 \text{ h}} = 8.4\% \text{ h}^{-1}.$$

It is possible that with a strong solar flux the

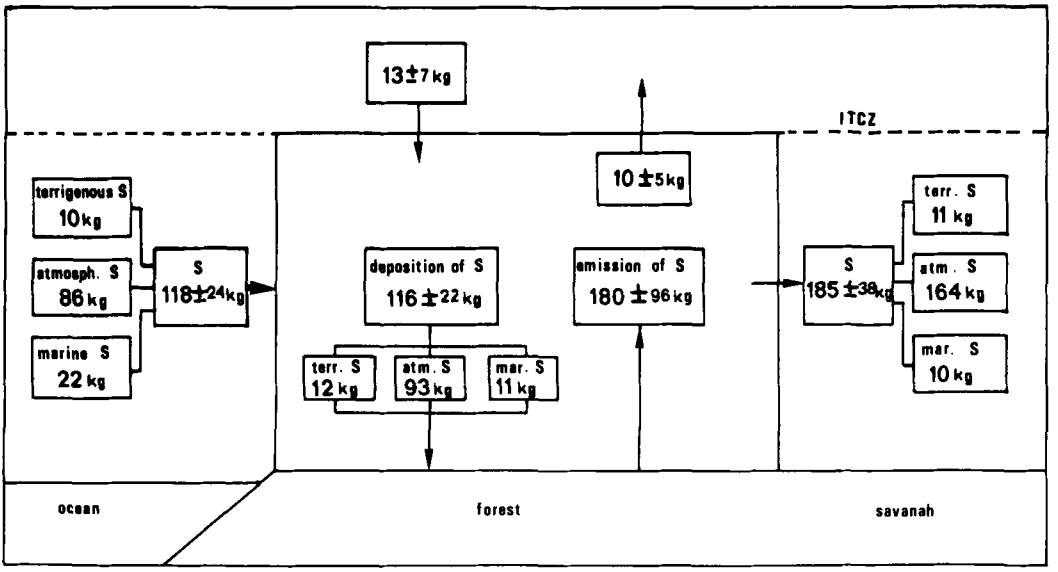

Fig. 7. Annual sulphur balance over the forested zone (area = 0.12 km^2). Soil-derived S: S in soil-derived particulates $SO_4^=$ form. Atmospheric S: S in gaseous (H_2S, SO_2) and solid ($SO_4^=$) compounds in the atmosphere. Marine S: S in oceanic particulates, $SO_4^=$ form.

formation of free radicals (such as HO, HO_2 and organics) is responsible for this rapid oxidation. It is also possible that with a high relative humidity (over 80%), heterogeneous reactions occur. The emission of DMS and MeSH by soils, followed by a rapid oxidation in the atmosphere, might also be the reason. The calculation month by month shows a variation from 5.3 to 12.9% h^{-1} and the arithmetic mean is 8.4% h ^{1}. This value is an order of magnitude higher than that of middle latitude rural zones with low pollution, and is similar to that of the urban zones, about 3 to 4.4% h^{-1} (Eggleton and Cox, 1978). Since the sulphur lost by diffusion through the ITCZ and by deposition on the ground were not considered, the calculated value is the minimal value.

4.6. *Annual global balance*

The annual sulphur balance in the box is presented in Fig. 7. It should be noted that more than 90% of the exchanged sulphur is of atmospheric origin. At the inflow of the box, the sulphur flux is strong. This flow alone could explain the deposition over the forested zone (118 kg S yr ^{1} compared to 116 kg S yr^{-1}). The emission intensity is higher, 180 kg S yr^{-1}. This is needed to sustain the outflow of sulphur to the savannah. The fluxes at the top of the box and through the ITCZ are an order of magnitude lower, about 13 kg S yr^{-1}.

5. Discussion

The accuracy of the results obtained in this study, and especially the emission value of the forests, depends on the accuracy of the chemical analyses, the accuracy of the meteorological parameters and the dry deposition speed.

Taking into account the great volumes of air, the maximum error of the SO_4^- measurements is 13%. That of the monsoon input is 25% owing to the errors in the estimated height of the monsoon layer and the mean wind speed. The calculated intensity of dry deposition depends on the deposition speed we have chosen. However, wet removal, about $\frac{2}{3}$ of the total, is predominant. The error of the deposition is estimated to be 20%.

The value of the exchange at the summit of the box is uncertain but low. This error is negligible in the calculation of the sulphur emission. Assuming a steady state regime, the error in the intensity emission of sulphur is the sum of the errors mentioned above, that is 50%. The calculation of the input by the monsoon was made using a

constant wind speed and a constant monsoon layer height. This model is not correct when the forested zone is under the influence of the harmattan, in particular in January and February. During this period, the emission of sulphur is minimal and the approximation we introduced is minimal. Therefore, it does not have a significant influence on the determination of the mean annual emission.

The emissions of certain sulphur compounds in particular that of DMS and MeSH have not been measured here, though they can be fairly high for some anoxic soils (Adams *et al.*, 1979). Nevertheless low concentrations of DMS have been measured in the air of the Banco forest, between 2.7 and 7.1 ng S m^{-3}, by the group of Dr. Nguyen B.C., Laboratoire mixte CNRS-CEA, Gif-sur-Yvette, France (personal communication). This compound has a short residence-time in the atmosphere, of the order of 1 h. It is oxidized over the forested zone and taken into account in the overall calculation of the atmospheric $SO_4^=$ concentrations and depositions. The calculation of the different fluxes probably integrates the greater part of the reduced compounds emitted by the decomposition of organic matter.

Considering the total balance, we find that the sulphur emission is slightly higher than the deposition. The difference between these two values is of the order of the estimated errors. As the balance is calculated over just 1 year, there is no significant loss in sulphur of the top soils, since deposition offsets emission. A long term study would be necessary to confirm this result.

It can be noted that at the inflow of the box, the input of atmospheric sulphur (86 kg S yr^{-1}) is much higher than that of the marine source (22 kg S yr^{-1}). Campaigns in March and May 1976 in the Gulf of Guinea showed a background of H_2S = 0.02 μg m^{-3} and SO_2 = 0.1 μg m^{-3} in the oceanic air, and an excess of $SO_4^=$ was very likely formed over the forested zones. This oceanic background gives a maximum input of 50 kg S yr^{-1} at the coast. A fraction of the sulphur which enters the box (80 kg S yr^{-1}) is therefore emitted by plant sources. This is confirmed by the seasonal variations in the $SO_4^=$ concentrations which are comparable at Adiopodoumé near the sea and at Lamto near the savannah (Delmas *et al.*, 1980). At present it is not known where the transfer of sulphur compounds over the continent through the ITCZ takes place.

6. Conclusions

Through a study of the natural sources and sinks of sulphur in the forested zone of the Ivory Coast, a balance has been set up. Over 1 year, the intensity of the source represented by the humid equatorial forest has been quantitatively evaluated. The mean emission of these forested soils is about 1.5 g S m^{-2} yr^{-1}, 40 times stronger than that of soils in temperate zones. For such an emission, the equatorial forests would emit 25 × 10^6 t S yr^{-1} into the atmosphere, which is $\frac{1}{4}$ of the present anthropogenic emissions. They therefore represent a major source, which must be taken into consideration in the global atmospheric sulphur cycle.

The whole sulphur cycle in this equatorial region, emission as well as deposition, is modulated by the rainfall and accelerated distinctly during the wet season.

The sulphurous compounds emitted into the atmosphere are rapidly oxidized into sulphur dioxide and sulphates. The transformation into sulphates has been estimated to be about 8.4% per hour. This oxidation is rapid for a natural atmosphere and explains the sulphate concentrations measured in the forested zone. The oxidation reactions are multiple and require special study. The oxidation most likely does not occur only by reaction with HO and HO_2 radicals, but also through reaction with organic radicals and through some heterogeneous reactions in the presence of high relative humidity.

The sulphate particles formed in the atmosphere are soluble and effectively eliminated by the rains over the forests. However, 50% of the particles do not take part in this deposition. They spread out over the savannah. These particles may then be carried over great distances to feed the tropospheric sulphate load. Feeding of the stratospheric load is still a matter of speculation as the sulphur dioxide and the sulphates are scavenged very effectively by the convective rain. The hydrogen sulphide which is quickly oxidized into sulphur dioxide, would also be eliminated through such scavenging.

The sulphates of atmospheric origin are soluble and could form condensation nuclei. Some measurements of such nuclei have been made in the Banco and the Taï forests. They showed diurnal

and seasonal variations of a concentration which could be attributed to the forest. This aspect of the rôle of the forests in the climate of the equatorial regions remains to be studied.

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