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A CONTINENTAL WELL-AGED AEROSOL IN THE GUINEAN SAVANNAH AT THE LEVEL OF A TROUGH ALONG THE ITCZ

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Abstract—Simultaneous measurements of Aitken nuclei, cloud condensation nuclei and aerosol particles sizes larger than 0.3 μm in the Guinean savannah during the dry season show an aerosol of very exceptional physical properties: numerous cloud condensation nuclei (2000–3000 per cm^3) active at low supersaturation (or slight 'undersaturation'), absence of very small Aitken nuclei active at 180% of supersaturation and concentrations of large aerosol particles ($D > 0.3$ μm) between 30 and 60 per cm^3. The analysis of the aerosol behavior during a 'typical' 24-hr period of the dry season and during a fog situation indicates that (1) the aerosol is a very homogeneous and aged one; (2) the active nuclei might be of a mixed nature or nuclei on the surface of which the capillary condensation plays an important role.

INTRODUCTION

Previous measurements carried out in the Abidjan area (Ivory Coast) showed that the concentrations of cloud condensation nuclei (CCN) vary during the day and according to the seasons (Desalmand *et al.*, 1980). Different experiments carried out in the Brazzaville Congo showed that the equatorial forest is a source of Aitken nuclei (Cros *et al.*, 1981).

But, until now, it was impossible to measure simultaneously the concentrations of the Aitken nuclei N_A and the concentrations of the larger particles (composed of CCN with a great participation of large and giant nuclei) and to evaluate in this way the relation between the concentration of the nuclei susceptible to be activated in the cloud formation process and the total concentration of aerosol. This relation is, however, of great importance for appreciating the nature of the nuclei source and judging the transformation of nuclei in the planetary boundary layer. In addition, the determination of CCN supersaturation spectra allows us to find the dependence of particle activity upon its physico-chemical properties.

In this study, we try to find the relations between N_S (concentrations of the nuclei activated at a supersaturation S %), N_A (concentrations of the Aitken nuclei) and N_D (concentrations of the particles with size $D > 0.3$ μm). The analysis of the nuclei measurements with the aim of describing the main nature of the CCN is the subject of a special study (Podzimek and Desalmand, 1982).

MEASUREMENT STATION AND EQUIPMENT

Measurement station

This is situated at Lamto, in the Ivory Coast, about 120 km from the Atlantic Ocean in the Guinean savannah zone on the border of the equatorial forest (Fig. 1).

The measurements extended over a 48-hr period in the middle of the dry season from 31 December 1981 to 1 January 1982.

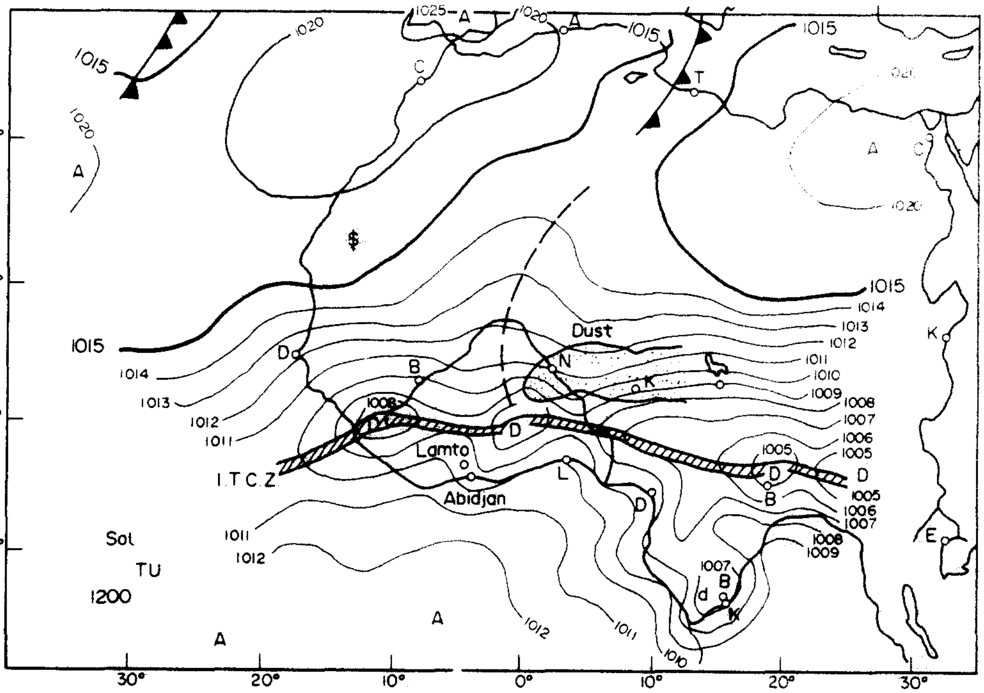

Fig. 1. West Africa on 1 January 1982 at 12:00 a.m.: isobars, intersection with the ground of the ITCZ.

Throughout this period the main meteorological parameters such as temperature, relative humidity, solar radiation were recorded and a wind vane gave the wind direction (Fig. 2). A rough estimate of the wind velocity was made during the day.

Figure 1 sketches the meteorological situation of West Africa on 1 January 1982 at 12:00 a.m. The intersection with the ground of the intertropical convergence zone (ITCZ) is located along the latitude 9° N, about 150 km North of Lamto. The station is, however, not necessarily in a maritime air mass because of the complicated air circulation pattern around the depression centers moving along the ITCZ. In January the station might be under the influence of a continental air mass which has been humidified by its passage above the forest (the relative humidity approaches 100% at daybreak: Fig. 2). The prevailing wind directions are from the South or Southwest.

From 1 to 21 December, the total amount of rainfall was 24.1 mm. After 21 December until the measurements period and during the last-named, no rain was recorded.

Equipment

Three types of counters were used. A Gardner counter allows the measurement of the N_A concentration of the Aitken nuclei which are activated at the supersaturation $S = 180\%$ (Podzimek *et al.*, 1982).

The cloud condensation nuclei (CCN) are activated in a thermal diffusion chamber with parallel plates, the model of which has been described by Twomey (1963); this chamber is cooled at the bottom and fitted with a video system (Serpolay, 1981). We determined the concentrations $N_S = (N_{0.25}, N_{0.50}, N_{1.0})$ of the CCN, respectively, activated at the supersaturations $S = (0.25, 0.50 \text{ and } 1\%)$. The N_S concentration of the CCN activated at the supersaturation S (%) follows the well-known relation:

$$N_S = CS^k, \tag{1}$$

where C and k are parameters depending upon the concentration and the nature of the CCN and in relation with the size distribution and the critical supersaturation $S = S(r)$ curve. It can be seen that $C = N_{1.0}$.

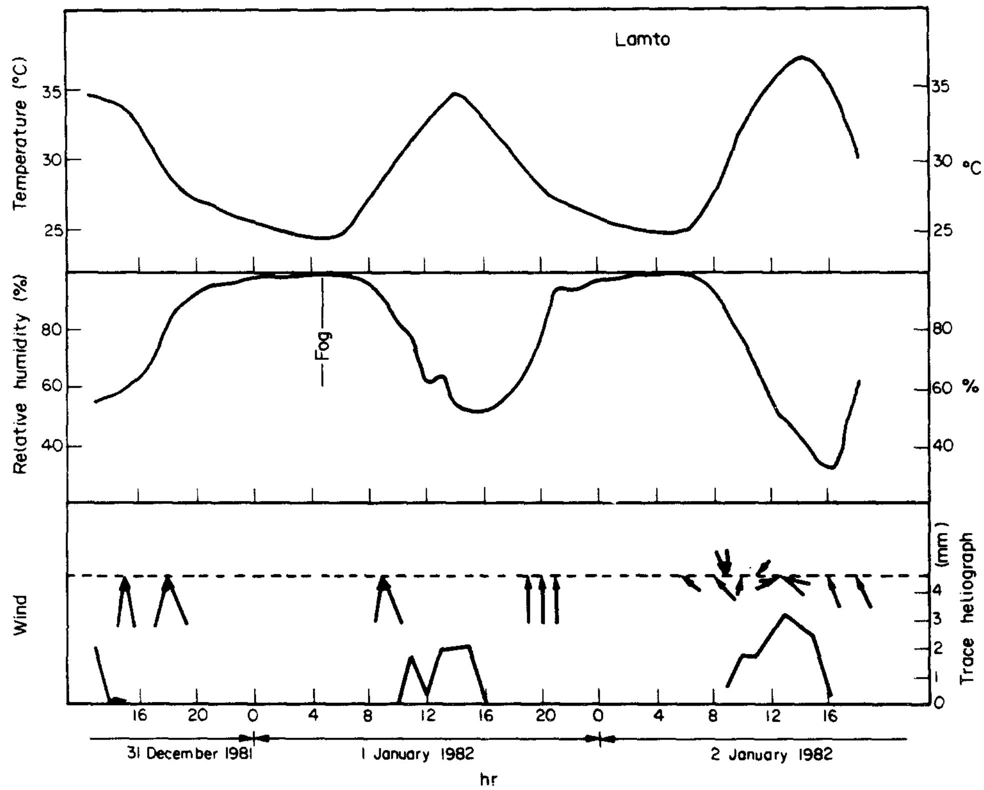

Fig. 2. Lamto, Guinean savannah, during the dry season on 1 January 1982: variation of some meteorological parameters.

Large particles are classified according to their radius and counted with the help of an optical Bausch and Lomb counter. We call N_B the concentration of particles of radius $> 0.3\ \mu m$, and also use the other particle radius classes in order to determine the size distribution of the coarse fraction of the aerosol.

Remark. Each value N_A or N_S is in reality the arithmetic mean of four consecutive air samplings.

Different potential sources of the aerosol

The area where the station is situated in the Guinean savannah is characterized by a very scarce population and a very weak anthropogenic pollution. The natural aerosol is dominant and can be derived from three main sources:

(1) The maritime source brings a negligible number of large and giant nuclei as a result of the distance of the Atlantic Ocean (120 km) and as a consequence of the situation during the long dry season.

(2) The remote terrestrial source did not act very much during this 1981 dry season because there was not a significant advection of dust particles from Saharan soils; however, this dust exists as a result of sedimentation through the ITCZ. The local terrestrial source also supplied aerosols, but not very intensively because the prevailing winds in the boundary layer were weak.

(3) The vegetal source is divided into two parts. The vegetal production of gas and little particles by the humid vegetation is much slower during the dry season, but might exist in the gallery forest along the Bandama River situated at about 500 m from the laboratory where an N_A concentration of 1000 per cm^3 was measured with the Gardner counter. On the other hand, the drying and grinding of plants furnish numerous particles. In addition to this, there

were probably gases and aerosols produced by bushfires during the preceding days as is usual during this season. We did not observe bushfires during the measurement period.

EXPERIMENTAL RESULTS

We determined the various concentrations of nuclei and aerosol particles (N_A, $N_{1.0}$, $N_{0.50}$, $N_{0.25}$, N_B) at each hour of the 48-hr period. We have selected a 24-hr period during which all the counters were working. This period begins on 1 January 1982, at 8:00 a.m. We have also investigated a fog situation on 1 January 1982 at 5:00 a.m.

Main results

In Table 1, the following data have been registered: the daily mean, $\bar{N}$, of the 24-hourly values corresponding to the different measurements; the mean of the 12-hourly values of the day time from 7:00 a.m. until 18:00 p.m.; the mean of the 12-hourly values of the night from 18:00 p.m. until 6:00 a.m.; the ratio between the day time mean and night mean denoted as day/night; and the ratio between the maximal value and minimal value observed during the day (24-hr) denoted max/min.

The examination of Table 1 leads to the following remarks:

(1) The aerosol is rich in very active nuclei: $N_{0.25} \simeq 2070$ per cm^3.

(2) The daily value of k (0.26) is abnormally low; in agreement with other works (Levin and Sedunov, 1966; Podzimek and Desalmand, 1982; Desalmand, 1984) this reveals a rather soluble CCN aerosol. The ratio between the maximal value and the minimal value of k during the day is 3; this low value is characteristic of the dry season (Desalmand *et al.*, 1980).

(3) The Gardner counter has a tendency to underestimate the concentrations because we found quite often $N_A \leqslant N_S$. However, as the concentration N_A of the Aitken nuclei approaches the concentration N_S of the CCN, we can assume that the weakly active and very small nuclei are absent from the spectrum. In agreement with the works of Fitzgerald and Hoppel (1982), this implies the particle radius to be $r \geqslant 0.02\,\mu$m. The absence of the nucleation mode of the Whitby model (1973) has already been noticed by several researchers over the ocean (Hoppel, 1979; Jaenicke and Schutz, 1982).

We may also put forward the hypothesis that very small particles (N_A) do exist in the savannah, but cannot be activated in the Gardner counter (Podzimek *et al.*, 1982) or they rapidly deposit on the numerous large particles. Therefore, we might assume that the large particles are of a mixed nature.

(4) The various categories of nuclei and particles present closely related variations: daytime mean ($\bar{N}_{day}$) similar to nighttime mean ($\bar{N}_{night}$); maximal value two or three times higher than minimal value.

Figure 3 completes Table 1: it represents the hourly variations of the different types of particles and confirms the similarity of their variations.

Table 1. Lamto, Guinean savannah, during the dry season: some data on and around the Aitken nuclei (N_A), CCN (N_S) and large particles (N_B) ($r \geqslant 0.15\,\mu$m) on the 1 January 1982

Lamto 1 January 82	$\bar{N}_A$	$\bar{N}_{1.0}$	$\bar{N}_{0.50}$	$\bar{N}_{0.25}$	$\bar{k}$	$\bar{N}_B$
$\bar{N}$ (cm^{-3})	2060	2980	2490	2070	0.26	38
$\bar{N}_{day}$	2080	3230	2700	2260	0.26	42
$\bar{N}_{night}$	2030	2730	2290	1870	0.26	34
day/night	1.02	1.18	1.18	1.21	1.00	1.23
max/min	2.50	2.08	2.17	2.61	2.93	2.52

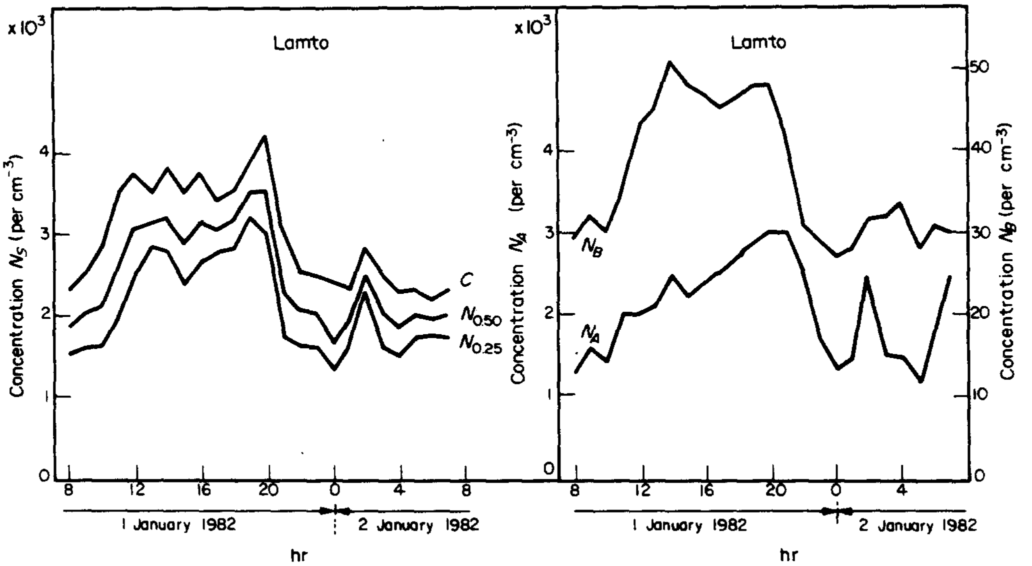

Fig. 3. Lamto, Guinean savannah, during the dry season: hourly variations of the N_A, N_B and N_S concentrations for the 24-hr period beginning on 1 January 1982 at 8:00 a.m.

Correlations between the hourly concentration N_S, N_A *and* N_B

We try to fit a power function to the different hourly measurements of the considered day by using the least-squares method:

$$\begin{aligned} N_S &= \alpha N_A^{\beta} \\ N_S &= \alpha N_B^{\beta} \\ N_A &= \alpha N_B^{\beta}, \end{aligned} \tag{2}$$

where α and β are constant.

The results are reported on Table 2 where r represents the correlation coefficient of the method.

Table 2. Lamto, Guinean savannah, during the dry season: power functions between the hourly concentrations of various particles determined by the least square method on 1 January 1982

N_S (cm^{-3})	Period		α	β	r
$N_{1.0} = \alpha N_A^{\beta}$	24 hr		61	0.56	0.72
	12 hr	day	51	0.54	0.64
		night	46	0.53	0.83
$N_{0.50} = \alpha N_A^{\beta}$	24 hr		26	0.61	0.74
	12 hr	day	15	0.68	0.74
		night	36	0.54	0.78
$N_{0.25} = \alpha N_A^{\beta}$	24 hı		20	0.61	0.69
	12 hr	day	4	0.82	0.78
		night	43	0.48	0.69
$N_{1.0} = \alpha N_B^{\beta}$	24 hr		172	0.78	0.86
	12 hr	day	367	0.60	0.80
		night	75	1.02	0.92
$N_{0.50} = \alpha N_B^{\beta}$	24 hr		116	0.85	0.88
	12 hr	day	193	0.71	0.87
		night	57	1.06	0.87
$N_{0.25} = \alpha N_B^{\beta}$	24 hr		87	0.87	0.84
	12 hr	day	108	0.81	0.84
		night	81	0.89	0.75
$N_A = \alpha N_B^{\beta}$	24 hr		95	0.84	0.72
	12 hr	day	171	0.67	0.76
		night	15	1.37	0.80

Table 2 shows a relatively high correlation between the concentration of usually smaller and larger particles because we calculated r around 0.7 and 0.9. Normally, the CCN constitute a rather small part of the Aitken nuclei and it is not possible to find a significant correlation between these two categories of particles (Twomey and Severynse, 1964), all the more so between N_A and N_B.

This result shows clearly that these populations of nuclei and particles may have the same origin. Previous measurements performed in the area of Abidjan, where various aerosol sources are present, show on the contrary that N_A is much higher than N_B; moreover, the correlation coefficient between N_A and N_S (ranging between 0.06 and 0.41) is much smaller (to be published). Figure 4 shows the variations of the $N_{1.0}$ concentration as a function of the N_A concentration (left part) and as a function of the N_B concentration (right part); in agreement with Table 2, the adjusted lines are represented.

In the same way, Fig. 5 displays the variations of N_A as a function of N_B and the corresponding adjusted line; the correlation coefficient is always rather high (0.72).

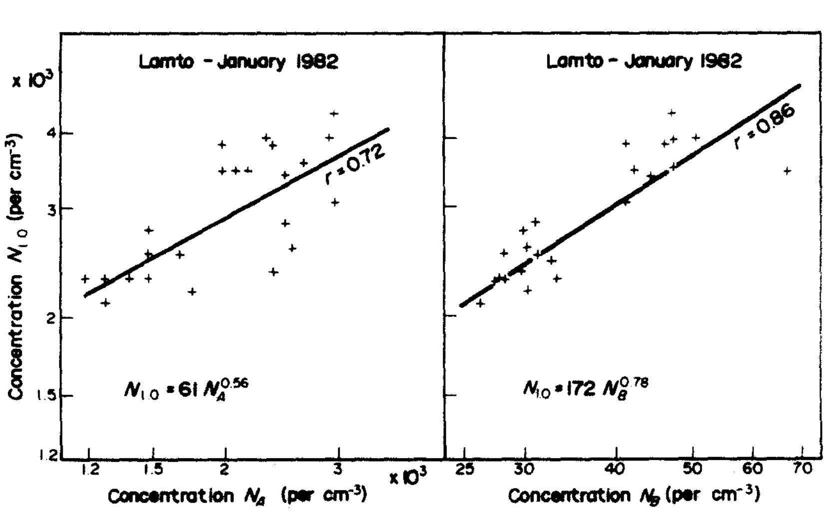

Fig. 4. Lamto, Guinean savannah, during the dry season: hourly variations of the $N_{1.0}$ concentration as a function of the N_A concentration (left part) and as a function of the N_B concentration (right part). Adjusted lines.

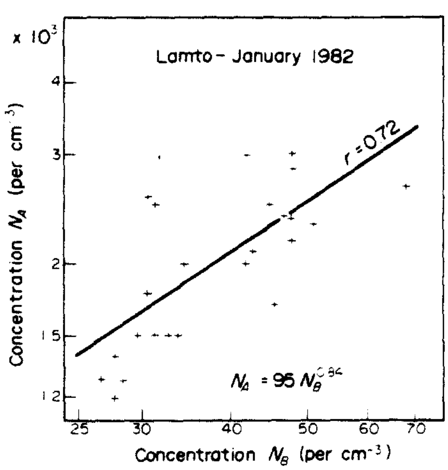

Fig. 5. Lamto, Guinean savannah, during the dry season: hourly variations of the N_A concentration as a function of the N_B concentration. Adjusted lines.

Examination of the parameter k *from the relation* $N_S = CS^k$

Table 3 shows the values of the constants α and β appearing in the power function:

$$N_S = \alpha k^{\beta}. \tag{3}$$

In the calculations, we took $S = (0.25, 1.0\,\%)$ and r is always the correlation coefficient of the least-squares method.

According to Table 3, the $N_{1.0}$ concentration is roughly independant of the parameter k, whereas the $N_{0.25}$ concentration is well correlated with the parameter k. Then the most active nuclei $N_{0.25}$ vary in the same way as the k-slope the small values of which already revealed the soluble feature of the CCN population.

Study of the fog situation

On 1 January 1982 at 5:00 a.m., a thick fog occurred in which the visibility was around 100 m or less; this fog was not present when we began our measurements at 4:00 a.m., and it dispersed at 5:20. In Table 4 the values of the different concentrations and humidity at 4:00 a.m., 5:00 a.m., and 6:00 a.m., i.e. before, during and after the fog occurrence are recorded.

Interpretation. The fog formed suddenly when the relative humidity H passed from 98 to 99 %, and suddenly disappeared when H took again the value 98 %. The activated nuclei produced sufficiently large droplets to be detected in the optical counter so that the N_B concentration of the large particles ($D \geqslant 0.3\ \mu$m) increased from the value $N_B = 28$ per cm^3 to the value $N_B = 50$ per cm^3 at the time of the fog, then decreased to the value $N_B = 27$ per cm^3 after.

These measurements stress the existence of numerous nuclei at the critical humidity of approximately 99 %. These slightly 'hygroscopic' nuclei are probably of a mixed nature, as mentioned before.

Size spectrum

The size spectrum is defined by the relation:

$$f(r) = -\mathrm{d}N/\mathrm{d}\log r \tag{4}$$

where N = concentration of particles activated at supersaturation S or with radius $\geqslant r$ (cumulative concentration).

The optical Bausch and Lomb counter classifies the particles according to their size: $r \geqslant (0.15\text{–}0.25\text{–}0.5\text{–}1.5\text{–}2.5\text{–}5\ \mu\text{m})$. We found that the number of particles $r \geqslant 2.5\ \mu$m was negligible; so for the present aerosol, we have roughly:

$$0.02 \leqslant r \leqslant 2.5\ \mu\text{m}. \tag{5}$$

According to the manufacturer, the Gardner counter measures the number of particles $r \leqslant 0.001\ \mu$m (a point to discuss).

Table 3. Lamto, Guinean savannah, during the dry season: power function between the CCN concentrations and parameter k on 1 January 1982

N_S (cm^{-3})	Period		α	β	r
$N_{1.0} = \alpha k^{\beta}$	24 hr		2500	−0.11	0.17
	12 hr	day	2860	−0.08	0.14
		night	2170	−0.15	0.23
$N_{0.25} = \alpha k^{\beta}$	24 hr		1090	−0.43	0.59
	12 hr	day	1250	−0.41	0.60
		night	940	−0.47	0.68

Table 4. Lamto, Guinean savannah, during the dry season: particle measurements and corresponding relative humidity during the fog situation at 5:00 a.m. on 1 January 1982

Time (a.m.)	N_A	$N_{1.0}$	$N_{0.50}$	$N_{0.25}$	k	N_B	H %
4:00	1400	2600	1900	1390	0.63	28	98
5:00	2200	2770	2120	1620	0.39	50	99
6:00	1600	2570	2100	1720	0.29	27	98

Following the measurements of Fitzgerald and Hoppel (1982), the particles activated at $S = (0.25\text{–}0.50\text{–}1.0\%)$ have on an average a radius $r \leqslant (0.05\text{–}0.03\text{–}0.02\ \mu m)$.

So, with these three devices, we may determine the size spectrum between 0.001 and 5 μm; the mean daily results are reported on Fig. 6 which shows that the size spectrum is stationary in the domain of the CCN spectrum.

Chemical analysis of giant particles

During this period of measurements a number of giant particles were collected on glass slides with an impactor and submitted later on to analysis with a Camebax microprobe. Among them two particles of different size ($\geqslant 30\ \mu m$) have been chosen as representative of this coarse aerosol fraction. It is probable that these particles proceeded from the aggregation of several others smaller on account of the high value of the humidity prevailing during the sampling.

Two volumes (about 1 μm^3 each) were scanned on the larger one; only one volume on the smaller.

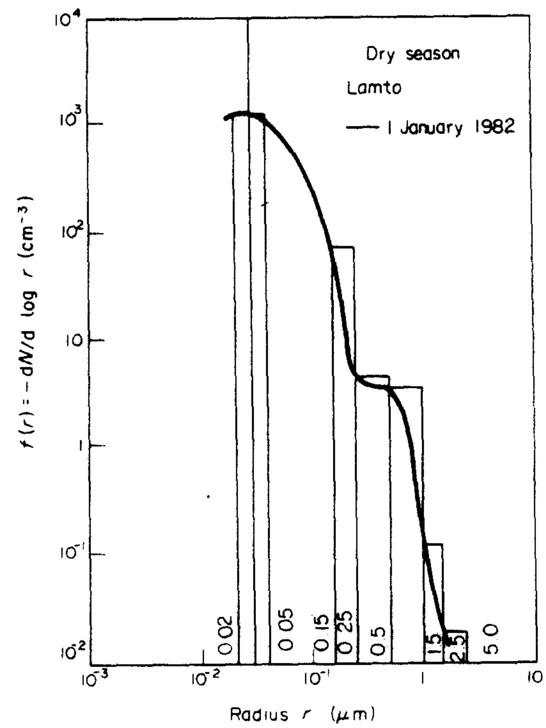

Fig. 6. Lamto, Guinean savannah, during the dry season: mean daily size spectrum determined with the help of:

Gardner counter	($r \geqslant 0.001\ \mu m$)
Thermal gradient chamber	($0.02 \leqslant r \leqslant 0.05\ \mu m$)
Bausch and Lomb counter	($r \geqslant 0.15\ \mu m$)

The results of this analysis are given below:

Large particle. 1st volume: Na, Mg, Al, Si, P, S, Pb, Cl, K, Ca, Fe-(traces).
2nd volume: Na, Al, Si, P, S, Cl, K, Ca.
Small particle: Na, Mg, Al.

Some elements, such as Si, Ca, Na, Pb and Mg, surely belong to the glass slide supporting the particles and not necessarily to the particles themselves.

Only the underlined elements have been taken into consideration in the analysis:

Al, Fe of terrestrial origin
P, S, Cl, K of terrestrial vegetal and maritime origin.

According to this chemical analysis, the present aerosol seems to result from a mixing of various air masses, as already pointed out by the analysis of the meteorological situation; this last situation evidently favoured the formation of mixed nuclei followed by the aerosol ageing and homogenization.

CONCLUSION

Our study revealed several results which tend to prove that the aerosol prevailing in the Guinean savannah at the level of a trough along the ITCZ during the dry season is of a very exceptional nature, particularly aged and homogeneous:

- by operating, the mixing of different air masses produces complex, mixed nuclei whereas the measurement period is void of fire and smoke at least since the preceding day;
- there is no very active source of small nuclei because $N_A \simeq C$ and the radii of the aerosol particles lie between 0.02 and 2.5 μm;
- the various categories of nuclei and particles behave in an identical way which reveals the homogeneous feature of the aerosol. In particular, the correlation coefficient between the concentrations N_A and N_B of small and large particles is about 0.70 whereas N_A is considerably higher than N_B (roughly 50 times higher). This seems to show that the different measurements of various nuclei and aerosol particles support the hypothesis of only one main and aged population free from very small particles;
- the abnormally low values of the *k*-slope (0.26) shows that the CCN population is rather soluble and abundant in nuclei activated at $S = 0.25\%$, this characteristic being that of a well-aged aerosol;
- on the size spectrum, the interval corresponding to the CCN spectrum is stationary;
- moreover, the fog occurrence on 1 January 1982 at 5:00 a.m. when $H = 99\%$ and its dispersal when $H = 98\%$ (Table 3) clearly show that the large nuclei are not entirely hygroscopic and constitute an homogeneous population. Accordingly, we may put forward the hypothesis that these nuclei were of a mixed nature and probably consisted of an insoluble part upon which very small soluble particles were deposited. The later ones may be produced by the bushfires (not present during the measurements) or by the photochemical reactions developing in the gas emitted by the vegetation (Delmas *et al.*, 1978; Delmas and Servant, 1982). They are assumed to be too small to be detected individually by the Gardner counter but a part of them might settle on larger particles from terrestrial source.

So, the sources of AN and CCN and their evolution seem to be the same on the border of forest during the dry season (Table 2). Measurements carried out in other sites of the Ivory Coast gave higher values of *k* (0.7 for example), particularly during the rainy season, which means a more significant difference of concentrations between the CCN activated at $S = 0.25\%$ and those activated at $S = 1.0\%$ (Desalmand *et al.*, 1982; Podzimek and Desalmand, 1982).

It was also observed that the mean concentration of nuclei is higher during the day than during the night, probably because of photochemical reactions.

Up to now we did not succeed in explaining why sometimes we measured N_S concentrations higher than N_A concentrations. An effort will be made to study the nuclei activation and the losses in the different counters under the specific conditions in the Guinean savannah.

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