Influence of Rainfall on the Seasonal Variations of Cloud Condensation Nuclei Concentrations in a Sub-Equatorial Climate

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ABSTRACT

Systematic measurements of cloud condensation nuclei (CCN) concentration have been carried out in the Abidjan area from December 1977 to June 1978, at 0700 local time (corresponding to a daily maximum). In that period of the year, from the main dry season to the main rainy season, a general decrease of CCN concentrations has been noted. This decrease is more marked for the more active CCN. In May and June 1978, during the continuous monsoon rains, the concentrations substantially increased, this effect being more important for the fraction of the less active CCN. Nuclei of continental origin accompanying dust haze in December 1977 were progressively eliminated from the atmosphere by dry or wet deposition. They were replaced by smaller nuclei, originating in vegetation, the production of which was increased by the continuous monsoon rains.

1. The meteorological situation of West Africa

a. The intertropical convergence zone (ITCZ)

Atmospheric circulation above West Africa is governed by the existence of two different air masses. The first, stationed above the Sahara, is very dry and overheated in the daytime; it is associated with the continental flow coming from the high pressures located in the region of the Tropic of Cancer at the level of the Azores. The second, stationed above the Atlantic, is tepid and moist; it supplies the monsoon flow generated by the Saint-Helena anticyclone (Tropic of Capricorn).

The convergence of these two air masses (northeast and southwest trade winds) constitutes the Intertropical Convergence Zone (ITCZ). Upward air motions are principally of mechanical rather than thermal origin. The previous name of Intertropical Front (ITF) now tends to be restricted to the intersection of the ITCZ with the earth's surface.

Fig. 1 represents the vertical structure of the ITCZ and shows that we can distinguish four zones:

- zone A located in the dry and subsident continental air
- zones B, C and D located in the monsoon air mass, humid and convective.

The small width of zone B generally does not favor the development of important cumuli; precipitation is rare. Zone C can be divided into two parts. In the first, the activity of convergence is greatest; perturbations are numerous and both tornadoes and squall lines occur. In the second, the activity of the convergence decreases and the rain becomes continuous. In zone D, thermal inversions appear at various altitudes and prevent the vertical development of clouds; precipitation decreases, though the air remains very humid. The geographical location of this structure is related to the solar zenith angle. The intersection line of the ITCZ with the earth's surface is at its most southerly at the latitude of Abidjan (about 5°N) and at its most northerly at the latitude of Tamanrasset (about 22°N). The ITF progression from south to north lasts about seven months, from mid-December to mid-July, whereas its return in the opposite direction is accomplished in five months, from mid-July to mid-December (Fig. 2).

b. The climate of the South Ivory Coast

The annual oscillation of the ITF accounts for the existence of four seasons in the Southern part of the Ivory Coast. From one year to the next, it is possible to distinguish the following:

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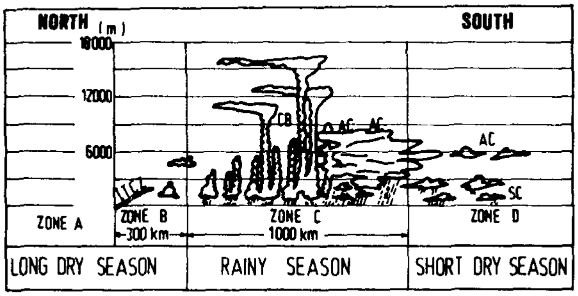

FIG. 1. North–south cross section of the Intertropical Convergence Zone (according to ASECNA, 1979).

1) A long dry season from mid-December to the end of March corresponding to the passage of zones A and B.
2) A long rainy season from the beginning of April to mid-July featured by the weather in zone C.
3) A short dry season from mid-July to the end of September, corresponding to the weather in zone D; the ITCZ is at its northernmost position.
4) A short rainy season from the beginning of October to mid-December, caused by the movement of the whole cloud system of zone C toward the south; further displacement of the system southward brings zones B and A over the coastal regions of the Ivory Coast and the full cycle is completed.

With two rainy seasons and two dry seasons, the climate of the southern part of the Ivory Coast is of the sub-equatorial type. The mean annual rainfall in the Abidjan area is about 2020 mm.

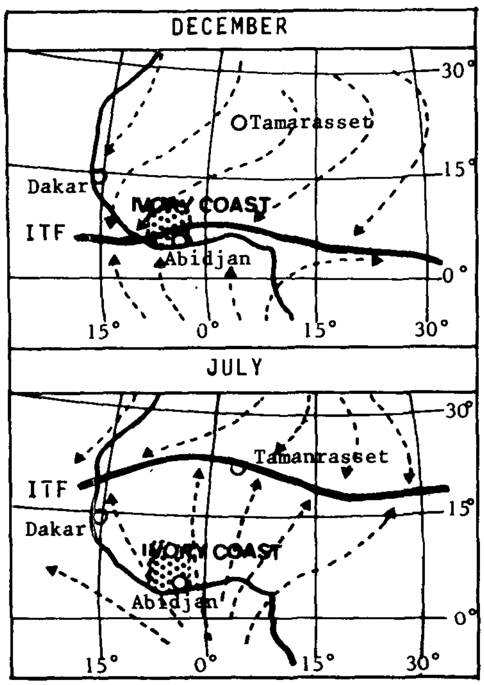

FIG. 2. Atmospheric circulation in the lower layer during December and July.

c. *Aerosol in the Ivory Coast*

Because of the presence of continental and maritime air masses, two major sources of aerosol can be expected in this region: one terrigenous and the other marine. We also have to take into consideration another natural source coming from the vegetation and a local anthropogenic source coming from the city of Abidjan.

1) THE TERRIGENOUS SOURCE: A REMOTE SOURCE

During December or January, enormous amounts of sand and dust are swept upward from Saharan and Sahelian soils. A fraction of these materials is deposited along the ITCZ where the wind is calm; the remainder is carried aloft and reaches the South American Coast above the Guianas after a transit time of 4–5 days (Prospero *et al.*, 1981).

2) THE MARITIME SOURCE

The monsoon layer carries marine aerosol with very low cloud condensation nuclei (CCN) concentrations. However, the CCN concentrations measured at a supersaturation of $S = 1.0\%$ in the Abidjan area (Table 1, Fig. 5) are considerably greater than the concentrations of $\sim 100\ \mathrm{cm}^{-3}$ measured above the oceans by Twomey and Wojciechowski (1969). This is probably due to the influence of continental aerosols during the dry season, and of vegetation-derived aerosols during the rainy period. In this way, the maritime influence on the composition of the aerosol measured at Abidjan, 8.5 km far from the coast of the Guinean Gulf, is neither the sole nor the preponderant one.

In addition, there is some evidence that the marine aerosol is very quickly removed from the atmosphere by dry and wet deposition in the Abidjan area (Crozat *et al.*, 1979a).

3) THE VEGETATION SOURCE

In the north of the Ivory Coast, the savanna is a prolific source of aerosol due to combustion (bush

TABLE 1. Abidjan. Dry season and monsoon season at 0700 local time. Averages, standard deviations, maxima and minima of $N_{0.25}$, $N_{0.50}$ and k.

Variable	Period	Average	δ	Maximum	Minimum
$N_{0.25}$	dry season	890	460	2170	290
	monsoon	730	440	1620	70
$N_{0.50}$	dry season	1960	840	4310	1960
	monsoon	1660	820	3610	150
k	dry season	1.18	0.35	1.89	0.36
	monsoon	1.31	0.46	2.37	0.61

fires), dessication and the crumbling of plants. The particles so produced are transported to the Abidjan area by the continental air masses (Crozat, Domergue, Baudet and Bogui, 1979). In the south, the equatorial forest grows and decomposes throughout the year; it provides a plentiful source of aerosol, especially during the rainy season (Crozat, 1979).

4) The human source

Because of the proximity of the Abidjan, which has heavy traffic in the morning, noon and evening hours, one must be concerned about the impact of these sources on the CCN measurements. However, the measurement in a very busy street of the downtown showed that CCN concentrations take the same value on Sunday when there is very little traffic, as on the following Monday during the heavy traffic hours. Moreover, the sampling site is situated in a residential district (Riviera), 8 km away from the southward located industrial zone, and out of the prevailing winds from the highly populated areas. This is strongly supported by the analysis of the long series of measurements, which does not indicate a strong impact of human sources, except for the period of bush fires during the dry season.

Although one cannot underestimate the impact of human sources on the aerosol production in the Abidjan area, mainly in the ultrafine particle domain, their influence on the CCN measurements seems to be marginal. Therefore the CCN variations will only be correlated with the continental and vegetation sources and their seasonal variation.

2. Characteristic property of CCN and experimental procedure

a. Characteristic property

To study the cloud condensation activity of the nuclei we used a static thermal diffusion chamber. The concentration N of CCN active at a supersaturation S (in %) can be represented by

$$N = CS^k . \qquad (1)$$

In this study, the parameter k is determined from the concentrations $N_{0.25}$ and $N_{0.50}$ of CCN active at $S = 0.25\%$ and $S = 0.50\%$, respectively, i.e.,

$$k = \left(\log \frac{N_{0.50}}{N_{0.25}}\right)(\log 2)^{-1} . \qquad (2)$$

Among the population $N_{0.50}$, we may distinguish the more active CCN (i.e., larger and/or more hygroscopic nuclei), and the concentration $N' = N_{0.50} - N_{0.25}$ corresponds to the less active CCN. The parameter k can be written:

$$k = \left[\log\left(1 + \frac{N'}{N_{0.25}}\right)\right](\log 2)^{-1} . \qquad (3)$$

Thus k expresses the relative wealth of the population $N_{0.50}$ in the less active CCN.

b. Characteristic of CCN measurements in the area of Abidjan

As can be seen in Table 1, the concentrations of CCN are very high, confirming the abundance of the sub-equatorial aerosol. The measurements of $N_{0.25}$ and $N_{0.50}$ carried out every hour from 0000 to 2300 local time during 11 periods of 24 hours display a maximum at about 0700 (Désalmand *et al.*, 1980). During the night, the aerosol from vegetation is confined beneath the forest canopy, because of micrometeorological conditions (i.e., cooling of the upper-surface layer of the forest). After sunrise, this aerosol is dispersed in the atmosphere (Crozat, 1979). The release of this material, and the ensuing photochemical reactions, lead to an increase in the CCN concentrations.

c. The aim of the measurements

The values of $N_{0.25}$, $N_{0.50}$ and k at 0700 were measured and the influence of various meteorological parameters was considered from December 1977 to June 1978. This period includes the long dry season and the long rainy season. It began on 27–29 December, when the ITF reached its most southerly latitude (Abidjan) and corresponds to the displacement of the whole cloud system shown in Fig. 1 toward the north.

3. Main components analysis

Because of the peculiar and discontinuous nature of the dust haze arrival, the last week of December 1977 has been numbered $w = 1$ and the following weeks $w = 2, 3, 4, \ldots$. The long dry season (from December to March) was separated from the monsoon period (May, June) by one month (April) without measurements (due to apparatus failure).

Every observation at 0700 may be associated with 11 variables: w, $N_{0.25}$, $N_{0.50}$, k, h (amount of rainfall during the preceding night from 1800 to 0700 the next day), H (total amount of rainfall since the passage of the ITF on Abidjan area when $w = 1$), ΔL (difference in latitude between Abidjan and the ITF), V_1 (meridional component of the wind), V_2 (zonal component of the wind), Nb (cloudiness) and I_n (number of hours of insolation during the previous day). Thus, each observation is represented in an 11-dimension space. The least squares statistical technique was used to determine the three principal axes that best reflect the distribution of points representing each individual observation. It gave the matrix of correlation between the 11 variables and the three principal components of the 11 unit vectors representing the 11 variables.

TABLE 2. Abidjan. Dry season at 0700 local time. Extract from the linear correlation matrix.

Variable	$N_{0.25}$	$N_{0.50}$	k
w	−0.420	−0.326	0.248
$N_{0.25}$	1.000	0.887	−0.468
$N_{0.50}$	0.887	1.000	−0.054
k	−0.468	−0.054	1.000
h	−0.145	−0.123	0.025
H	−0.216	−0.124	0.180
ΔL	−0.246	−0.167	0.153
V_1	0.281	0.244	−0.166
V_2	0.337	0.323	−0.116
Nb	−0.237	−0.228	0.053
In	−0.002	−0.110	−0.171

TABLE 3. Abidjan. Monsoon season at 0700 local time. Extract from the linear correlation matrix.

Variable	$N_{0.25}$	$N_{0.50}$	k
w	0.361	0.489	0.089
$N_{0.25}$	1.000	0.924	−0.626
$N_{0.50}$	0.924	1.000	−0.341
k	−0.626	−0.341	1.000
h	0.019	−0.173	−0.311
H	0.322	0.377	−0.052
ΔL	0.307	0.187	−0.355
V_1	−0.427	−0.432	0.153
V_2	−0.364	−0.480	−0.048
Nb	0.271	0.133	−0.331
In	0.045	0.137	0.197

a. Dry season

The correlation values for the dry season are low (Table 2). However, one should notice that in Table 3 (for monsoon season) the correlation coefficients change sign. In this way, the same parameters, in particular the total rainfall H, have an opposite effect. This is an important result, since it shows that the total rainfall H might increase CCN concentrations.

In order to smooth down the very important day-to-day variation, we have calculated weekly averages. This resulted in a considerable increase in the correlation coefficients (to values of ~0.8 in Tables 4 and 6).

A careful examination of Table 2 shows that the decrease in the concentrations of CCN with w, H, h, ΔL is greater for the most active nuclei ($N_{0.25}$); the corresponding increase of the parameter k indicates a relative enrichment of the less active CCN (N') in conjunction with a more efficient removal of the more active CCN ($N_{0.25}$).

Fig. 3 gives two of the principal components of the unit vectors relative to the 11 variables and completes the correlation matrix: $N_{0.25}$ and $N_{0.50}$ vectors are anticorrelated with w, h, H and ΔL vectors which are associated with the progression of the monsoon flow over the continent.

b. Monsoon season

Table 3 has been prepared from a very different correlation matrix: in this case it can be seen that the concentrations $N_{0.25}$ and $N_{0.50}$ increase when w and H increase. This behavior is confirmed by Fig. 4, which shows that the $N_{0.25}$ and $N_{0.50}$ unit vectors are close to those of w and H.

c. Interpretation

Dust haze ("brume sèche" in French) consists of dust and sand blown away from the Saharan and Sahelian soils. During our period of measurements, this phenomenon occurred only once, reaching the latitude of Abidjan on about 28 December 1977. These terrestrial aerosols include numerous and large particles: on the 28th the daily mean values were $\bar{N}_{0.25} = 1130\ \mathrm{cm}^{-3}$, $\bar{N}_{0.50} = 2040\ \mathrm{cm}^{-3}$ and $\bar{k} = 0.85$.

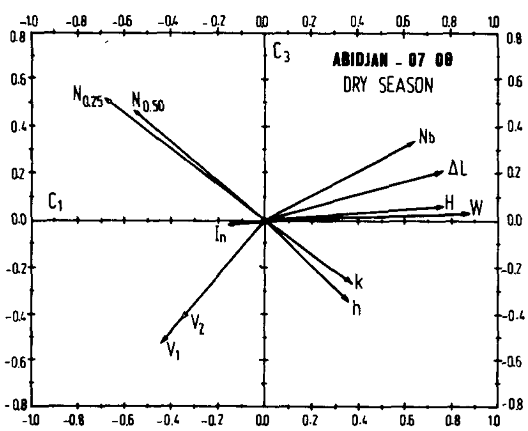

FIG. 3. Abidjan 0700 local time. Dry season: projection in the principal plane of the eleven unit vectors.

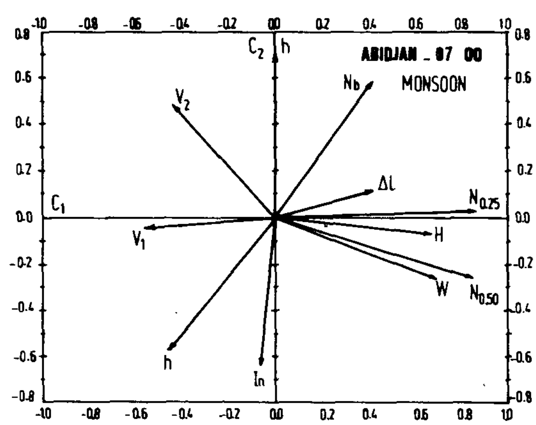

FIG. 4. Abidjan 0700 local time. Monsoon: projection in the principal plane of the eleven unit vectors.

TABLE 4. Abidjan. Adjustment by a linear function between the variables $N_{0.25}$, $N_{0.50}$, k and the number w of weeks since ITF passage. At 0700 local time.

Variable	Period	$X = A - Bw$	r
$N_{0.25}$	dry season	1390 − 83w	0.83
	monsoon	−1230 + 95w	0.71
$N_{0.50}$	dry season	2750 − 141w	0.84
	monsoon	−3550 + 255w	0.81
k	dry season	1.01 + 0.02w	0.47
	monsoon	0.48 + 0.04w	0.37
	all	1.08 + 0.01w	0.37

In addition, nuclei originating in vegetation are released every day in the atmosphere after sunrise, although their production is minimum during the dry season.

Thus, CCN of natural origin are particularly numerous at the end of December, but, as time passes, the largest are progressively eliminated from the atmosphere. The concentrations decrease and k increases when zone B of the monsoon flow and the beginning of zone C pass over Abidjan. This situation persists until the end of March when $H = 230$ mm. On 7 May 1978, the mean values of $\bar{N}_{0.25}$ and $\bar{N}_{0.50}$ were respectively 250 cm^{-3} and 740 cm^{-3}. During the intense monsoon rainfalls ($H > 500$ mm), the concentrations stop decreasing and begin to increase. It is obvious that neither remote nor near terrigenous sources supply CCN at the end of zone C (Fig. 1).

On the other hand, the humidity is always near the saturation point and favors the bacterial decomposition of plants and the formation of sulphureous particles (Delmas, Baudet and Servant, 1978).

Another source of aerosol production, increased by rainfall, is the phenomenon of guttation, by which plants expel droplets rich in soluble substances (Crozat, 1979). It seems reasonable to attribute to this source the increase in the concentrations of CCN observed at 0700, in spite of the intense washing out of the atmosphere. For example, on 15 May 1978, the average concentrations were $\bar{N}_{0.25} = 550$ cm^{-3} and $\bar{N}_{0.50} = 1320$ cm^{-3}.

4. Seasonal evolution of the weekly averaged variables

Because of their very large day-to-day fluctuations, the daily values of $N_{0.25}$, $N_{0.50}$ and k have been grouped week by week and for each number of w the averaged variable $\bar{X}$ has been calculated. Henceforth the symbol $\bar{X}$ indicates an arithmetical weekly mean.

a. Evolution in time

Table 4 displays the linear adjustments, obtained by least squares, between the variable $\bar{X}$ and the number w of the corresponding week. r designates the linear correlation coefficient: for the concentrations $N_{0.25}$ and $N_{0.50}$, its value is equal or close to 0.8. Fig. 5 represents the different pairs (w, $\bar{X}$) and the corresponding adjusted lines. During the dry season the concentrations decrease, and during the rainy season they increase; k increases slightly.

b. Rainfall influence

Table 5 gives the amount of rainfall H for each value of w; w and H are counted from the ITF passage at the latitude of Abidjan. From Table 5, it can be deduced that the months of January, February and March 1978 represent quite well the dry season of a sub-equatorial climate. The monthly amounts of rainfall are:

January : 7.5 mm
February : 99.2 mm
March : 123.3 mm

In the same way, the months of May and June 78 are characteristic of the monsoon with the following amount of rainfall:

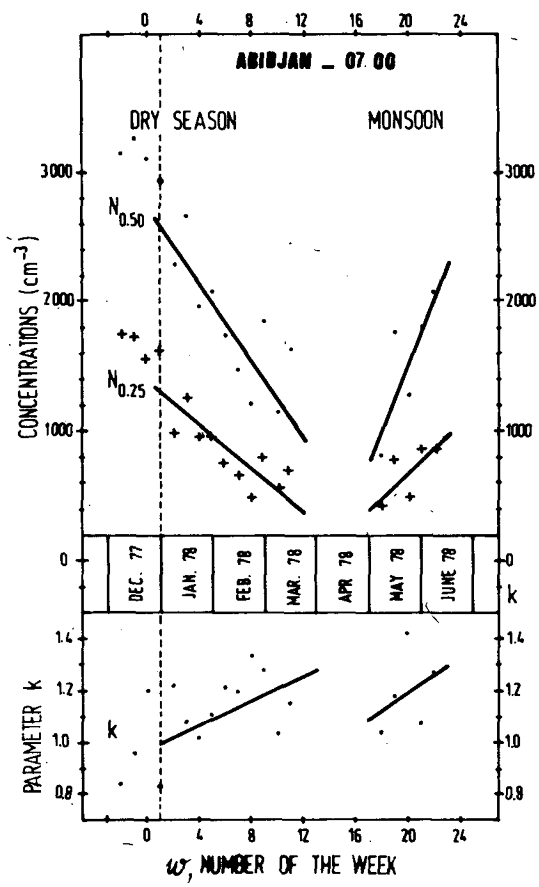

FIG. 5. Abidjan 0700 local time. Weekly average variables $\bar{N}_{0.25}$, $\bar{N}_{0.50}$ and $\bar{k}$ as a function of w (the number of weeks since ITF passage) and adjustments by linear functions.

TABLE 5. Abidjan. Cumulative amount of rainfall H precipitated at week w (number of weeks since the passage of the ITF) from the last week of December 1977 to the first week of June 1978.

Period	w	H (mm)
24–31 December 1977	1	0
January 1978	2	0
	3	7.5
	4	7.5
	5	7.5
February 1978	6	48.8
	7	81.3
	8	85.8
	9	106.7
March 1978	10	200.0
	11	227.0
	12	227.0
	13	230.0
April 1978	14	244.9
	15	305.5
	16	461.7
	17	508.2
May 1978	18	541.7
	19	786.5
	20	970.3
	21	1154.2
June 1978	22	1394.4

May : 646.0 mm
June (first week) : 240.2 mm

Table 6 presents the adjustments of $\bar{X}$ by a power function of H for the different pairs $(H, \bar{X})$; these functions are represented by lines in the logarithmic diagram of Fig. 6. Except for the variable k, the coefficients of the linear correlation are high and around 0.8.

c. Conclusions

A period of CCN concentration measurements at Abidjan has been divided into two parts: the dry season and the monsoon season. The conclusions of

TABLE 6. Abidjan at 0700 local time. Adjustment by a power function between the variables $N_{0.25}$, $N_{0.50}$, k and the total rainfall H.

Variable	Period	$X = AH^B$	r
$N_{0.25}$	dry season	$1450H^{-0.169}$	0.81
	monsoon	$5.47H^{0.699}$	0.74
$N_{0.50}$	dry season	$2920H^{-0.143}$	0.77
	monsoon	$3.63H^{0.880}$	0.85
k	dry season	$1.03H^{0.029}$	0.43
	monsoon	$0.39H^{0.164}$	0.48

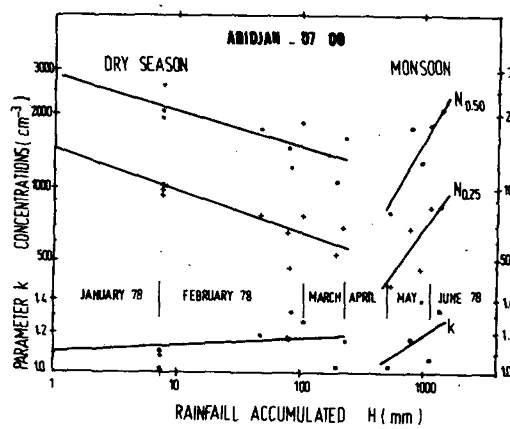

FIG. 6. Abidjan 0700 local time. Weekly averaged variables $\bar{N}_{0.25}$, $\bar{N}_{0.50}$ and $\bar{k}$ as a function of the rainfall H after the passage of the ITF and adjustments by power functions.

the main components analysis carried out with the daily values are consistent with some considerations on the probable origin of the related aerosol. In order to smooth out the large daily fluctuations of the CCN concentrations another type of analysis has been performed using weekly averaged CCN concentrations as a function of the week number w and the corresponding total amount of rainfall H. The results of this study give high values of the correlation coefficient (around 0.8), suggesting that rainfall plays a major role.

5. Conclusions

In this study, the variation of CCN concentrations measured at 0700 local time near Abidjan and their dependance on the ITF displacement and the seasonal influence of rainfall have been clearly demonstrated. During the dry season, provided that $H < 200$ mm, the CCN concentrations decrease either by dry or wet deposition; during the rainy season the CCN increase, particularly when $H > 500$ mm. Rain exercises a double influence: it washes out the more active CCN from the atmosphere and it activates CCN production by vegetation. This production supersedes the effects of washing out during the continuous rains of the monsoon season. Day-to-day variations in CCN are quite important; evidence for CCN from vegetation is provided by the analysis of the average weekly CCN concentrations. The parameter k, which expresses the relative enrichment of the least active CCN, increased continuously during the period of measurements. The large and active CCN, principally of continental and vegetable origin, were progressively eliminated from the atmosphere and replaced by smaller CCN originating from vegetation.

This study has been based on measurements taken from December to June. A more comprehensive view of the subject would be possible if measurements were available for the period from July to December.

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