Seasonal Variations and Frequency Distributions of Ice Nuclei Concentrations at Abidjan, West Africa

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ABSTRACT

Atmospheric ice nuclei concentrations were measured at Abidjan for 27 months, with a mixing chamber operated at −20C. Seasonal variations appear to be linked to the position of the Intertropical Front. Air masses arriving from continental Africa correspond to high ice nuclei concentrations. The washing out of the atmosphere due to rain gives rise to low concentrations. The distribution of daily concentration averages may be represented by a log-normal distribution with high probability of convergence.

1. Introduction

The study of ice nuclei concentrations in air is interesting because of the importance of the ice phase in the development of rain, and because of the role played by ice nuclei. In Central Africa, desert and semi-desert areas are very important sources of dust particles which can travel great distances (Delany *et al.*, 1967) and can have a considerable influence on rainfall (Stevenson, 1969). On the advice of Prof. H. Dessens, we set up in Abidjan a systematic measurement of ice nuclei concentration (Bertrand, 1969). We present and analyze here the results of these daily measurements over a 27-month period.

2. Geographical and climatic location of Abidjan

The city of Abidjan is located on the west coast of Africa, on the mainland side of the lagoon behind the coastal strip. The measurements were made on a plateau 11 km from the sea (5°20′N, 3°59′W, 50 m MSL).

The different seasons in west Africa are linked to the periodical movement of the Intertropical Front (ITF).

On the continent, the ITF is the theoretical surface of separation between the tradewinds of the Northern Hemisphere, moving from a northeasterly direction, and the tradewinds of the opposite hemisphere which become westerly after crossing the equator. These latter winds are known as the equator-crossing monsoon (see Fig. 1). In fact the ITF coincides with the boundary between dry subsiding Saharan air and the humid air of the equatorial regions. Its ground position can easily be determined by changes in dew point and other meteorological variables. This front slopes gently with altitude. The monsoon layer is driven like a wedge under the Saharan Harmattan; and although of high humidity, it is thermally stable (Fig. 2).

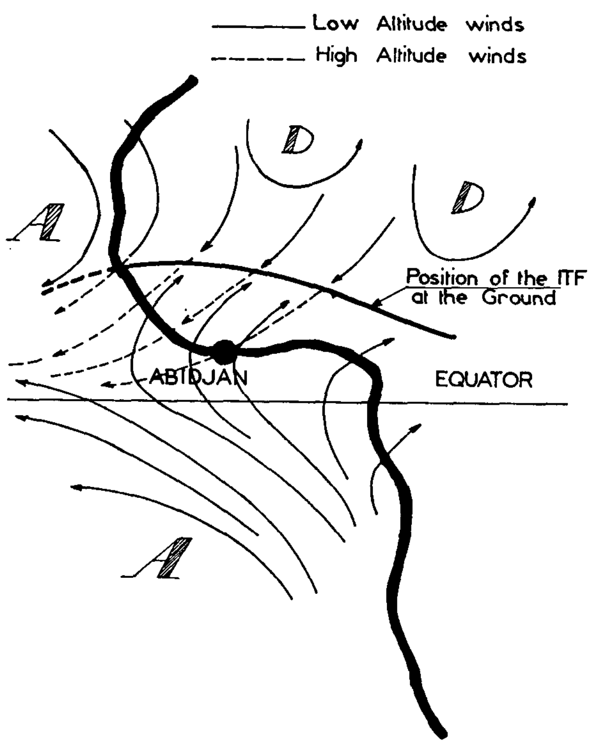

Fig. 1. General circulation over West Africa.

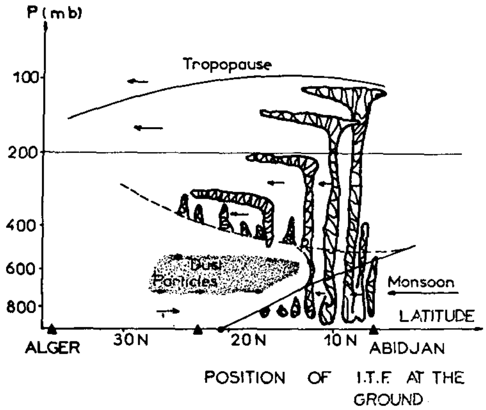

FIG. 2. Vertical section of the ITF in August as a function of latitude.

There are four seasons in Abidjan:

1) A long dry season from mid-December to the end of April, due to a reduced or non-existent monsoon layer; it is at this point that the ITF reaches its southernmost point.

2) A long rainy season from the beginning of May to mid-July.

3) A short dry season when the ITF is at its maximum northeast position, and when the influence of the anticyclone in the St. Helena Island region is felt.

4) A short rainy season from mid-October to mid-December.

In general, the climatic conditions (humidity, temperature and wind) vary little and slowly. Ground humidity is always very high except in the case of the full Harmattan (a few days per year). Mean temperature is about 28C with small daily and seasonal variations. Winds are constant and weak, west-southwesterly in the lower layers and north-northeasterly in the upper.

3. Measuring procedure

A 2-liter mixing tank is used, cooled with a eutectic solution of water and glycerine in direct contact with the walls of the tank to insure thermal homogeneity. The rate of cooling is rapid down to −15C, at which point it slows and asymptotically approaches −20.5C. The air in the tank is humidified when it reaches −20±0.3C. Humidification is accomplished by introducing a 15 W electric bulb wrapped in moist gauze for 1 min. The ice crystals produced are collected in a

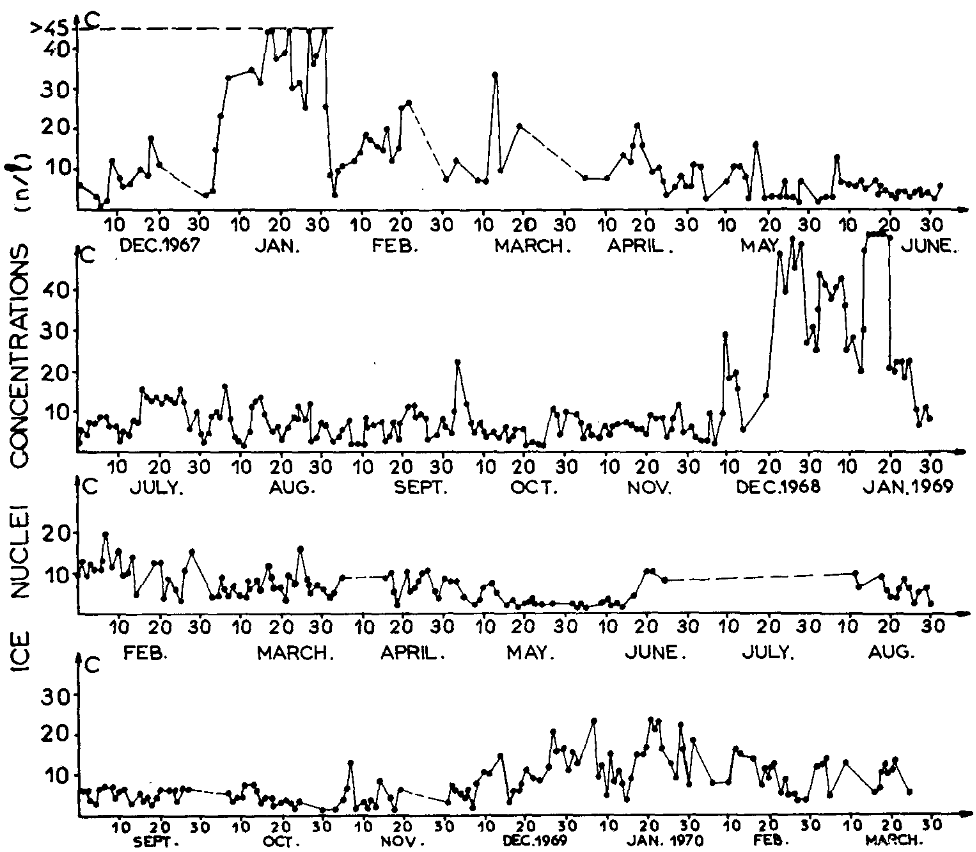

FIG. 3. Daily averages of ice nuclei concentrations at Abidjan in units of number of nuclei per liter.

supercooled sugar solution (130 gm sugar plus 17 gm glycerine per 100 gm water).

A fixed experimental procedure was followed in order to eliminate as many variables as possible, or to reduce their effects to a minimum. We were aided in this by the great stability of most atmospheric parameters.

After many measurements we feel that this method has proved to be satisfactory. It possesses, in our opinion, the great merit of simplicity. The operator sees and controls what goes on at each stage of the procedure; on the other hand, the measurements take considerable time and require the continuous presence of an operator.

The comparison between this 2-liter counter and similar 10-liter counters tested during the first International Workshop on Cloud Nuclei in Lannemezan (Weickmann, 1968) has been made by Bénech (1968). Except for low concentrations of the order of 1 liter^{-1} or less, there is a satisfactory agreement between these two types of instruments.

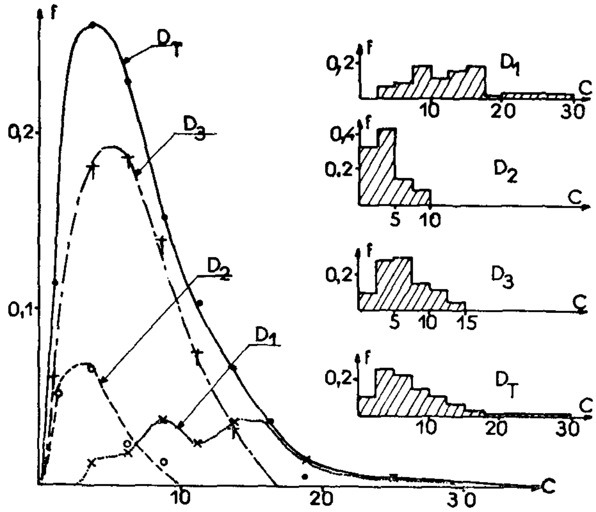

FIG. 5. Same as Fig. 4 except for Year B.

4. Results of ground-level measurements at Abidjan

A total of 1754 measurements were made over a 530-day period between December 1967 and April 1970. As a rule two readings were taken at 0800 and two others at 1500 (local time).

a. Instantaneous values

The fluctuations in the course of a single day remain relatively small compared with those recorded over longer periods. This enables us to consider the daily average obtained from three or four measurements as representative of the concentration of ice nuclei for that day.

b. Daily average

We shall analyze the results on the basis of daily averages, each day thus having the same weight in the distributions. Fig. 3 gives the daily averages from December 1967 to March 1970, with the concentrations being given in numbers of ice nuclei per liter.

Two facts emerge very clearly: 1) high concentrations in December–January, 1967–68, 1968–69 and to a lesser degree in 1969–70; and 2) low concentrations in the May–June period.

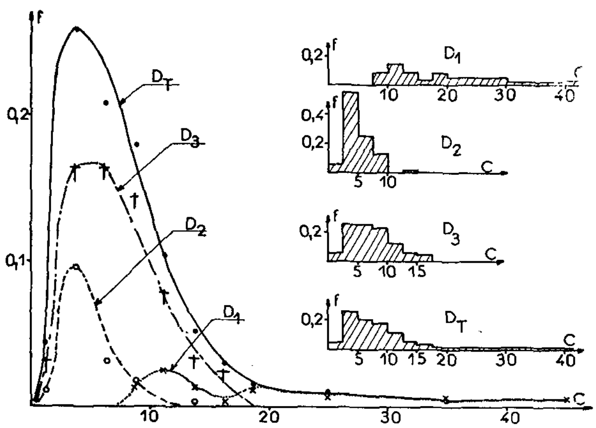

FIG. 4. Relative frequency distributions and histograms for the daily averages of ice nuclei concentrations for year A.

c. Monthly average

This is a rather arbitrary division since the time unit can extend over very different climatic periods. It is, however, quite revealing. It does, in fact, enable us to trace clearly the four seasons mentioned previously.

During the dry season there was a sharp rise in the concentration during December, reaching a high peak in January with a mean value of 30–40 nuclei liter^{-1}; a slower decrease through February, March and April; a minimum concentration of about 5 liter^{-1} in May and June during the long rainy season; a weak rise during the short dry season; and a further decrease in October and November at the time of the short rainy season (refer to Fig. 6 for the reciprocal values of the monthly averages).

5. Analysis and interpretation

Because of the important seasonal variations measured, we have analyzed the results for two years:

Year A: April 1968 to April 1969 (Fig. 4)
Year B: April 1969 to April 1970 (Fig. 5)

The counts from December 1967 to April 1968 were studied separately because we had more regular and more numerous measurements for the corresponding months of 1969.

For each year, the general frequency distribution D_T grouping all the daily averages follows a log-normal law:

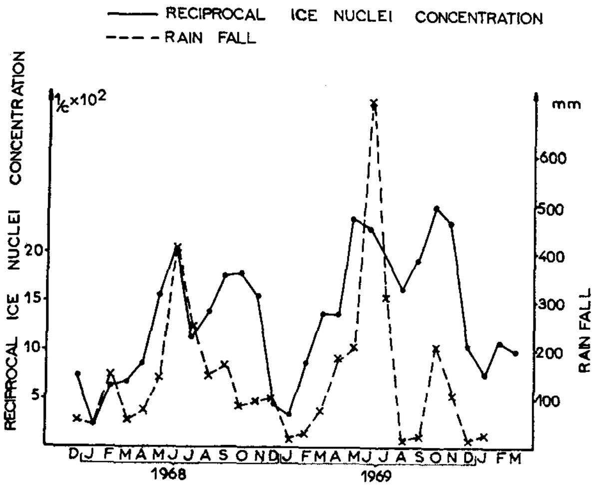

Fig. 6. Reciprocal monthly average of ice nuclei concentration and the corresponding monthly rainfall.

the daily concentration obtained would be due to the results of the interaction of a large number of independent causes whose effects are multiplicative, no one of these causes being preponderant. This result corroborates that of Isaac and Douglas (1971), who found that frequency distributions of ice nuclei concentrations obtained with four types of ice nuclei counters, operated at several locations and at various temperatures, are log-normal. Within this general D_T distribution we distinguish:

Distribution D_1, which corresponds, in the middle of the dry season, to the arrival on the coast of the continental air mass when the ITF is at its southernmost position.

Distribution D_2, corresponding to the long rainy season.

Distribution D_3, which groups all the other observations.

The following interpretations can be proposed:

1) The Harmattan seasons: D_1

There are three Harmattan seasons which emerge very clearly from Fig. 3. They regularly occur from mid-December to mid-February. The position of the ITF at ground level rarely reaches Abidjan, but its vertical structure explains the high ice nuclei concentrations. These continental air masses, which are moved by east-northeasterly winds, are loaded with mineral dust from the desert or semi-desert areas of central Africa. Even though they do not often reach the ground, they are observed at low altitudes during the Harmattan period, sometimes no more than several hundred meters above ground level. It thus seems that we can explain the high concentrations measured during these periods in terms of suspensions of dust of terrestrial origin, if we postulate pollution of the monsoon layer both by fallout and by mixing with the upper air mass.

A comparison of the three Harmattan seasons, showing the importance of the ITF position during these periods, supports this hypothesis. During the first season the ITF ground position reached Abidjan twice, resulting in very high concentrations over a much longer period. In 1968–69 the Harmattan ground position failed to reach the Abidjan area and stopped 150 km to the north. Because of the very gradual slope of the ITF, the continental air mass remained for some weeks at an altitude of several hundred meters (we observed it at 300 m), which explains the heavy concentrations measured. Finally, the 1969–70 Harmattan season shows relatively weak concentrations and a corresponding ITF position which did not extend south of 7N. During its movement, deep troughs over Europe drew air northward and caused an unusual recession of the front. This strengthened the monsoon layer and the fallout recorded the previous year was less marked.

These results concerning the strong concentrations of ice nuclei, linked to the arrival of Saharan air, are consistent with those of Isono *et al.* (1959) and Gagin (1965), who found peaks of concentration linked to the arrival of China loess and to the dust raised over North Africa and over the Negev desert.

2) The rainy season: D_2.

Distribution D_2 corresponds almost exactly to the long rainy season; the low level of ice nuclei concentrations at ground level would be due to the thorough cleaning of the atmosphere by rain.

Numerous other observations made outside these periods corroborate this hypothesis. It is interesting to compare monthly rainfall with the reciprocal of the monthly averages of ice nuclei concentration (Fig. 6). A correlation appears between the two curves. Rainfall becomes particularly important in May–June when there are high maxima for 1968 and 1969. However, during the short dry season in August–September, even though the rainfall decreases sharply, ice nuclei concentrations remain weak (i.e., their reciprocals remain high).

This phenomenon has a natural explanation when one considers that this period corresponds to the northernmost position of the ITF, and thus to a monsoon layer of maximum depth. The air mass is essentially of marine origin, which results in low ice nuclei concentrations despite sparse rainfall.

3) The "normal" seasons: D_3.

Distribution D_3 covers the periods in which there is no dominant meteorological situation, as in the preceding distributions. They are characterized by a low-level marine air mass of variable thickness ($\sim$1.5–2 km) overlaid by a more continental air mass with prevailing east-northeasterly winds. It should also be added that these air masses are almost stationary; winds are very weak, and closed systems are often found around small continental lows north of 5N. Beyond this latitude the Coriolis force is enough to balance the pressure. The air masses thus mix, warm up, and gather moisture. The characteristics obtained seem representative of ice nuclei activity for three-quarters of the year in Abidjan.

6. Measurements as a function of latitude and altitude

During three field trips, in December 1969 and January 1970, measurements related to latitude were made (Fig. 7). These measurements, even though they are too few to draw definite conclusions, are of some interest. In each case a gradual and sizeable increase in ice nuclei concentration was found as the ITF ground position was approached.

The longest field trip, that to Ouagadougou, yielded the maximum concentration when crossing the ITF ground position; further north there was a significant decrease in concentration, although it was possible to assess qualitatively that the dust density at Ouagadougou was the highest observed along the route.

Four aerial field trips during the Harmattan period yielded compatible results. A rapid decrease of ice nuclei concentration in the monsoon layer was observed from ground level up, followed by a strong increase upon reaching the upper air mass which is of different origin.

It is to be noted that the ice nuclei concentration measured in dust clouds was not as high as had been expected. These results show that there is not necessarily a fixed ratio between the concentrations of dust and of ice nuclei. We can postulate a selective accumulation of ice nuclei on the leading edge of the ITF.

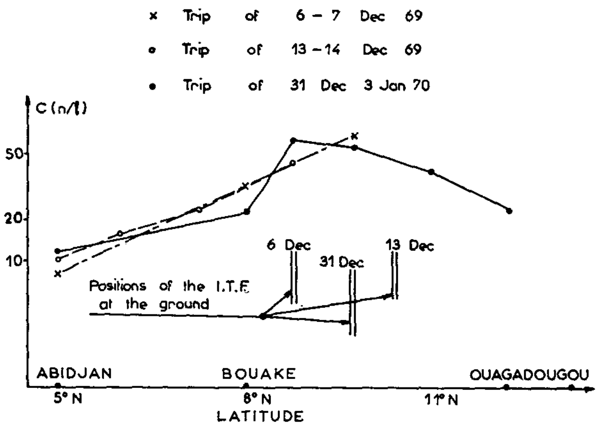

Fig. 7. Ice nuclei concentration as a function of latitude.

7. Conclusion

Even if the absolute values of the measurements are not significant, the results obtained clearly show the terrestrial origin of the ice nuclei. These measurements are in agreement with what is known of the structure and of the movements of the ITF. They point out the dominant influence of the air mass origin on the ice nuclei concentrations. The Harmattan is linked to high concentrations and the maritime monsoon to weak ones. While the latitude and altitude measurements appear to show a selective accumulation of ice nuclei along the ITF, this hypothesis has yet to be confirmed.

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