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# Dust, Clouds, Rain Types, and Climatic Variations in Tropical North Africa

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Dust and processes of raindrop formation in the clouds play a very important role in the climatic evolution of tropical north Africa. Sedimentologic, stratigraphic, pedologic, geomorphologic, and palynologic data converge to show that a major environmental change occurred in tropical Africa about 7000 yr B.P. In the Sudanian and Sudano–Guinean zones (wet tropical zone), from 15,000 to 7000 yr B.P., rivers deposited mostly clay, while from 7000 to 4000 yr B.P. they deposited mostly sand. During the first period, pedogenesis was vertisolic (montmorillonite dominant), associated with pollen belonging mostly to vegetation typical of hydromorphic soils, while during the second period pedogenesis was of ferruginous type (kaolinite dominant) with pollen belonging mostly to vegetation typical of well-drained soils. The great change near 7000 yr B.P. is linked chiefly to a major hydrological change that appears related to a change in the size of raindrops: from fine rains associated with considerable atmospheric dust (raindrop diameter essentially less than 2 mm) to the second period associated with thunderstorm rains (raindrop diameter mostly greater than 2 mm). The size of raindrops is related particularly to cloud thickness and dust concentration in the troposphere. Thunderstorm activity is influenced also by fluctuations of the atmospheric electricity, modulated by the sun.

## INTRODUCTION

Many studies have shown that tropospheric dust affects climate by absorbing and scattering the incoming short-wave solar radiation and so making the surface of the earth cooler or warmer (Twomey, 1977). Dust particles smaller than 1 $\mu$m, the most common, do not greatly disturb the outgoing long-wave infrared terrestrial radiation. Dust also greatly affects formation and evolution of clouds that play a major climatic role, first in rainfall processes and second by affecting the surface temperature. Indeed, because most cloud droplets are larger than 1 $\mu$m, the incoming solar radiation is greatly reduced (albedo effect) and, in this way, also the surface temperature is reduced. By reducing infrared terrestrial radiation lost to space (greenhouse effect), however, clouds also have a warming effect. The net result of these two opposing effects appears to be a decrease in the surface temperature (Schneider, 1972; Paltridge, 1974; Ohring and Clapp, 1980).

The present article concerns the role of dust in the formation and evolution of clouds, in the formation of raindrops, and in the effects of rain types in hydrological, sedimentological, pedological, geomorphological, and vegetational evolution during the late Quarternary in tropical north Africa.

## GEOLOGICAL AND PALYNOLOGICAL DATA

Dust has had an important sedimentological role in wetter parts of tropical north Africa during certain periods, because there are many loesslike deposits (colluvial loess) in the Sudanian and Sudano–Guinean zones (Fig. 1). The last main dated phase of loesslike deposits is between 15,000 and 7000 yr old (Maley, 1980). Figure 2 presents a stratigraphic synthesis of available data on deposits at the longitude of the Chad Basin where data and radiocarbon dates are most numerous. Evidence further west shows that essen-





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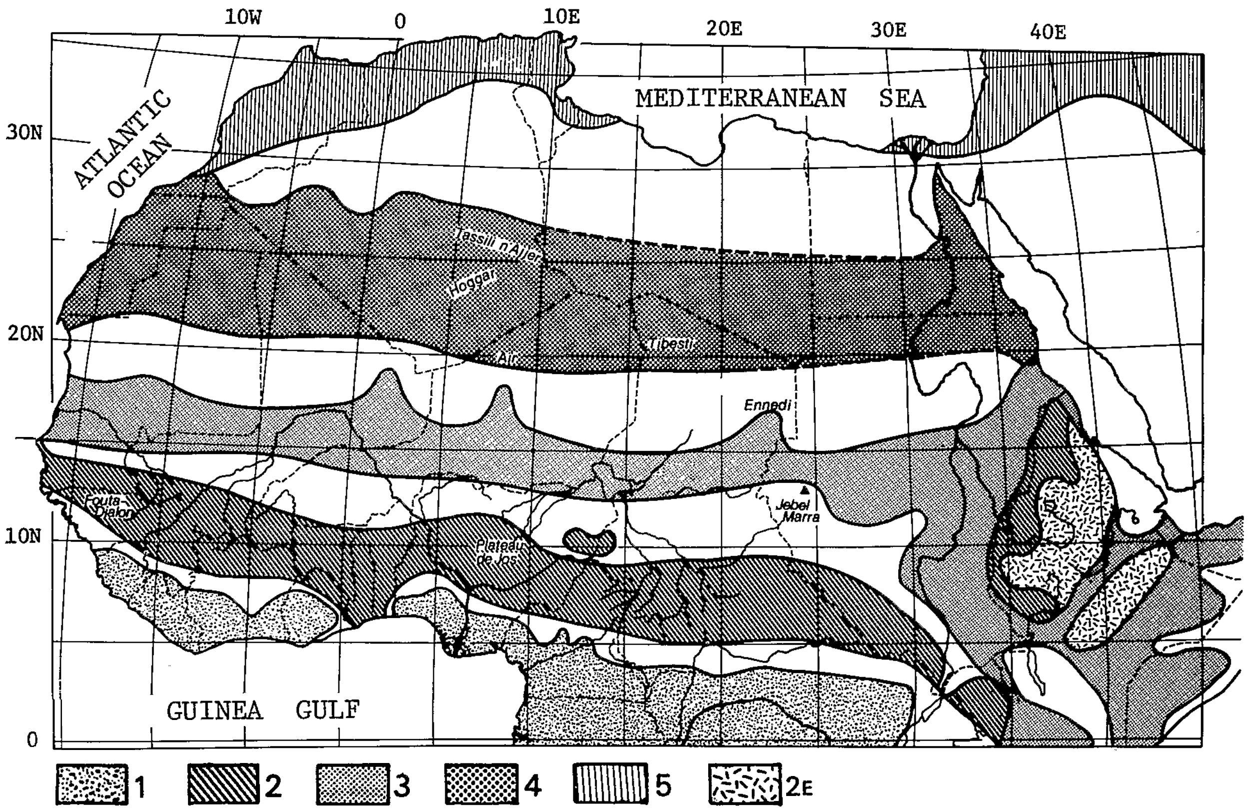


FIG. 1. Map of principal vegetation and climatic zones in Africa north of equator. Every other zone represented in white, moving south to north, is indicated by "b" in the legend. (1) Guinean zone (rain forest), (1b) transition zone (forest–savanna mosaic); (2) Sudano–Guinean zone, (2E) Ethiopian high plateaus, (2b) Sudan zone; (3) Sahel zone, (3b) southern or tropical Sahara zone; (4) central Sahara zone, (4b) Saharo–Sindian zone, (5) Mediterranean zone. Sources: for the Sahara, the solid lines are adapted from Quézel (1965) and the dotted lines are estimated from diverse data, cf. Maley (1980). For the south of the Sahara, the solid lines are mainly from the vegetation map published in 1958 by the Association pour l'Etude Taxonomique de la Flore d'Afrique Tropicale (AETFAT), with the assistance of UNESCO, Oxford University Press (from Maley, 1980).

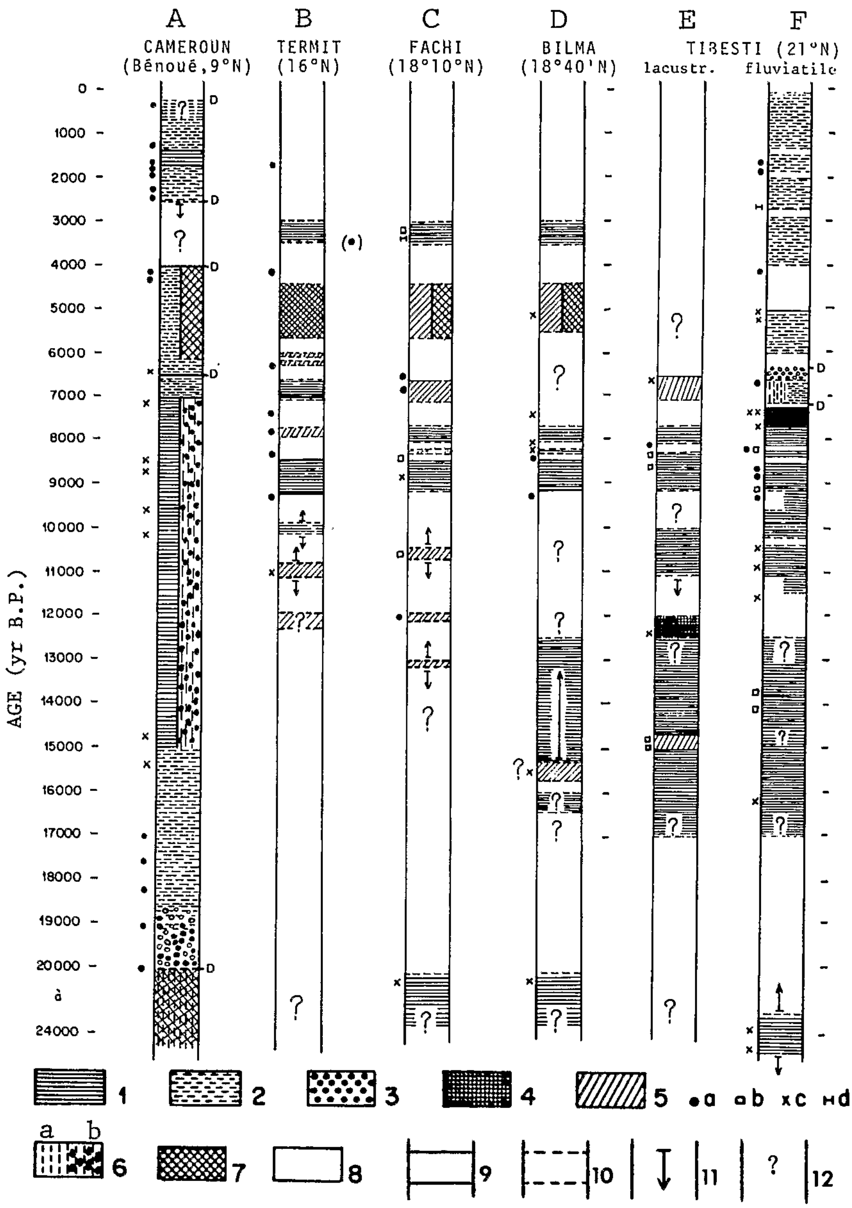


FIG. 2. Stratigraphic synthesis of deposits at the longitude of the Chad Basin for lakes or rivers with relatively small catchment areas covering almost only one climatic zone. 1—Lacustrine extension with fine sediments or relatively fine and layered fluvial deposits; 2—sands and gravels; 3—pebbles; 4—calcareous crust; 5—low lacustrine level or swamp formation; 6a—various paleosoils; 6b—vertisol with calcareous nodules; 7—ferrugineous crust or ferrugineous-type paleosoil; 8—arid period (eolian sands, etc); 9—relatively well-dated limits; 10—estimated limits; 11—possible displacement of a chronological limit; 12—data or periods particularly requiring further studies; D—major discontinuity. Position of radiocarbon dates and nature of dated samples: (a) charcoal or vegetable remains, (b) shells, (c) carbonates, (d) bone, ( ) important dating at a neighboring site. (cf. Maley, 1980 for the numerous references to basic stratigraphic data). *Note:* The Bilma lacustrine deposits from the end of the Pleistocene, if their chronological position is confirmed, would probably result from artesian waters coming from central Sahara (from Maley, 1980).

tially the same sequences prevail in the rest of tropical Africa, exhibiting a rather close zonal synchrony of the phenomena within the principal climatic belts (A, wet north tropical; B, Sahel; C and D, southern Sahara; E and F, central Sahara; Fig. 2) (Maley, 1980).

An examination of Figure 2 shows that the succession of deposits is often different between the principal climatic zones studied here. Nevertheless, during certain periods the same type of deposits extends across several zones. For instance, fine laminated sediments formed during the wet phase of the early part of the eighth millenium B.P., or during the middle Holocene, the vast extension of tropical ferruginous soils often were associated with the formation of iron crust. Of particular note is a major sedimentological change occurring near 7000 yr B.P., corresponding to a transition from clay to sandy sediments. Despite the predominance of clay sedimentation, however, in the wet north tropical zone between 15,000 and 7000 yr B.P., a relatively important dry season must have existed, given that the pedogenesis at this time was vertisolic with formation of montmorillonite and calcareous nodules (Maley, 1980; for vertisols, cf. Millot, 1978). In Cameroun, the vertisols formed on fine loesslike deposits which almost covered the landscape. In contrast, the reappearance of coarse sandy sediments in the middle Holocene, between 7000 and 4000 yr B.P., corresponded with a sharp renewal of erosion which is well documented from the Nile to the Senegal, and with the development of tropical ferruginous soils (Maley, 1980). Such pedogenesis requires a warm climate and abundant rain, but nevertheless with a relatively important dry season because kaolinite that forms particularly in these soils needs a climate of fairly high evaporation. This alternation during the Holocene between montmorillonite and kaolinite is, in fact, the result of the fundamental geochemical opposition which separates the conditions of genesis of these two clay minerals (Bocquier, 1973; Bocquier *et al.,* 1970; Millot, 1978). Such variation occurs spatially at present where montmorillonite forms in the confined soils of valley bottoms, because of the prolonged annual presence of a water table near the surface, while kaolinite, which requires strongly leaching conditions, develops in well-drained soils of interfluve slopes. Furthermore, in soil catenas, following augmentation of confinement or drainage, an increase in either montmorillonite and vertisols, or of kaolinite and tropical ferruginous soils is observed (Bocquier, 1973; Bocquier *et al.,* 1970).

Palynological studies have shown that pollen of typical taxa of the Sudano–Guinean zone were brought by rivers flowing from the southern part of the Chad Basin (Maley, 1972, 1980). This gives some information on the evolution of the vegetation in this zone during the Holocene (Maley, 1980). First, the rain forest does not seem to have reached the southern rim of the Chad Basin during the Holocene, because no pollen belonging uniquely to typical rainforest taxa was transported to Paleochad by the Logone or the Chari Rivers. Among the Sudano–Guinean pollen types, those belonging to *Alchornea cordifolia,* living particularly on the hydromorphic soils of the valley bottoms, were dominant in the early Holocene until about 7000 yr B.P. Afterward, in the middle Holocene, pollen of *Hymenocardia acida,* currently growing on the well-drained soils of the slopes, was dominant until about 4000 yr B.P. The evolution of some Sudanian pollen types can also be explained by similar alternations. In addition, one notices that, in comparison with the middle Holocene, the montane species *Olea hochstetteri* was more extensive in the early Holocene, probably indicating cooler conditions during this time. With respect to the Sahel zone, the percentages of the arboreal pollen in the Tjeri spectrum show a strong increase from 7000 until about 5000 yr B.P., which corresponds to an increase in arboreal vegetation, probably with an extension of the Sahelian savanna at this time (Maley, 1977, 1980). These diverse pollen data fit well with the sedimentological and pedological evidence.

Because the succession of deposits often occurs differently between the dry and the wet tropical zones (Fig. 2), during some periods humid conditions continue or reappear in the wet tropical zone while the dry tropical zone becomes drier, particularly in the Sahel and the southern Sahara, with an increase in eolian activity and a consequent increase in atmospheric dust. This phenomenon is probably the origin of the fine loesslike sediments that were formed in the wet tropical zone, especially between 15,000 and 7000 yr B.P. (Maley, 1980).

## DISPERSION OF SAHARAN DUST IN TROPICAL NORTH AFRICA

At present, when a polar trough extends above the Sahara, an intensification of the continental trade winds (harmattan) at ground level is often observed, which causes sandstorms to occur (Bernet *et al.*, 1967). Toward the south, beyond the Sahara, these sandstorms are transformed into dry hazes by loss of the heavier particles. Suspension in the air of the lighter particles leads to aerosol formation. These particles are composed essentially of quartz and clay, the latter consisting mostly of kaolinite, montmorillonite, and illite in variable proportions (Bertrand, 1976, 1977; Bertrand *et al.*, 1974). The zones of generation and the principal fluxes of dry haze occurring in west Africa, as schematized by Bertrand (1977), are shown in Figure 3. The southern Sahara constitutes the principal source of dust for tropical north Africa.

Data concerning present-day eolian sedimentation in tropical north Africa are rare. From measurements at N'Djaména (Dupont, 1967), a deposition rate of 42 $\mu$m/year is obtained for the period 1966–1967 (Maley, 1980). At Kano, a rate of 116 $\mu$m/year was calculated for 1978 to 1979 (McTainsh, 1980). The mass of dust currently put into motion above tropical north Africa is sometimes very large. Bertrand (1976, 1977), from data on visibility, calculated that the dust in suspension above west Africa, including the Guinean zone, from Cameroun to Guinea and between about 5° and 15° N, was $2.13 \times 10^6$ tons on November 27, 1973 and $8.6 \times 10^6$ tons on March 7, 1973. Such data explain the formation of loesslike deposits in tropical

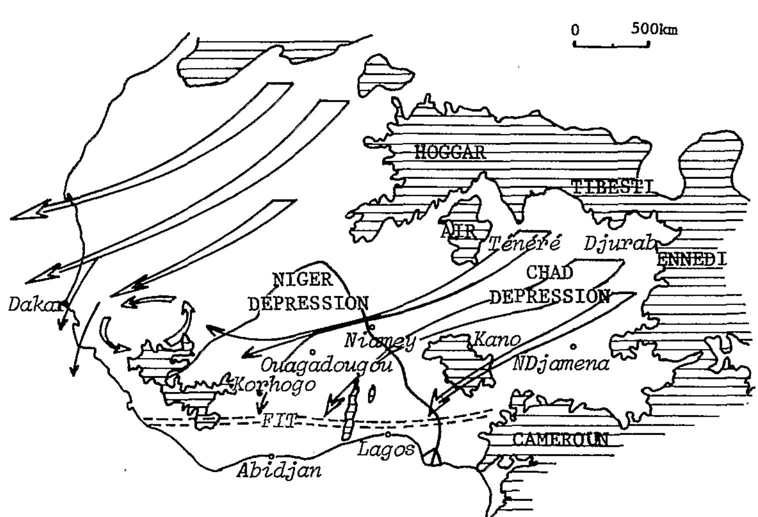


FIG. 3. Dry haze and dust movements in West Africa (adapted from Bertrand, 1977).

north Africa during periods with persistent dry hazes.

Table 1 presents the granulometric distribution of particles larger than 0.3 μm in the dry haze at Abidjan. The particles were measured with a Bausch and Lomb optical diffusion granulometer which gives the number of particles with a diameter between 0.3 and 20 μm (Bertrand, 1976, 1977). At stations close to the dry-haze source regions (Bobo-Dioulasso, Ouagadougou, Niamey), the granulometric distribution is rather similar to that of Abidjan, with nevertheless a more important proportion of larger particles (10–20 μm), particularly at Niamey. From these data, Bertrand (1976, 1977) estimated that a very rapid increase in particle concentration and size must occur between Niamey and the source at Ténéré-Djourab.

At Abidjan, 50 to 60% of the particles measured are between 0.3 and 0.5 μm in diameter (Bertrand, 1976, 1977). Although data are missing for particles below 0.3 μm (Aitken nuclei), a rather good relationship exists between the classical size distribution of natural aerosols established by Junge (1972), particularly for dust of Saharan origin, and the distribution measured at Abidjan for the 0.3- to 20-μm size, which allows for the use of Junge's diagram to obtain a gross approximation of the Aitken nuclei in the north African dry haze. This diagram shows that in continental environments the concentration of Aitken particles (about $10^{-5}$ to $10^{-7}$ cm in size) is about 10 to 100 times higher than those between 0.5 and 0.3 μm in diameter, which therefore leads to an estimate of 1 to 5 × $10^6$ to $10^7$ particles/liter for tropical north Africa.

TABLE 1. Granulometric Distribution of Particles Larger than 0.3 μm in the Dry Haze at Abidjan[a]

| Size (μm) | Number per liter (approximate) |
|---|---|
| 0.3–0.5 | 100,000–500,000 |
| 0.5–1 | 30,000–100,000 |
| 1–2 | 80,000–100,000 |
| 2–3 | 30,000 |
| 3–5 | 7000–8000 |
| 5–10 | 400–1000 |
| 10–20 | 100 |

[a] Mean for four measurements, from Bertrand, 1976.

## DUST AND PROCESSES OF CLOUD AND RAIN FORMATION

In dry atmosphere, the presence of dust increases thermal stability of the air, but in wet atmosphere the role of the dust is very different (Murty and Murty, 1973). Indeed, during the year in tropical north Africa, sandstorms and dry hazes are most frequent in January and February, but they can also occur with a high frequency as early as October and persist until May. In summer, sandstorms can occur in north or central Sahara (Dubief, 1952) and part of the dust can flow southward (Bertrand, 1976, 1977). Dust fluxes can be important therefore in wet tropical Africa during large parts of the rainy season making extensive contact with the monsoon flow (Fig. 4). Dust sedimentation is then carried out essentially by rain and mist. The dust particles that participate in the formation of cloud droplets and subsequently of raindrops are transported to the ground by rain which also washes a large part of the dust from the atmosphere (Twomey, 1977).

Dust particles can be transformed into condensation nuclei, particularly when the dust penetrates the humid air of the monsoon, because certain ones are activated by the absorption of water molecules (Bertrand, 1977). It is generally observed that over land very few cloud-forming nuclei are of marine origin (Mason, 1971; Gambell, 1962). It has been shown that in the tropospheric aerosol of the Ivory Coast, elements of marine origin such as Na and Cl decrease very quickly in the first kilometers from the shore and that beyond 100 to 200 km inland Na is no longer of marine origin (Crozat *et al.*, 1973). In contrast, the influence of continental elements on the sea is very obvious: in pelagic sediments off West

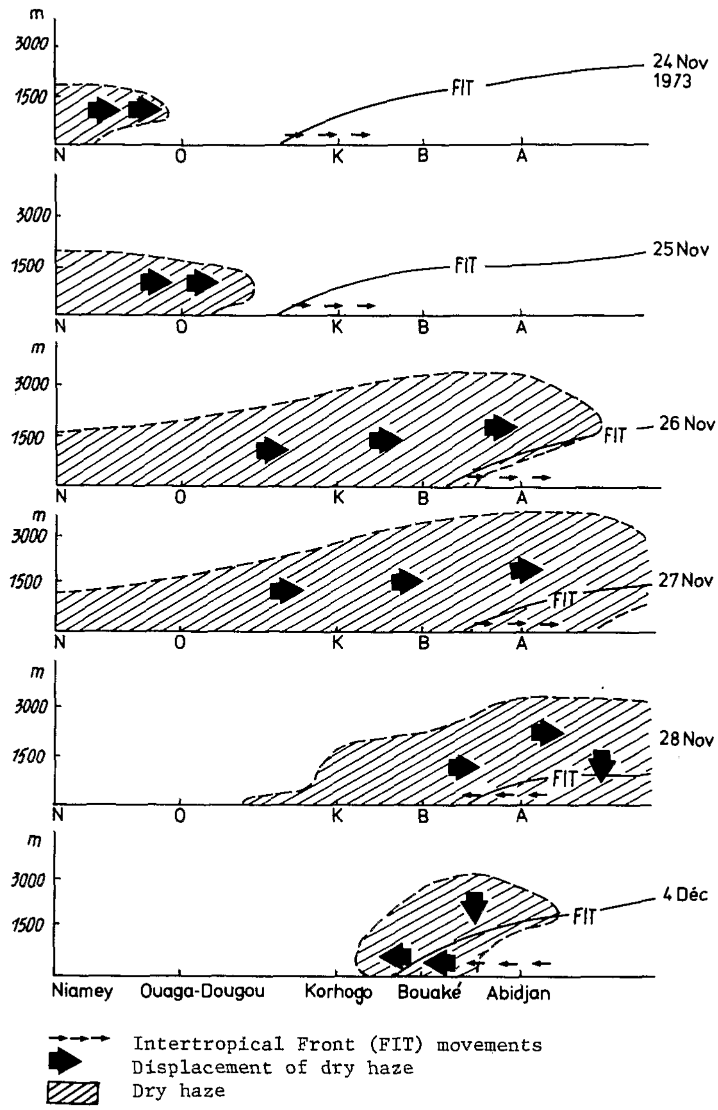


FIG. 4. Evolution of the dry-haze cloud in northern tropical Africa and its interaction with the monsoon in November 1973 (from A. Drochon, ASECNA, in Bertrand, 1977).

Africa the importance of particles of continental origin is shown by the presence of kaolinite which has a maximum along the Guinea Gulf (Biscaye, 1965).

In the processes of cloud formation, part of Aitken nuclei and larger particles act as condensation nuclei for the formation of *cloud droplets* (Mason, 1971). At low latitudes, in "warm" clouds without ice crystals present, droplets larger than about 20 $\mu$m, formed on giant nuclei (1–50 $\mu$m), can grow into *raindrops* in some cases by coalescence with smaller cloud droplets (Mason, 1971; Twomey, 1966). Workers in this field distinguish *maritime-type clouds* from others of *continental type*. Beyond their preferential location over sea or land, the principal difference between the two types of clouds does not depend as much on their water content nor on the relative abundance of giant sea-salt nuclei as on their microstructure (Squires, 1958b). Indeed, there is a direct correlation between the concentration of cloud droplets and the concentration of cloud nuclei in the air in which the clouds form (Twomey and Squires, 1959). Because continents are the principal source of cloud-forming nuclei and exhibit a very large concentration of Aitken nuclei (Junge, 1972), continental clouds frequently have large numbers of droplets, as opposed to a relatively small number on the seas (Twomey and Squires, 1959). For the same water content, the average droplet size decreases with increases in the number of droplets. Therefore the droplet sizes in continental-type clouds exhibit a narrow spectrum with practically no cloud water in droplets larger than 20 $\mu$m, while the maritime-type clouds exhibit a large spectrum ranging from a few micrometers to 40–60 $\mu$m, with the maximum frequently near 20–25 $\mu$m (Squires and Twomey, 1960). Because of the low coagulation efficiency of small droplets during the coalescence process, droplet growth to the size of raindrops (up to 100 $\mu$m) will be considerably easier and faster in a cloud with, say, 50 droplets/cm$^3$ (maritime type) than one with 800 droplets/cm$^3$ (continental type) (Squires, 1958a; Twomey, 1966).

Observations carried out far inland on warm cumuli giving rainfall have shown very low droplet concentrations, so colloidal instability in continental clouds and raining processes are apparently sometimes associated with a maritime type of microstructure (Squires, 1958a; Twomey, 1959). On the other hand, in continental regions inside shallow cumuli of stratiform type, stirring motions that transfer droplets several times from one level to another increase the probability of collision; also, because of the presence of some giant-size nuclei formed on dust particles, turbulence can trigger the rain process (Mason, 1971). In stratiform clouds, limited depth generally restricts the size of raindrops to no more than 2 mm in warm clouds of the temperate zone (Mason and Andrews, 1960) as well as in tropical Africa (Barat, 1957). The final raindrop size at the base of the clouds is almost independent of the collection efficiency of the droplets, but depends primarily on updraft velocity inside the clouds (Mason, 1971). Therefore the larger raindrops are formed in very deep clouds with great updraft velocities, such as cumulonimbus, which frequently extend to the top of the troposphere.

In summary, the concentration of dust in the atmosphere plays a very important role in inhibiting or retarding the raining process and also in favoring the persistence of clouds, which tend to reduce evaporation from the earth's surface. At the same time, the concentration of dust in the atmosphere, by lowering the radiative exchange, increases the atmospheric stability, which has the effect of impeding or constricting the rising motions necessary to cloud formation. In such an environment, it is necessary that dynamic processes linked to atmospheric circulation intervene to trigger cloud and then rain formation. In tropical north Africa, such processes are probably linked with the action of the two easterly jet streams which circulate above the monsoon (Tropical Easterly Jet and the low-level African Easterly Jet) (Fig. 5) (Maley, 1980). In short, these processes can act by increasing convergence and lifting air masses to form clouds, by mixing air masses with a relatively low number of condensation nuclei to reduce nuclei concentration in the clouds, by inducing some stirring motions in the clouds, or by thickening the clouds until they transform into cumulonimbus (Ludlam, 1966).

To study the variations of the pluviosity on tropical north Africa during the late Quaternary, it thus seems interesting to consider the phenomena from the point of view of the evolution of clouds and the modifications in their microstructure. Sutcliffe (1966) and Lamb (1972) have already pointed out that such modifications may lead to very large climatic changes.

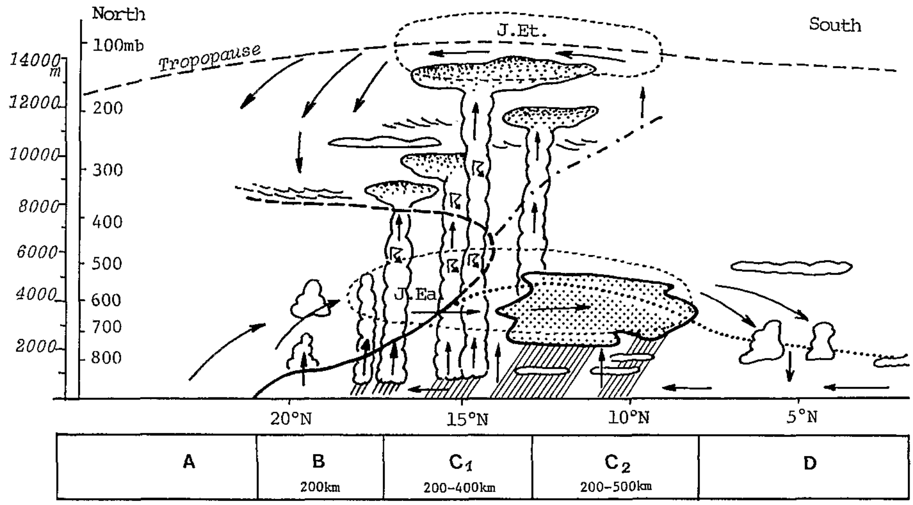


FIG. 5. Schematic north–south section of the troposphere in August above West Africa near the Greenwich Meridian. Principal weather zones: (A) zone without rain, (B) zone with isolated storms, (C1) zone where mobile depressions dominate, (C2) zone where quasi-stationary depressions dominate, and (D) zone with low rains. Arrows schematize fluxes and particularly convection or subsidence movements. (—) Intertropical front (FIT); (—·—) lower limit of upper equatorial air; (...) upper limit of the monsoon. J. Et., Tropical Easterly Jet; J. Ea., African Easterly Jet. This figure is a synthesis of diverse data, mainly from Dhonneur (1974) and Burpee (1972) (from Maley, 1980).

## PRESENT-DAY WEATHER AND RAIN PATTERNS

At present in the monsoon of tropical north Africa, meteorologists schematically distinguish several weather zones which occur in zonal belts almost parallel to the equator (Trewartha, 1961; Dhonneur, 1974). During the maximum extension of the monsoon in August (Fig. 5), one distinguishes from north to south: *zone A,* without clouds, to the north of the Intertropical Front (FIT in figures); *zone B,* with isolated storms because of the shallow depth of humid air; *zone C1,* where mobile depressions, or disturbances lines (Eldridge, 1957), form; these depressions are composed of very deep cumulonimbus rows, generally with a north–south axis; *zone C2,* where stratiform clouds linked with quasi-stationary depressions dominate; and *zone D,* where clouds and rain are reduced because of subsidence phenomena.

In zone C1, between the passage of mobile depressions, sunshine is high, causing high evaporation and thermal convection. In contrast, in zone C2 these phenomena are not important because cloudiness is high or total. Although the exact conditions of genesis and evolution of mobile depressions (Aspliden *et al.,* 1976) and of quasi-stationary depressions (Dhonneur, 1974) are rather poorly known, several authors insist that dynamic motions, triggered particularly by the two easterly jets streams, play an important role (Burpee, 1972; Dhonneur, 1974; Kidson, 1977) (Fig. 5).

When the two principal rainy zones are considered, one notices that the clouds giving rain further inland are cumulonimbus of zone C1, which frequently extend to the top of the troposphere, while in zone C2, further south, they are frequently thinner and of stratiform type. Although data on the microstructure of clouds do not seem to exist for tropical north Africa, this cloud distribution seems to be explained by their microstructure. Indeed, the closer one goes toward the Sahara, the greater is the concentration of dust and the condensation nuclei in the monsoon, which ultimately tends to increase cloud stability. At present, the principal process of raindrop formation seems to be turbulence which develops inside stratiform clouds of zone C2, while in the more continental zone C1 it seems to be associated with the rapid updrafts linked to the thickening of the clouds. Going inland, such thickening of rain clouds has been observed in North America from the Gulf of Mexico to the semiarid southwestern United States (Battan and Braham, 1956), as well as in Australia (Twomey, 1959). It has also been shown that cloud thickening is associated with the augmentation of condensation nuclei in the air where the clouds form (Twomey, 1959).

Portig (1963) pointed out that in the intertropical zone there are two basic kinds of rain, one associated with much electrical activity (thunderstorms) and one with little. Moreover no relation exists between the quantity of water that falls and the kind of rain. In West Africa during the rainy season the number of thunderstorm-days is very much larger in the dry tropics (Portig, 1963). Following this work, Ramage (1971) defined two types of precipitation for the monsoon regions: first, the *showers,* related to thunderstorms and associated with towering cumulus or cumulonimbus and, second, the *"rains,"* associated with deep stratiform clouds. The structure of the monsoon is different for these two types; a conditionally unstable lapse rate and insolation heating are favored for thunderstorm development and *showers,* but reduced insolational heating and near-stable lapse rate, which inhibit thunderstorm formation, give way to a *"rains"* regime.

Independently, Barat's research (1957), mainly in tropical West Africa, has confirmed and extended these results. First, Barat (1957) showed that in zone C1 rains from cumuliform clouds (*Showers* sensu Ramage or *Heterogenous Rains* sensu Barat) are chiefly characterized by big drops larger than 2 mm in diameter, while in zone C2 the rain from stratiform clouds (*"Rains"* sensu Ramage or *Homogenous Rains* or *Monsoon Rains* sensu Barat) is chiefly fine rain with drops smaller than 2 mm. Furthermore, Barat (1957) showed (Fig. 6) that the fine rains of zone C2 (*Monsoon Rains*) infiltrate instantaneously or with a short delay, producing only slight runoff with limited erosive action. For these reasons this type of rain leads to silt or clay-type deposits. In contrast, the rain with large drops typical of zone C1 (*Showers*) produces strong runoff that leads to linear erosion with significant removal of material and to coarse deposits of sandy sediments in the rivers. For instance, on the Adamaoua Plateau generally, such erosional differences are observed in certain rainy seasons when, in August, zone C2 is well established in the Sudano–Guinean zone. At this time, the alluvial load of the rivers decreases or remains at the same level although the discharge continues to increase, while later, in September and October, the load increases again when zone C1 crosses the region a second time during the last phase of the rainy season (Maley, 1980; hydrological data from Nouvelot, 1972).

## EXAMPLES OF RAIN TYPES AND CLIMATIC CHANGES

Because of the relatively short annual stay of zone C2 in the wet north-tropical zone, the influence of fine rains on present-day morphogenesis is extremely low. The generalized erosion which is currently observed in this zone, even in uninhabited regions (Vogt, 1968; Michel, 1978; Maley, 1980), and which is accompanied by coarse, sandy sedimentation, is linked to the present-day dominance of large-drop rains formed in cumulonimbus mobile depressions.

### *The Second Part of the 19th Century*

In the Sudano–Guinean zone of the Adamaoua Plateau (Cameroun), historic

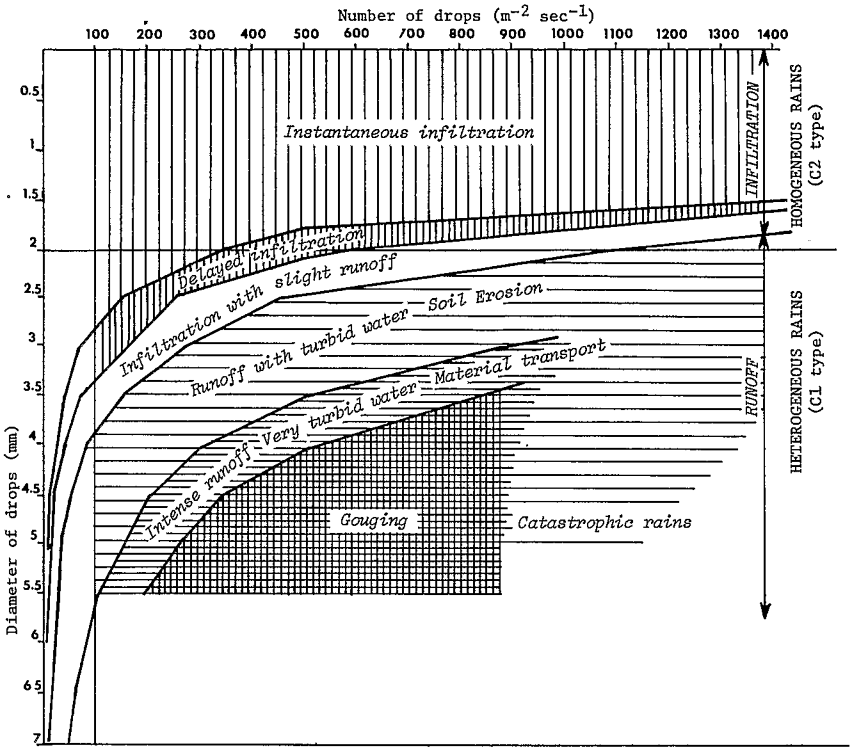


FIG. 6. Effects of different rain types on the ground (adapted from Barat, 1957).

witnesses interviewed by the geographer Hurault (1975) near Banyo (6° 45′ N, 12° E), told him that near the end of the last century the situation was different. While many tributaries now almost completely dry up after the flash floods of the rainy season, at that time the depth of water courses varied only slightly during the year and floods rose slowly. Older people also reported that rivers deposited principally mud and fine sand, which Hurault confirmed by sedimentological studies, while today they deposit coarse sand and pebbles. These witnesses also reported that trees at that time were extremely rare on all of the slope surfaces (Hurault, 1975). This vegetational point is very important, because it implies that the great diminution of erosion, deduced from the fine sedimentation, was not caused by an extension of arboreal cover. From this fact, the only possible cause apparently lies in a modification of the character of the rains, which must have been fine for the most part.

These deductions are of great consequence, particularly because, for equal volumes of precipitated water, the losses by evaporation are very different according to rain type. Fine rain, associated with greater cloud cover, infiltrates for the most part and the water is then progressively restored to the water courses during the year. The major part of large-drop rain does not infiltrate but runs off, and because of the sunshine between the passage of mobile depressions, suffers important evaporational loss resulting in a certain edaphic dryness. In addition, losses by evaporation are then amplified in flood zones of rivers because they cannot rapidly dispose of the flash-flood waters linked to this second type of rain. The annual and multi-annual hydrological balances will be very different, therefore, according to the dominance of one type of rain or the other. So, one can conclude that significant changes such as the higher level of Lake Chad which occurred during the second part of the last century and which ended suddenly about 1900 (Maley, 1973, 1980), or the Nile floods which, at the same time, averaged 20 to 30% higher than they were subsequently during the first part of the 20th century (Riehl *et al.*, 1979) can be due essentially to a change in rain type.

Other data concerning the second part of the last century and coming from the Sahel zone, particularly from Sénégal (Hubert, 1920), indicate first that a diminution of mobile depressions did occur there, and secondly that the rainy season did not last longer then than it does today (Maley, 1980). From this fact, the longer annual duration of C2-type rains in the wet north-tropical zone cannot be explained by a longer annual stay of the monsoon in West Africa. On the contrary, one must conclude that it is a more general change, first in cloud microstructure, and secondly probably in the dynamics of atmospheric circulation in tropical north Africa.

One would think at first glance, by referring to the above, that the reduction of cloud thickness, which is deduced from the increase in fine rains, could be associated with a decrease of condensation nuclei. This phenomenon could be explained, for instance, by a greater inland penetration of humid monsoon air masses of direct marine origin whose condensation-nuclei concentration is relatively low. Nevertheless, although data are not available for Saharan eolian activity, this activity was probably relatively more important at this time. The second part of the 19th century has been identified as a cool period (Lamb, 1972), which would tend to be linked synoptically with an increase in polar troughs above the Sahara, not only in winter, but also in spring and autumn. Associated with these troughs is the formation of tropical or Saharan depressions, ahead of which there are frequently sandstorms (Jalu *et al.*, 1965; Maley, 1977, 1980). So, it would be possible that the increase in fine rains during the second part of the 19th century was due essentially to an increase in condensation nuclei.

When other time intervals in the Holocene are examined, a relationship appears also between the dust variation and the rain types.

### *The Early and Middle Holocene*

During the early and middle Holocene, the evolution of events in tropical north Africa (Fig. 2) shows particularly that the periods before and after 7000 yr B.P. fit well with the two types of regimes just described. Indeed, as can be seen in the relationships established above between sedimentology and rain types, it appears that in the wet tropical zone during the late glacial between about 15,000 yr B.P. and the early Holocene the extension of fine clay-type deposits must have corresponded to a period dominated by fine rains, while during the middle Holocene between about 7000 and 4000 yr B.P., deposition of coarse sediment of sand or gravel type must have corresponded to a period dominated by large-drop rain (Maley, 1980). The change in rain types induced an important hydrological change in the rivers, particularly with suspended load before 7000 yr B.P. and bed load after that time.

The dominance of rain with small or large drops seems to be associated with the dust concentration in the air, because between about 15,000 and 7000 yr B.P. the dust concentration was important above tropical north Africa and adjacent zones. Evidence of this phenomenon appears chiefly in the extensive loesslike deposits in the wet north-tropical zone dated between about 15,000 and 7000 yr B.P. (Fig. 2), and also, during the same period, in large eolian imports in the Guinea Gulf (Pastouret *et al.*, 1978) and the Gulf of Aden (Olausson and Olsson, 1969). These events ended suddenly about 7000 yr B.P. Furthermore the deposition of fine laminated sediment before about 7000 yr B.P. and coarse sediment after, also occurred in the drier parts of tropical north Africa; deposition of coarse sediment lasted until about 4400 yr B.P. in the sahel and southern Sahara, and until about 5000 yr B.P. in central Sahara (Fig. 2), which implies a diminution in the emission of Saharan dust during most of the middle Holocene. From these facts, the inferred dominance of thick cumuliform-type clouds, in which large-drop rains form, therefore essentially corresponded to a period of decreased dust in the air. Moreover one can also conclude that the change near 7000 yr B.P. corresponded to a dramatic modification of atmospheric circulation, probably related in part to an important change in the dynamic of the two easterly jets streams of this region.

### *The Late Holocene*

One other well-documented example similar to the last concerns the first millennium A.D. (Maley, 1980), during which the cooling phase near the middle corresponded to deposition of widespread fine clay-type sediment in the wet tropical zone and the warming phase of the second part of this millennium to widespread sand and gravel deposits (Fig. 2). Between about 3500 yr B.P. and the present there have been several phases when fine clay-type deposits formed.

## CONCLUSIONS

In tropical north Africa it appears first that there are periodical alternations of two different types of humid periods. Each period is characterized by different sedimentological, pedological, geochemical, hydrological, geomorphological, and vegetational evolutions, and which are, in a certain sense, opposite.

The alternation between these two basic types of humid periods, linked with the two types of rain and of clouds described above, can cause the elimination of taxa and their replacement by others better adapted to the new conditions. This alternation probably also has a direct relationship with the numerous pairs of related species with close taxonomic affinities (for instance *Lophira alata* and *L. lanceolata*), which are frequent in these regions, either in humid or in relatively dry environments or soils (Aubreville, 1949). Eventually the evolution of such pairs of species (the pairs are sometimes under the species level such as ecotypes) are probably related to the repetition of these two types of humid periods, because one can infer that this climatic alternation, which is frequently repeated in the course of time, must act on taxa like a "species-pump," to repeat the expression and the evolution model used by Stebbins (1974).

Certain differences appear within postglacial time. Thus, in the early Holocene the increase of dust in the air was associated with an extension of the fine rains and stratiform clouds, whereas the increase of dust in the Northern Hemisphere over about the last 50 yr (Gunn, 1964; Cobb, 1973) and, particularly since the beginning of the 1970s, the increasing concentration of tropospheric dust around the Sahara (Prospero and Ness, 1977) occurred without a noticeable change in rain character. The decrease in rain south of the Sahara in the 1970s does not seem to be associated with a change in the rain character, but more probably with a change in intensity of the Hadley circulation (Newell and Kidson, 1979; Maley, 1980). The recent persistence of large-drop rains in tropical north Africa could perhaps be due to the fact that either a certain threshold of aerosol concentration has not yet been reached, or that other phenomena also intervene to determine the character of the rain. Beyond phenomena linked to atmospheric circulation, some other hypotheses are possible. Atmospheric electrical phenomena, still poorly known, may control the dynamics of clouds by acting either on the stability of the dust (Twomey, 1977), on the condensation nuclei, or on the clouds droplets (Vonnegut, 1963; Mason, 1971). Possibly the clouds and the complex processes leading to the rains are one important link between solar activity, which modulates the atmospheric electricity (Markson, 1975, 1978), and the climates of the earth. One cannot help but be impressed by the observance that the postulated dramatic increase of thunderstorms about 7000 yr B.P. in the tropical African zone occurred precisely at the time of a major change in the evolution of the earth's magnetic field (cf. the curve in Bucha, 1970, Fig. 6a), also influenced by solar activity. Furthermore, the change from fine to coarse sediments, which is related mainly to the characteristics of the rains, is sometimes a more widespread phenomenon. For instance about 7000 yr B.P. this change can be detected not only in the tropical zone, but also at higher latitudes as in the Mediterranean zone (cf. Fig. 2 in Rohdenburg, 1977), or in North America where the difference of rain types could explain a sedimentological change but also some vegetational modifications (cf. Martin, 1963; Byrne *et al.*, 1979; Watts, 1979, 1980; R. W. Fairbridge, personal communication, 1981). In conclusion, one sees that clouds are an essential link in the control of climatic evolution.

This article constitutes a first approach to these problems because much remains to be learned, first on the microstructure of present-day clouds and their interaction with atmospheric circulation in tropical Africa, second on atmospheric electricity and its role in cloud and rain formation, and finally on the details of the climatic evolution of tropical Africa.

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