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THE MICROPHYSICS OF THE SAHARAN DUST AND ITS IMPLICATIONS ON CLIMATE

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1. INTRODUCTION

The prevalence of a dry season in West Africa during the months of November through April primarily derives from the seasonal transport of the Saharan dust, otherwise known as the Harmattan dust haze in Nigeria. The dust has attracted the attention of many scientists from many parts of the world.

The influence of the dust is felt seasonally in many parts of the world as a result of its distant transport trajectories into many parts of the world (See Fig. 1). The following are known important long-distance trajectories of the Saharan dust plumes: the summer transport across North Equatorial Atlantic and the Caribbean Island (e.g. Carlson and Prospero, 1972; Carlson, 1975; Schutz, 1979; etc), across Southern Europe and the Alps (Prodi and Fea, 1978, 1979) the transport axis into the Middle East and Israel (e.g. Yaalon and Ganor, 1979) and finally the winter transport into West Africa across Nigeria and the Gulf of Guinea Coast of Africa (e.g. Aina, 1972; Kalu, 1979; Prospero, et al., 1981; etc)

In most of these studies, not much has been said about the microphysics of this strong global source of soil-derived aerosol from the Sahara and its impact on climate. However, some works on the dust from the point of view, for example, of the physicist have been given (e.g. Dubief, 1979), on a synoptic basis (e.g. Aina, 1972; Morales, 1979a; Kalu, 1979, 1983, etc) on the chemical properties (Rahn et al., 1979; Cox et al., 1982) and on its medical aspect (Adefolalu, 1984; Kalu, 1983).

A close study of the Saharan dust aerosol is important because the dust affects the radiation balance of the Earth-Atmosphere System, especially in regions where dust transport is strong seasonally as in West Africa.

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At present the extent of this radiative impact is not known quantitatively. It should be seriously addressed by tropical modellers.

2. Chemical and Mineralogical Composition of the Saharan Dust

a. Dust Source Regions

It may be necessary to have an insight into the dust source regions of the Sahara as this will help us understand the discussions that follow in this section. The Saharan desert has several important sources for its aeolian dust output into different parts of the world. These sources affect different parts of the world at different times in the year, depending on windflow pattern in the lower atmosphere.

However, the South-Eastern fringe of the Sahara covering the semi-arid Sahel region, notably the Bilma - Faya Largeau alluvial plain, west of the Tibesti Massif (Kalu, 1979), constitutes one major source region of the dust forming the Harmattan haze which affects Nigeria and neighbouring West African countries north of the Gulf of Guinea. There are other sources which affect different regions of the world as depicted in Fig. 1.

It will therefore be most useful for us to examine briefly the chemical and mineralogical composition of the Saharan dust in view of its observed strong influence on solar radiation. At the moment, it is still verydifficult to assess or, in fact, identify a particular element of the dust which therefore enhances its observed affinity to solar radiation fluxes. Many works on the composition of the Saharan dust have already been presented (e.g. Goodman et al., 1979; Rahn et al., 1979, etc). It is however

not my intention here to repeat these works, but my main objective is to summarize those physical/Chemical properties

Table 1. Chemical and Mineralogical Composition of aeolian dust from the Sahara. Slightly adapted from Yaalon and Ganor (1979).

mineral (Clay-free) Component: Element	%	Clay Component	Organic Matter Component
Quartz	35 - 45	Montimorillonite	presently only
Calcite	30 - 40	Kaolinite	in small fractions
Dolmite	10 - 20	illite	but very
Halite	1	Palygorskite	important in soil fertility
Salts			Roughly 11%
$(NH_4)_2SO_4$	Vari-	This gives the characteristic reddish coloration of the dust and changes to grey over its over its long-distance trajectories.	
$CaCO_3$	able		

of the dust which may be associated directly or indirectly with their microphysical influence on cloud genesis and hence its impact on climate.

b. Chemical Elements present in Aeolian Dust

Recent chemical analysis of the Saharan dust by means of microscopic examination of dust filter samples obtained in various dust concentrations in the Saharan aerosol layer by Rahn et al., (1979) and others, reveal that the following chemical (clay-free) elements are present in the dust. These are: Fe, Ca, Al, Na, K, Mg, among others. The percentage composition of some of these elements is indicated in Table 1.

Alot of studies on the chemical composition of the Saharan dust is available in the literature. For example, mineralogical analysis of Saharan dust samples collected on mesh at Barbados by Prospero and Carlson (1970), a microscopic analysis at the Imperial Institute, London (Hamilton and Archbold, 1945), the electron microscopic analysis method of dust filter samples obtained by means of flying of light aircrafts within a dust plume layer (Rahn et al., 1979) using an acid - washed 11cm - Whatman No. 41 cellulose and nuclepore filter paper samples.

Results of the various chemical and microscopical analysis of the African dust indicate that the Saharan aerosol is typical of known global aerosols (Yaalon and Ganor, 1979) and constitutes a major aeolian dust aerosol content of the Trade wind air over the North Atlantic, for example.

Present estimates indicate that the Saharan dust accounts for about 79 percent of the aerosol mass of the tropical atmosphere. (Yaalon and Ganor, 1979). It also includes some quantities of ammonium sulphate and organic matter.

In our present discussion, the chemical and mineralogical

composition of aeolian dust from the Sahara has been subdivided into the following three basic components, samely:

(a) mineral component,

(b) clay component (which is mineral-free), and

(c) organic matter comprising of vegetable and animal tissues in very minute forms only identified by microscopic examination of dust samples.

The various components and their constituent elements are given in Table 1.

As may be noticed from Table 1, the Saharan dust can appropriately be described as "aggregate" aerosol particles consisting mostly of quartz, mica and clay minerals. Also important in dust constituent elements are large amounts of organic detritus elements averaged about 11 percent in composition, but it is highly variable. The amount of organic matter as determined chemically is relatively low compared with the other major elements of the aerosol and is usally associated with the coarse grain size of the dust.

The composition of ferric oxide (Fe_2O_3) - an important constituent of the mineral dust generally - is fairly close to the core mean of the dust content (Eriksson, 1979). This is probably due to the coating by iron oxide observed on many of dust grains. There is therefore a marked increase in the iron oxide content of the dust aerosol from the Sahara. It is the high percentage content of Fe_2O_3 that gives the dust its reddish colour, especially near the source of mobilization, but becomes grey at long distances downwind.

It is perhaps the clay component of the dust especially the presence of montimorillenite, kaolonite, illite, etc which may be responsible for its observed active thermal and radiative response. This is not yet very clear and needs further investigation.

c. Economic Importance of Saharan Dust

Furthermore, it is pertinent for me to draw your attention to the economic importance of the presence of plankton in the aeolian dust from the Sahara. This evidence from detailed study of the Saharan dust may be of great economic importance especially in fishing industry. This is because plankton is an important food substance for fishes (Kalu, 1983) and is found in the Harmattan dust haze, in view of a large amount of loess deposition over the coastal areas of West Africa, e.g. the Gulf of Guinea Coast of Africa (for the winter dust transport) and the Canary Island off the Cape Verde Islands of Senegal (for the Summer dust trajectory into North Atlantic). See Fig. 1.

Another aspect of the economic importance of the Saharan dust in West Africa and over major trajectories of the dust, especially over land, is the soil-enrichment factor of the Saharan dust through solid and wet deposition of the dust along its trajectories. This is true when it is remembered that chemical salts like $CaCO_3$ and $(NH_4)_2SO_4$, important in soil fertility, are also present in sizeable quantities in the Harmattan dust aerosol. Observations in Israel on the deposition of aeolian dust indicate that the dust has a constant accretion identifiable in the soil and has a significant influence on the nature and fertility of soils in Israel (Yaalon and Ganor, 1973). Removal processes of the dust from the atmosphere through dry deposition and rain-out mechanism add large quantities of soil materials of some nutritive importance to the soil. The performance of cereal crops in Northern Nigeria may be attributible to this seasonal enrichment of the soil through both solid and wet removal processes.

Some of the useful economic aspects of the Saharan dust transport across West Africa, established through research on the Saharan dust, for example, soil-enrichment through solid and wet deposition of the dust as lipids (Cox et al., 1982), provision of food for fishes and hence making loess deposition as fertile grounds for large-scale fishing and, of course, the pronounced cooling of the air through active attenuation of incoming solar radiation, should be further investigated, especially as a means of profitable fishing and agricultural activities in regions of intense Saharan dust transport.

3. CLIMATIC IMPACT OF THE DUST

The impact of the Harmattan dust on climate may be discussed in terms of the radiative response of the dust on incoming short-wave radiation. This is because, as has been pointed out by Junge (1975,1979), mineral aerosol particles can affect climate primarily through their effects on the radiation budget of the Earth-Atmosphere System (EAS). The radiative interaction between solar radiation and suspended dust particles in the atmospheric boundary layers (ABL) below 700 hpa is therefore important in our effort to understand the role of dust aerosols on the microphysics of ABL clouds, on the one hand, and their impact on climate dynamics, on the other hand.

During the 1977 Gothernburg Workshop on the Saharan Dust transport (which the author participated), three mechanisms were identified relating to the microphysics of clouds and rainfall processes. These are summarized thus (Morales, 1979):

1. radiative effects in a cloud-free air,
2. effects on cloud albedo, and
3. effect on the microphysics of rain formation.

In the above, (1) is a direct effect which occurs through attenuation processes in the atmosphere accomplished by a combination of scattering, reflection and absorption of incoming solar radiation (Kalu, 1983), while (2) and (3) are collectively considered as an indirect effect achieved through the modification of the optical properties of the cloud, particularly atmospheric albedo (Junge, 1979).

While the direct effect has so far received a considerable attention in the literature, this is not the case with the indirect effect (in West Africa, for example) which seems more relevant to climate problems. This is probably because the development of low clouds and weather systems resulting therefrom during the northern winter dry season in West Africa is minimal, especially north of the Inter-Tropical Discontinuity (ITD) and therefore does not readily catch the imagination of research meteorologists.

Evidence is still lacking in support of the hypothesis for an enhacement of rainfall and its formative processes through nucleation process by soil-dust aerosol particles in West Africa or any other parts of the world for that matter. This is because available observational evidence in Nigeria - a country lying along a major winter dust trajectory (Kalu, 1979; Prospero et al., 1981) - is instead in favour of an anhydrous non-hygroscopic behaviour of the dust. This non-hygroscopic property of soil-dust aeroso particles generally gives a clear distinction between sea-salt aerosol particles and aeolian dust particles.

However, an important influence of the dust particles is on the stability of boundary layer cumulus clouds in humid and cloudy regions where dust transport is intense. Kalu (1983) has identified that a most significant process through which dust can affect climate is on its stabilizing influence in the boundary layers of the atmosphere where dust transport is strong in West Africa. An extensive study has been made by Kalu (1983) on the possible atmospheric mechanisms through which soil-dust aerosol particles can influence climate in West Africa. His studies reveal that the most significant feature which is relevant to climate dynamics is a pronounced stable boundary layer where a south-westward dust transport is strong climatologically.

This effect for a dust-laden atmosphere is more clearly observed in regions with persistent cloudiness than areas with a high frequency of clear skies. The pronounced stability of the planetary boundary layer in dusty atmospheric conditions may be identified by the following observational synoptic processes:

a. a low-level capping inversion (Fig. 2) and
b. a rapid dissipation of cumulus clouds along a dust plume trajectory.

The climatological implications of (a) and (b) will now be considered in detail. The synoptic significance of the presence of a low-level atmospheric capping inversion to weather development is not new. It had been discussed by Riehl (1954), among others, especially as it concerns the reduction in the convective liability of the lower tropical atmosphere (Palmen and Newton, 1969). Pasquill (1974) has also discussed the influence of aerosol particles on the stability of the atmospheric environment.

Recent studies of the dust-climate relationship by Kalu (1983) indicate that the influence is temperature-related. A climatological significance of such peculiar temperature characteristics of a dust-laden atmospheric boundary layer has been revealed through a three-dimensional thermodynamical analysis of the tropical atmosphere under cases of severe dust episodes. See Fig. 3 . When the dust plume moves into the Trade wind confluence zone, as is the case over the North-Equitorial Atlantic over the coastal areas of West Africa, the observed effect is normally to reduce the effectiveness of the ascending branch of the Northern Hemispheric Handley Circulation (Newell and Kidson, 1977). See Fig. 4 . This suggests, following our concept of the stabilizing influence of the Saharan dust, that the vertical overturning of cumulus clouds on which hangs the whole precipitation machinery of the tropical atmosphere, is seriously checked dynamically. In other words, we are saying that convection of the atmosphere is reduced resulting from the radiative response of dust cloud. This is extensively observed in Nigeria where, as a result of a strong transport of dry Saharan dust, the microphysical processes of cumulus clouds is considerably weakened. As a result rain does not fall, especially north of the ITD or its frequency and intensity south of the ITD is reduced and we have the dry season in the region overlain by the Saharan aerosol layer (SAL).

It is the view of the author, that the primary meteorological component of the causes of the recent Sahel drought of 1968 - 1973 and beyond, when the tropical general circulation was such that there was an equatorward displacement of the major climatological pressure system, e.g. the Northern hemispheric subtropical high, otherwise known as

the Saharan High Pressure (SHP) (Kalu, 1985) and the Equatorial Trough sometimes tagged Monsoon trough. This, as noted by Lamb (1982), is the cause for the unusual persistence of the sub-Saharan drought and its equatorward extension into Northern Nigeria (Kalu, 1984).

Now, we shall consider the second factor - the observed rapid clearance of cumulus cloud clusters. This is a most reliable synoptic indication of the inhibitive property of the Saharan dust on cumulus cloud growth and so on the precipitation forming processes of the tropical atmosphere. It is in this respect that we shall examine the climatic implications of the microphysics of cumulus clouds in a dust-laden atmospheric environment. Kalu (1983) has shown this by means of satellite images over regions of intense aeolian dust transport from the Sahara, for example, along the North Equatorial Atlantic (Carlson and Prospero, 1972). The presence of the dust in large concentration seasonally, as is climatologically the case over West Africa, affects climate and weather in many ways, some of which are still unknown to us (Carlson and Caverly, 1977), and in fact, on the dynamics of the tropical atmosphere over areas where dust transport is pronounced seasonally.

This effect is a microphysical phenomenon which is distinctly noticeable in the cloud pattern of a region lying along the trajectory of the African dust plume (Kalu, 1979). Not much is at present known about this property of the dust and its impact on cumulus cloud dynamics and so on climate, but Kalu (1983) has drawn attention to this very intriguing feature of the tropical atmosphere. Although much has been written about the Saharan dust generally (Morales, 1979), not much is known about its climatic influence.

The very fact that cumulus clouds dissolve as soon as the dust-front* arrives at a place shows precisely that the process does not enhance the growth of cloud droplets. This means that aeolian dust is not hygroscopic.

The effect is better observed from an aircraft altitude when flying above the haze top as has been observed by Dubief (1979). The author himself has photographed an extensive dust cloud over Southern Sahara in December 1980 during a dust outbreak (See Plate A). The strongly "eroded" cumulus cloud towers appear like brown domes of cloud trying to break through the extensive thick blanket of grey dust.

The vertical development of the hot concective cloud towers which has been well described by Riehl and Malchus (1958), Stephen and Wilson, 1980) and Stephens (1980), are strongly checked in a dusty environment. In fact, the emergence of the dry season in West Africa is as a result of the increased transport of aeolian dust across the sub-region as soon as the ITD withdraws equatorward, following the astronomical movement of the Earth relative to the sun in October.

*Dust-front is defined as a boundary between the forward edge of a dust plume and dust-free ambient air. It is created essentially by the existence of a visibility gradient along a horizontal axis and is defined with respect to 1km visibility isoplet which defines a severe dust outbreak in West Africa (Kalu, 1983).

Table 2a. An illustration of the rapid clearance of low and medium clouds on arrival of a dust plume at Calabar, 1200GMT, December, 1980. The figure "9" and X represent sky obscurred by dust.

Date (December 1980)	Total Cloud Amount below 2500m	Low Cloud Type	Low Cloud Base(m)	Medium Cloud	Visibility (km)	Significant Weather at 1200GMT
9	5	CuSc	450	0	8.0	∞
10	7	CuSc	450	0	15.0	∞
11	6	CuSc	450	0	10.0	∞
12	0	0	-	0	2.0	∞
13	9	X	X	X	0.1	S
14	9	X	X	X	0.1	S
15	0	0	-	0	0.4	S
16	0	0	-	0	1.0	S
17	0	0	-	0	2.0	∞
18	2	Sc	300	0	4.0	∞
19	5	Sc	450	0	2.0	∞
20	0	0	-	0	2.0	∞
21	0	0	-	0	2.0	∞
22	0	0	-	0	3.0	∞

Table 2b As Table 2a, except for Ikeja.

Date (December, 1980)	Total Cloud Amount below 2500m	Low - Clouds		Medium Cloud	Visibility (km)	Significant weather (ww code
		Type	Base(m)			
9	6	CuSc	450	0	20.0	Nil
10	7	CuSc	420	0	15.0	Nil
11	7	CuSc	480	0	8.0	∞
12	6	CuSc	510	0	15.0	∞
13	9	x	x	x	0.1	S
14	0	0	-	0	0.4	S
15	0	0	-	0	0.4	S
16	0	0	0	0	0.6	S
17	0	0	0	0	1.2	∞
18	0	0	0	0	2.0	∞
19	0	0	0	0	3.0	∞
20	0	0	0	0	2.0	∞
21	0	0	0	0	5.0	∞

4. THE THERMODYNAMICS OF CUMULUS CLOUD INHIBITION

It will be necessary for us to consider briefly the thermodynamics of the microphysical process which gives rise to the observed inhibition of cumulus cloud growth in a dust-laden atmospheric environment, or its total rapid clearance on arrival of the dust-front as defined

Since aerosol particles can absorb and retain a certain amount of the incoming solar radiation (Kellog, 1978; Kalu, 1983), the upper part of a low-lying aerosol layer, as has been observed by Kellogg (1975), will be warmed in proxi. The process is schematically illustrated in Fig. 5.

The observed phenomenon of a rapid dissipation of cloud clusters on the arrival of a dust-front over an area with a high frequency of cloudiness (low and medium clouds) is purely a microphysical process. When an aerosol absorbs energy from the sun, it becomes warmer and therefore heats its surrounding air (Fig. 5). In a similar manner, the heat which the dust particles absorb from solar radiation which is incident upon them is used to warm the air in the immediate neighbourhood of the dust plume. Literally, this implies raising the mean local temperature of the cloud droplets. Thus, the water droplets become thermally agitated and unstable and so cannot grow much further. Consequently, they evaporate, leaving a generally clear sky or a conspicuous decrease in thickness of the cloud cluster. This whole process is depicted in Fig. 5. This simple illustration explains the degradation of cumulus cloud banks into cumulus humilis cloud species with greatly reduced vertical growth, or in some severe cases of dust concentration, a total clearance of the available clouds (See Table 2).

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This is what happens as the dust plume moves into an area of towering cumulus clouds. As a result of this thermal erosion on clouds by dust particles, the dust plume creates a clear boundary between the dust-front and tropical cumulus cloud banks as can be seen in Plate B.

In Nigeria, this rapid and general clearance of low clouds is the most easily observed inference on the arrival of a dust plume at a station with sufficient cloud cover and has a high prediction potential for dust outbreaks. It externally reveals complex thermodynamical and microphysical processes taking place within the cloud ensemble unseen by an unaided vision. This is the case over the Southern part of Nigeria during times of severe dust outbreaks such that the coastal areas become affected by the dust. A long-time observation of dust episodes by the author in Nigeria seems to suggest that aeolian dust cannot coexist comfortably with water droplets.

According to a discussion by Fouquart (1985), radiation in boundary layer clouds should be addressed from essentially two oppositely-directed points of view, namely:

(i) their impact on the planetary radiation budget, and

(ii) the impact of radiation on boundary layer clouds.

Each of these views has been considered in our illustration on the dynamics of cumulus clouds in West Africa resulting from aeolian dust influence on the microphysical processes.

Owing to their high albedo combined with their low altitude, boundary layer clouds (mainly cumulus clouds species) considerably reduce the net radiative energy input at the top of the atmosphere. Their impact on the surface radiation budget is also quite significant since they considerably reduce the available solar energy at the ground surface (ECMWF, 1984).

In this respect the main problem in the derivation of their radiative impact is to adequately characterize their radiative properties in terms of predictable quantities such as liquid water content and to determine to what extent and how their spatial structure affect their radiative properties in relation to strongly polluted atmosphere.

We should stress the fact that the microphysical influence of the Saharan dust on the dynamics of boundary layer clouds in West Africa (i.e. cumulus clouds) is essentially a radiative process. For example, a state of equilibrium of a cloud topped aerosol layer may result from a competition between radiative cooling, entrainment of warm and dry air from above the cloud,since the dry saharan air is usually found above much more dense cumulus clouds in most severe dusty atmospheric conditions. Entrainment is itself dependent on the radiative, fluxes, which, in turn, depends on thermodynamical and microphysical properties of clouds as well as on small scale horizontal inhomogeneities of the cloud layer itself.

5. LONG-DISTANCE CLIMATIC INFLUENCE OF SAHARAN DUST

The climatic effect of the Saharan dust may be important on a global basis in view of the observed long-range transport of the dust from the Sahara into many parts of the world -- Eastern Mediterranean and Israel (Yaalon and Ganor, 1979), Western Europe and Scandinavian countries (Prodi and Fea, 1978,1979; Eriksson, 1979), North Equatorial Atlantic and the Caribbean (Carlson and Prospero, 1972) and West Africa into the Gulf of Guinea (Aina, 1972; Kalu, 1979, 1983; Prospero et al., 1981).

The coincidence of the peaking of the Sub-Saharan drought in 1972/73 period now tagged the Sahel drought in West Africa and the observed increased transport of dust from Africa (Prospero and Nees, 1977) which has been estimated at about 60 - 200 million metric tonnes per summer season during the early 1970s (Morales, 1979), suggests a causal relationship between climate and dust transport. The increased dust transport is caused by the extremely dry condition which prevailed in the dust source region (Kalu, 1979) from the early part of 1968 and culminated in the near catastrophic drought of 1972/73 in West Africa and which is still continuing in varying degrees in some parts of the Sub-Saharan region of Africa (Lamb, 1982).

In Section 3 we had considered the climatic implications of the microphysical précesses in the atmosphere by examining the dynamics of low clouds along major long-distance trajectories of the Saharan dust plume. The weather and climate of the British Isles are significantly affected when the atmospheric cirulation system, for example, the prevalence of a blocking condition, is such that southerly dust-laden winds affect the Midlands of the United Kingdom (Berry, 1979).

Not infrequently in conditions of intense anticyclonic blocking over the Mediterranean, continental tropical air mass originating from the Sahara desert which therefore may be dust-laden, particularly in winter, can make northward incursions into Southern Europe. The presence of the African dust has been reported by observers in various physical forms, for example, "Red Rain", "Yellow Snow" (Laskey et al., 1979) through rain-in and rain-out processes (Kalu, 1983) or its cut-off effects on radio-wave communication and television transmission. This is especially the case in winter when,

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resulting from the meridionally displaced climatological pressure system, following the apparent movement of the sun, as has been discussed by Kalu (1985), the Saharan High Pressure and its dust-laden winds affect Southern Europe, the United Kingdom Midlands (Berry, 1979). Under such a weather situation, coloured precipitation in the form of snow flakes caused by the interaction of the grey African dust particles with cloud droplets may be observed. This type of improved weather condition which therefore gives a big relief from the characteristic cold and cloudy British winter atmosphere with snow covered grounds to a few days of increased sunshine is usually welcomed by people in the middle latitudes generally. In fact, the prevalence of the British summer is related in some extent to an increased persistence of anticyclonic circulation associated with the sub-tropical high pressure whose centre of action is displaced further poleward during northern summer.

Kalu (1985) has considered a long-distance climatic influence of the Saharan dust over Europe as an atmospheric teleconnection process in Europe/West Africa zone. Two types of atmospheric teleconnection processes discussed are summarized as follows:

i) Teleconnection process with extratropical forcing for which the mobilization phase of severe Harmattan dust outbreaks over West Africa has been used to illustrate the middle latitude forcing (MLF)

ii) Teleconnection process with tropical forcing (TF) illustrated by means of poleward surges of Saharan dust plumes with characteristic stabilizing influence on the effectiveness of rain-producing systems over Western Europe and so on the prevalence of good (dry) weather in this area.

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A typical illustration of tropical teleconnection process over Europe/West Africa with significant climatic implications is poleward surges of Saharan dust into the North Atlantic and extending over the British Midlands. This is especially the situation when the low-level subtropical anticyclone becomes meridionally aligned, thereby strengthening the influence of dusty southerly winds over Western Europe. Under this type of synoptic situation, satellite images are most helpful in delineating the configuration of African dust plumes. The climatic impact of such extended Saharan dust transport into Europe is an inhibition of the micro-physical rain-bearing processes as has been presented in this paper. The result is usually a reduction in the vertical growth of clouds or their clearance in some severe cases giving rise to increased sunshine.

Kalu (1985) has considered this generation of remote atmospheric influences in one region by synoptic weather systems in another region remotely separated as an essential characteristic of teleconnectivity which demands further investigation.

6. FORECASTING DUST OUTBREAK BY SATELLITE IMAGES TECHNIQUE

One of the important practical applications of the observed strong influence and affinity of aeolian dust on solar radiation and moisture content of the lower atmosphere is in forecasting the arrival of a dust plume downwind of its source of mobilization, especially in cloudy and humid environments. Satellite images are therefore very useful in this type of synoptic exercises, especially in view of the identified influence of aeolian dust on the microphysics of cumulus clouds and rain formation. This is particularly the case if satellite image data are available on real-time basis as to enable the

TABLE 3

Table 3 Daily variation of relative humidity, temperature and visibility at the ground surface during dust outbreaks, 1200GMT, Kano.

MARCH 1977			
Date	T(°C)	R.H. (%)	Vis. (km)
1	29.4	19	1.3
2	28.3	11	10.0
3	24.7	23	0.8
4	22.2	16	0.2
5	21.9	08	0.3
6	24.6	08	0.3
7	26.9	06	0.6
8	27.8	07	0.7
9	29.0	08	0.4
10	30.0	08	0.6
11	28.9	07	1.0
12	28.6	07	0.5
13	28.7	05	0.5
14	32.2	05	1.6
15	29.8	03	0.5
16	28.5	05	0.3
17	27.5	06	0.3
18	26.6	03	0.3
19	27.2	04	0.7
20	29.0	08	0.8
21	31.1	08	4.0

FEBRUARY 1974			
Date	T(°C)	R.H. (%)	Vis. (km)
9	30.6	07	30.0
10	26.7	08	6.0
11	23.6	18	10.0
12	24.6	10	0.2
13	26.6	08	1.5
14	28.3	10	30.0

DECEMBER 1973			
Date	T(°C)	R.H. (%)	Vis. (km)
25	30.0	11	25.0
26	26.1	09	5.0
27	24.8	14	1.5
28	23.3	15	1.1
29	25.0	16	1.6
30	26.7	14	4.0
31	27.2	16	10.0

DECEMBER 1980			
Date	T(°C)	R.H. (%)	Vis. (km)
10	28.0	24	14.0
11	23.5	26	0.3
12	19.7	32	0.2
13	20.6	29	0.3
14	22.1	24	1.2
15	23.4	28	1.4
16	22.5	30	1.6
17	25.4	28	3.5
18	27.4	27	15.0

JANUARY 1975			
Date	T(°C)	R.H. (%)	Vis. (km)
11	23.8	20	25.0
12	20.3	17	0.4
13	20.0	18	0.4
14	19.9	18	0.5
15	21.7	15	1.1
16	20.0	15	1.0
17	20.1	19	0.7
18	22.9	19	5.0
19	25.6	12	4.0
20	23.9	11	25.0

monitoring of the downwind progression of the dust plume from its source of mobilization.

Since it has been clearly established that the dust exerts a strong influence in the complex microphysical processes associated with cumulus cloud convection, it is hereby suggested that this response can be applied as a predictor variable for forecasting dust outbreaks in humid areas. When a dust plume arrives at a place previously without any trace of the dust, the following three synoptic situations are often observed to occur simultaneously. These are:-

a) A rapid clearance of cumulus clouds or a reduction in the vertical growth of cloud clusters,
b) A marked fall in visibility as a result of the presence of dust particles, and
c) A drop in air temperature.

Each of the above three synoptic observations lends itself easily to the application of satellite image data on real-time basis. This is the background of the usefulness of satellite images in atmospheric air pollution problems. The response of the dust is particularly very interesting in view of the relevance of the appearance and texture of cloud surfaces on satellite photographs generally. Any variation in cloud structure is readily observed on satellite images covering that region.

In the above, item (a) has been fully discussed in this paper. Item (b) is a quantitave indication of the presence of the dust in large concentrations as it tends to impair the transparency of the atmosphere and (c) is a reflection of the strong attenuation of solar radiation by the suspended dust. As shown in Table 3 and Fig. 6 each of the three synoptic

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phenomena illustrated above responds actively on arrival of the dust plume at a location downwind of its source of mobilization. A change in atmospheric convection is immediately reflected in the variation of surface visibility, a drop in air temperature and a clearance of clouds present within the dust plume layer on its arrival at a place.

This method of forecasting dust by satellite technique using the microphysical response of the dust may also be used to forecast the clearance of a dust spell. It is known that as soon as the dust plume withdraws from a place, following the establishment of favourable synoptic features (Kalu, 1983), the visibility field, the temperature/radiation field and low cloud dynamics will be found to cover to their pre-dust stage. A successful prediction of these phases of dust transport depends very much on the professional ability of the meteorologist to master these symptomatic synoptic features of the lower atmosphere which are clearly revealed on synoptic weather charts usually available in Meteorological Forecast Offices.

7. CONCLUDING REMARKS:

A general conclusion, therefore based on our discussion, is that, since the radiative effect of the Saharan dust is so pronounced as has been established on synoptic basis by Kalu (1983) and others, in regions of the world where the transport of dust is strong, realistic climate models of the Earth-Atmosphere System should, as a matter of scientific necessity, take into consideration the presence of the African dust and its radiative response. This is necessary especially when modelling the dynamics of the tropical atmosphere over these regions of strong aeolian dust transport as in African Sahara and adjoining lands and Middle East and Caribbean Islands, etc.

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In many studies, however, this has not been done. In West Africa for example, the overall effect of the Saharan dust on climate has not been fully surveyed. This is because some of the radiative characteristics of the African dust are not fully understood owing to lack of actnometric data. However, the results of the work by Kalu (1983) has shown that studies directed towards this type of environmental problem may yield some very significant results which will be important for a better understanding of climate dynamics in Sub-Saharan Africa and other areas of the world where dust transport is pronounced seasonally. Perhaps this may give a clue to the present meteorological problem facing African meteorologists - the ongoing climate variability in Africa, especially in relation to droughts and desertification in Sub-Saharan Africa.

Furthermore, a better understanding of the climatic implications of the microphysical response of cumulus clouds under conditions of dusty atmosphere is by examining the response of the cloud ensemble in humid atmospheric environment overlain by dust clouds. The behaviour of the clouds in the presence of a polluted atmosphere will indicate the impact of dust aerosol particles on climate since clouds are visible dynamical processes taking place within the atmosphere.

The observational evidence of the rapid dissipation of cumulus clouds in a dusty atmosphere has been fully illustrated as an intense climatic influence of aeolian dust and if this dust persists over a given region as has been observed along the major world-wide trajectories of the Saharan dust plumes, low cloud development will be greatly affected and this implies the prevalence of a dry climate. A typical example of this clear climatic impact in West Africa is the prevalence of a dry season with essentially clear skies north of the ITD and during the dry season in the sub-region.

Finally, a consideration of the climatic influence of the Saharan dust over remote regions of the world suggests that atmospheric teleconnection processes can play a leading role in controlling the climatic features of remote regions of the world through an ative impact on atmospheric boundary layer cloudiness.

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Figure Description

Fig. 1 Long-distance transport trajectories of Saharan Dust Plumes originating from three major source areas:
(a) The Bodele Erg of Bilma-Faya Largeau alluvial plain, west of the Tibesti Massif.
(b) The Cheng Erg, west of the Ahaggar Highland
(c) The Libyan Erg, east of the Soda Mountain.

Fig. 2 Temperature profiles (daily) in a dusty atmosphere for March 1977 (a) and February, 1974 (b) at 1200GMT for Kano showing dust-induced low-level capping inversion.

Fig. 3 Vertical cross-section of temperature variation for January, 1975 dust outbreak, Kano, 1200GMT. ΔT represents the day-to-day variation of air temperature from dust-free value.

Fig. 4 The General Circulation of the atmosphere for a rotating non-uniform Earth showing the Tropical Hadley Circulation cell in relation to the Other Components of the Atmospheric General Circulation System

FIGURE DESCRIPTION CONTD.

Fig. 5. A Schematic illustration of the influence of aeolian dust on the microphysics of cumulus clouds.

Fig. 6 Temperature and relative humidity distribution in dusty condition at Kano (12°03'N, 08°32'E), February, 1974, 1200GMT.

TABLE DESCRIPTION

Table 1. Chemical and Mineralogical composition of aeolian dust from the Sahara. Slightly adapted from Yaalon and Ganor (1979).

Table 2a. An illustration of the rapid clearance of low and medium clouds on arrival of a dust plume at Calabar (04°58'N, 08°21'E), 1200GMT, December, 1980. The figure "9" and the letter X both represent sky obscured by dust.

Table 2b. As in Fig. 2a, except for Ikeja (06°27'N, 03°24'E).

Table 3. Daily variation of relative humidity, temperature and visibility at the ground surface during dust outbreaks, 1200GMT, Kano.

PLATE DESCRIPTION

Plate A An extensive dust cloud photographed by the author on board an aircraft, December 15, 1980, over Southern Sahara

Plate B Clearly defined boundary between dust plume and Cumulus cloud bands. ATS III images (After Kalu, 1979).

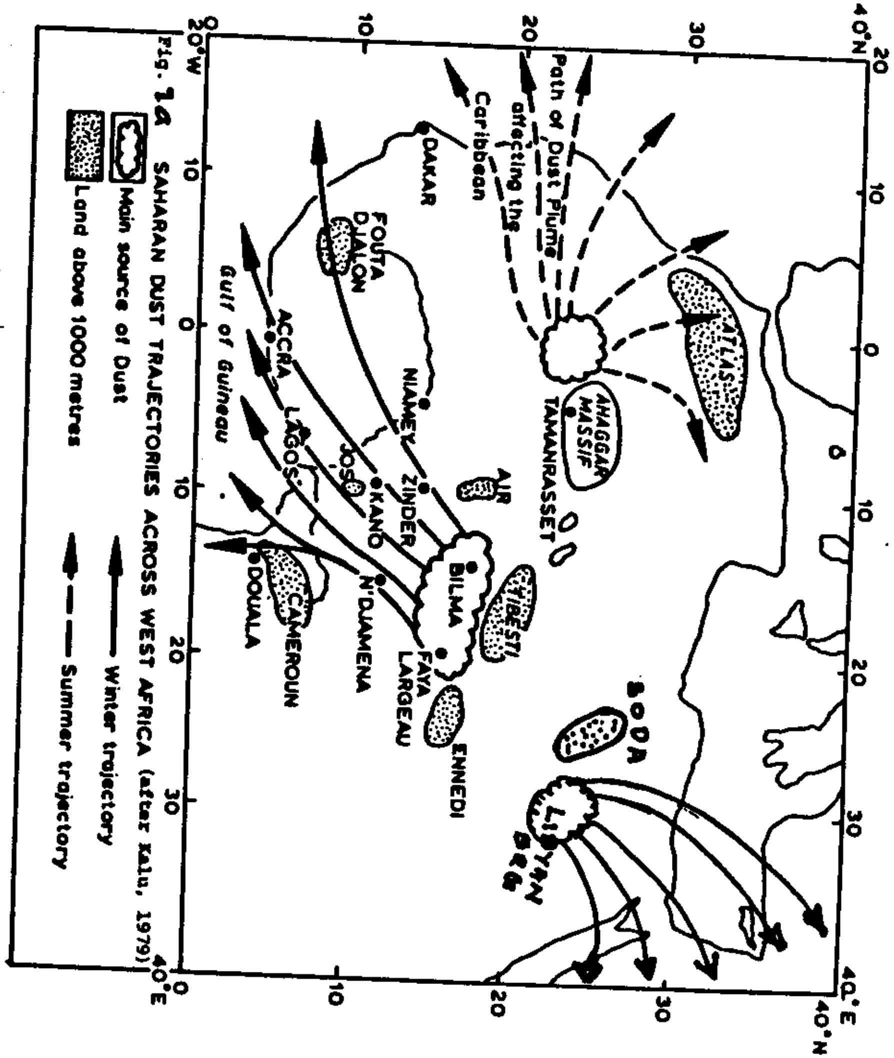


Fig. 1a SAHARAN DUST TRAJECTORIES ACROSS WEST AFRICA (after Kalu, 1979)

Fig 1a

Fig 2a

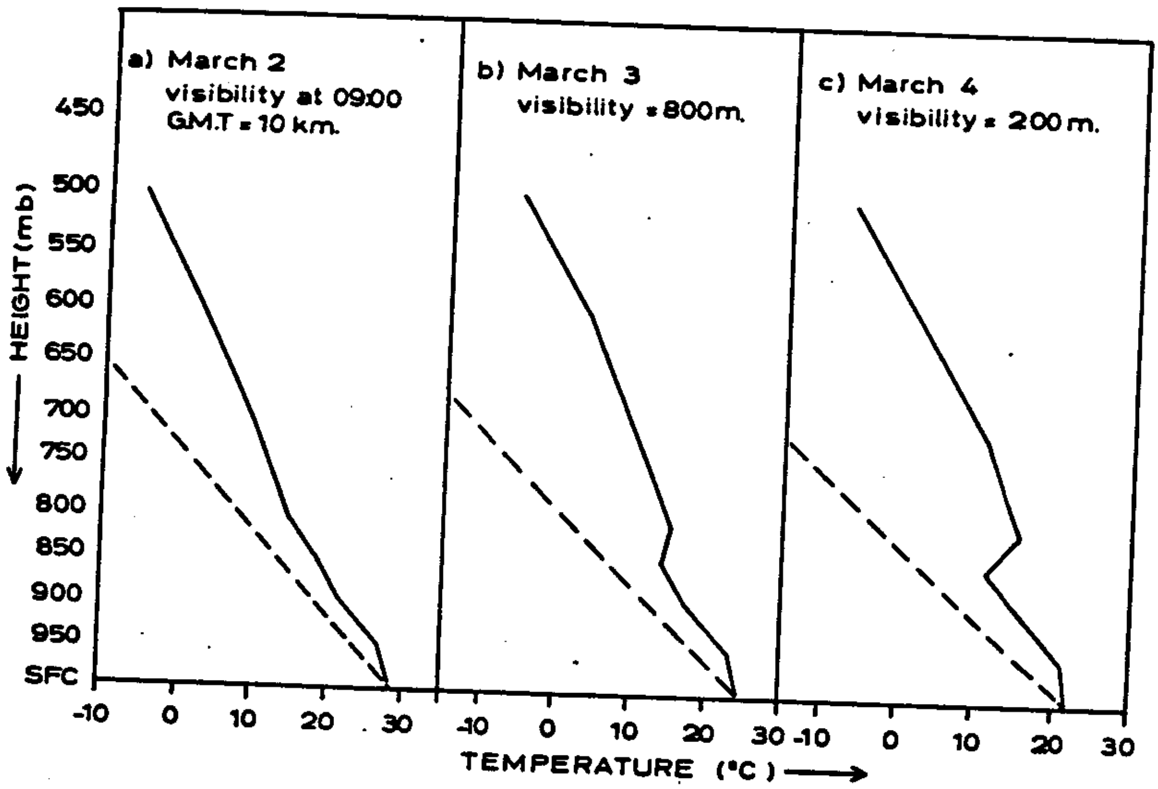


Fig. 1b

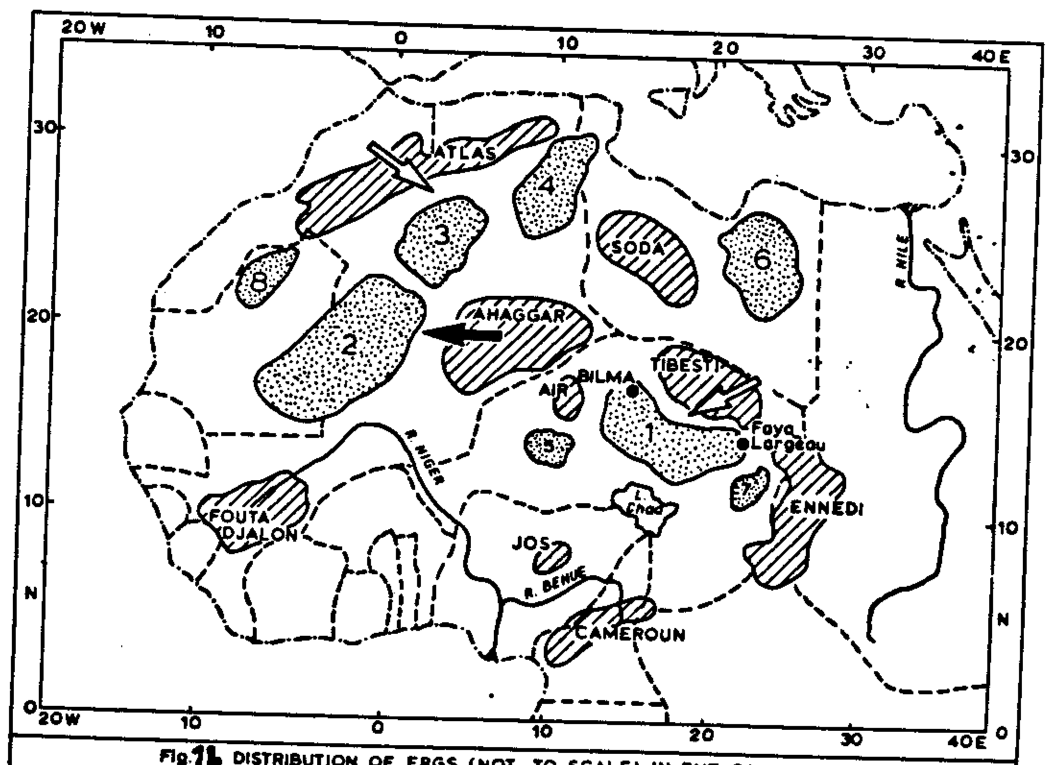


Fig. 1b DISTRIBUTION OF ERGS (NOT TO SCALE) IN THE SAHARA

fig. 3

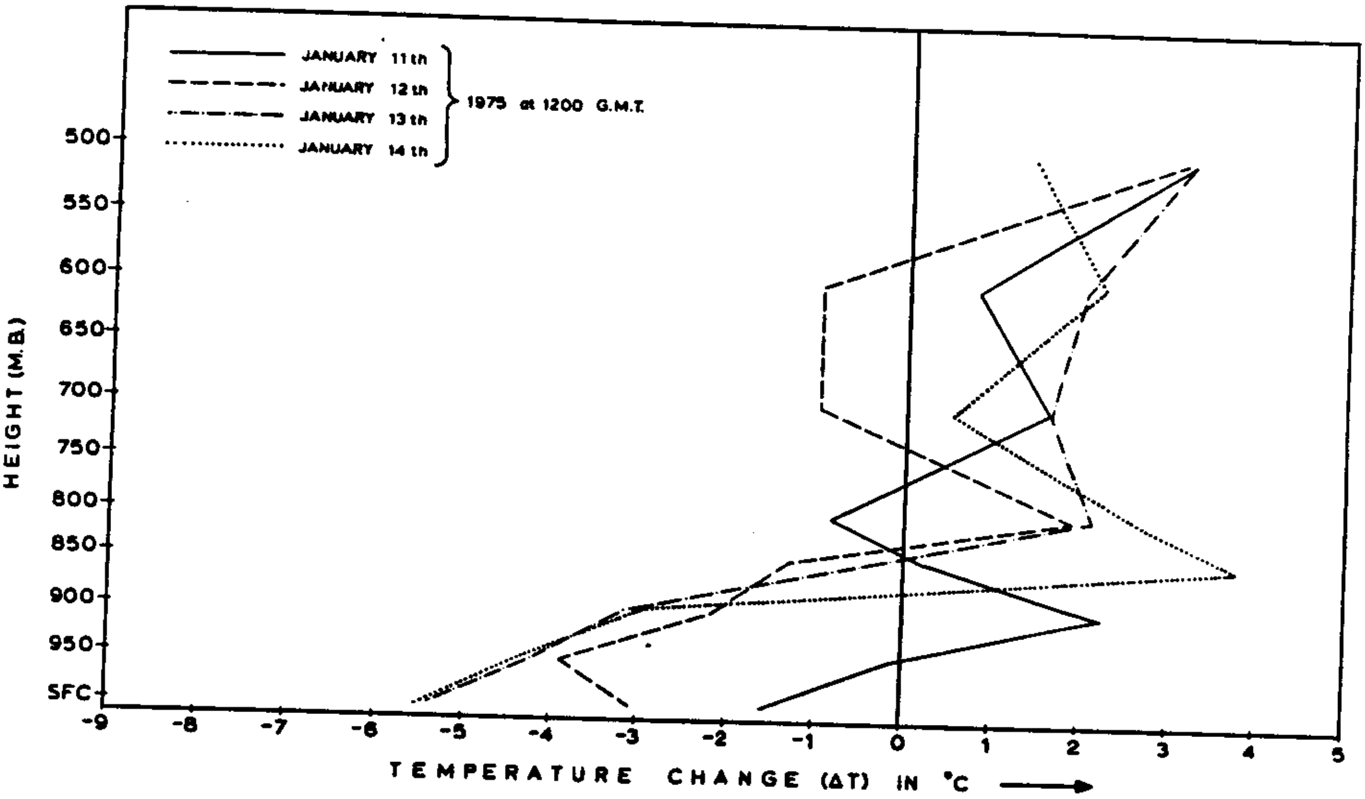
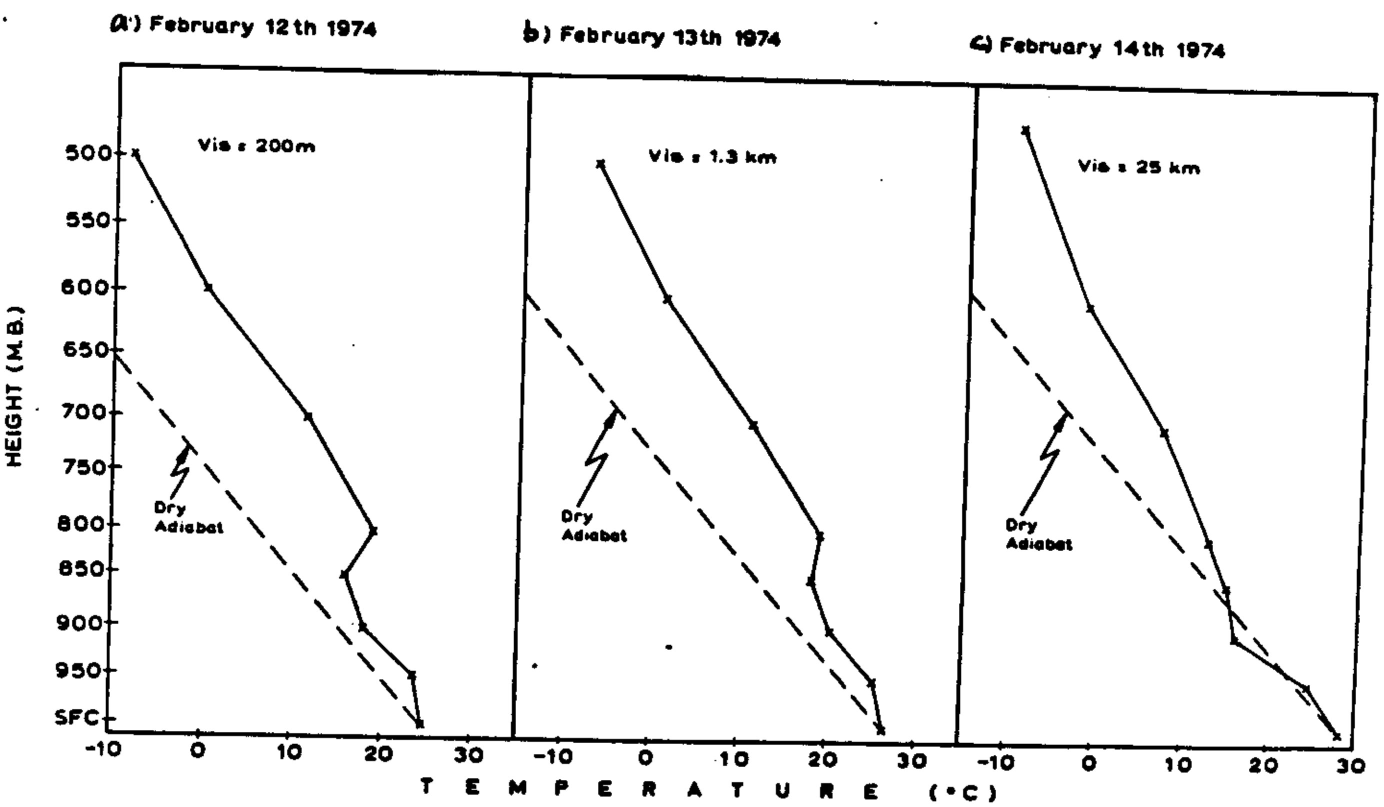
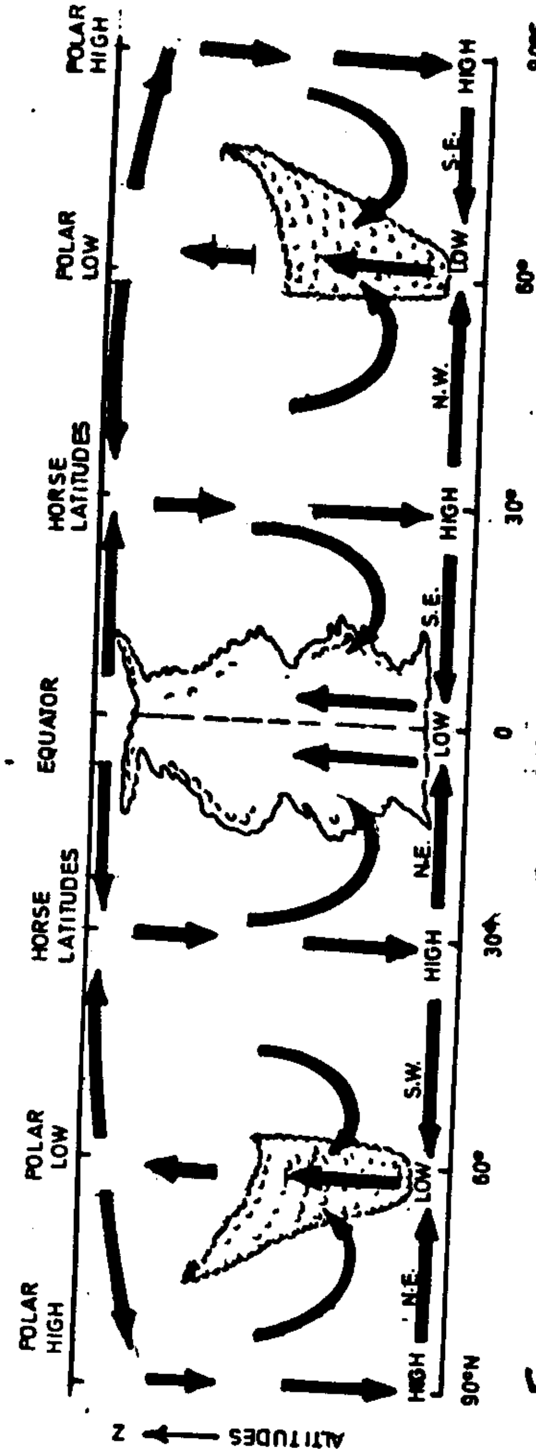

JANUARY 11th
JANUARY 12th
JANUARY 13th
JANUARY 14th
1975 at 1200 G.M.T.
HEIGHT (M.B.)
500
550
600
650
700
750
800
850
900
950
SFC
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5
TEMPERATURE CHANGE (ΔT) IN °C

fig. 2b


a) February 12th 1974
b) February 13th 1974
c) February 14th 1974
Vis = 200m
Vis = 1.3 km
Vis = 25 km
Dry Adiabat
HEIGHT (M.B.)
500
550
600
650
700
750
800
850
900
950
SFC
-10 0 10 20 30
TEMPERATURE (°C)



LATITUDES

FIG. 4 THE GENERAL CIRCULATION OF THE ATMOSPHERIC FOR A ROTATING NON UNIFORM EARTH

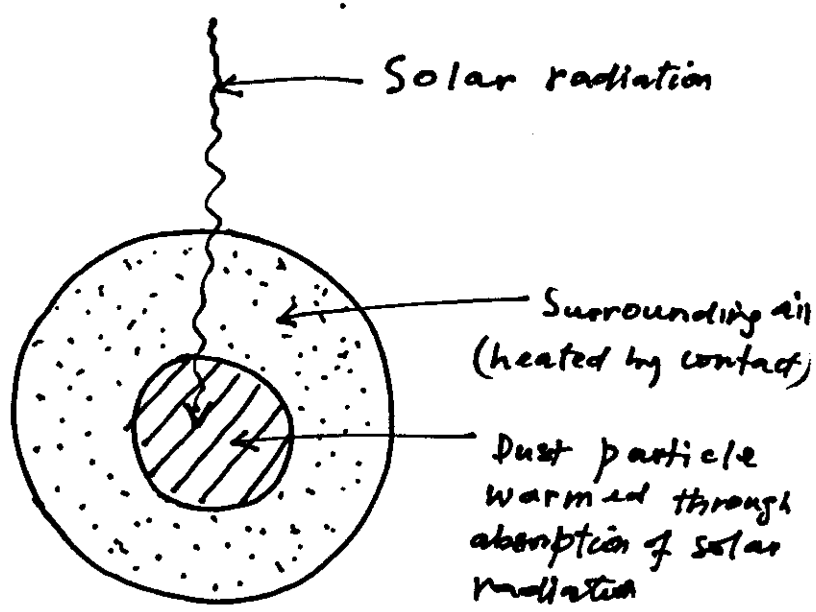


FIG. 5 A Schematic illustration of the influence of aeolian dust on the microphysics of cumulus clouds.

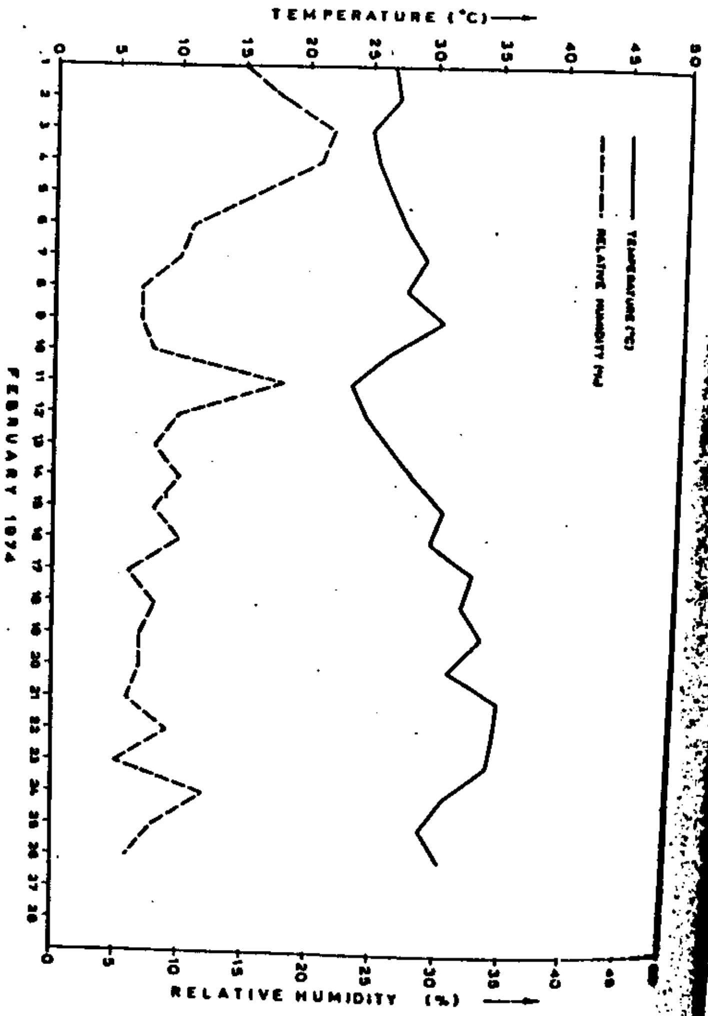


Fig. 6 Temperature and relative humidity distribution in dusty condition at Kano, February 1974, 1200GMT.

METEOSAT 1983 MONTH 1 DAY 10 TIME 1155 GMT (NORTH) CH. VIS 2
NOMINAL SCAN/RAW DATA SLOT 24 COPYRIGHT - ESA -

METEOSAT IMAGE CATALOGUE SUMMARY FOR YEAR 1983 DAY 10 - 10/01/83

SLOT	TIME	VIS	IR	WV	RAW
1	0000-0030		Y	Y	
2	0030-0100		Y	Y	
3	0100-0130		Y	Y	
4	0130-0200		Y	Y	
5	0200-0230		Y	Y	
6	0230-0300		Y	Y	
7	0300-0330		Y	Y	
8	0330-0400	Y	Y	Y	
9	0400-0430	Y	Y	Y	
10	0430-0500	Y	Y	Y	
11	0500-0530	Y	Y	Y	
12	0530-0600	Y	Y	Y	
13	0600-0630	Y	Y	Y	
14	0630-0700	Y	Y	Y	
15	0700-0730	Y N	Y N	Y N	
16	0730-0800	Y	Y	Y	

SLOT	TIME	VIS	IR	WV	RAW
17	0800-0830	Y	Y	Y	
18	0830-0900	Y	Y	Y	
19	0900-0930	Y	Y		
20	0930-1000	Y	Y	Y	
21	1000-1030	Y	Y		
22	1030-1100	Y	Y	Y	
23	1100-1130	Y	Y		
24	1130-1200	Y N	Y N	Y N	
25	1200-1230	Y	Y		
26	1230-1300	Y	Y	Y	
27	1300-1330	Y	Y		
28	1330-1400	Y	Y	Y	
29	1400-1430	Y	Y		
30	1430-1500	Y N	Y N	Y N	
31	1500-1530	Y	Y		
32	1530-1600	Y	Y	Y	

SLOT	TIME	VIS	IR	WV	RAW
33	1600-1630	Y	Y		
34	1630-1700	Y	Y	Y	
35	1700-1730	Y	Y		
36	1730-1800	Y	Y	Y	
37	1800-1830	Y	Y	Y	
38	1830-1900	Y	Y	Y	
39	1900-1930	Y	Y	Y	
40	1930-2000	Y	Y	Y	
41	2000-2030		Y	Y	
42	2030-2100		Y	Y	
43	2100-2130		Y	Y	
44	2130-2200		Y	Y	
45	2200-2230		Y N	Y N	
46	2230-2300		Y	Y	
47	2300-2330		Y	Y	
48	2330-2400		Y		

DIGITAL DATA : X = CONDITIONED , Y = ONLY DEMULTIPLEXED - N = PHOTOGRAPHIC NEGATIVE,FULL DISK,20X20CM