

## CHAPTER 14

# *Sahara Dust Transport Over the North Atlantic Ocean — Model Calculations and Measurements*

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### ABSTRACT

The Sahara Desert is one of the major source areas for mineral dust particles which are transported long distances through the atmosphere. The transport mechanism for the Sahara dust itself now seems to be fairly well understood — for instance the transport which takes place in the NE-tradewind region.

This paper is concerned with a dust-transport model for the Sahara dust and measurements of the mineral dust component over the Atlantic. The model is based on the knowledge about the transport mechanism within the NE-tradewind area over the Atlantic. A steady-state transport of mineral particles will be considered which includes horizontal transport by wind and sedimentation as well as vertical turbulent diffusion. Mineral mass concentrations and particle volume distributions which had been measured across the Atlantic could be explained by the model. Both calculations and measurements indicate a very different behavior of sub-micron and giant particles during their long-range transport over the Atlantic.

### 14.1 INTRODUCTION

Investigations of the areawide distribution of Sahara dust and its chemical composition over the Atlantic were stimulated by the study of Delany *et al.* (1967). These authors as well as others studied the mineral composition and mass concentrations of mineral dust originating from the Sahara Desert. From these studies it became clear that large quantities of mineral dust are carried from the Sahara over the Atlantic, contributing to the aerosol budget of the tradewind region and to the Atlantic deep-sea sediments.

Details of the mechanism of large-scale transport of Sahara dust over the Atlantic were reported by Prospero and Carlson (1970, 1972) and Carlson and Prospero (1972). According to their investigations the main mass transport of Sahara dust takes place above the tradewind inversion layer. There the mineral dust is transported westward within the steadily blowing 'harmattan', which is in agreement with earlier findings by Semmelhack (1934). The dust layer extends

vertically from approximately 1500 m to 5000 m altitude near the West African coast. After one week travel the dry and dust laden air masses reach the Caribbean Sea, where the dust layer converges to 1500 m until 3000 m in altitude. The dust plume emerging from the Northwest African continent covers an area roughly between 15°N and 25°N latitude.

The relatively warm and dry continental air masses above the inversion layer are undercut by the cool and moist air of the tradewind boundary layer. This layer is originally free of dust because air mass trajectories never originate from the continent. Dust particles within this layer therefore must be supplied from the reservoir above by downward turbulent mixing and sedimentation. The inversion layer, however, suppresses vertical exchange between the dust layer above and the boundary layer beneath. One has to expect, therefore, that the vertical flux of smaller particles (radius  $r < 1 \mu\text{m}$ ) which are mainly subject to turbulent diffusion will be reduced. Larger particles ( $r > 1 \mu\text{m}$ ) remain practically unaffected by the presence of the strong inversion layer due to their high sedimentation velocities. Thus, larger particles will reach the ocean surface within relatively short distances from the source area, whereas smaller particles are deposited only after longer transport distances. Such a different behaviour of those particle-size fractions certainly has consequences for the size distribution of the mineral particles and the total suspended mineral matter found over the ocean when moving westwards under the plume.

The seasonal variation of incoming solar radiation causes seasonal dependence of both the generation of airborne dust over the Sahara Desert and of transport conditions over the ocean. The superposition of both effects produces an annual variation in the large-scale dust transport over the Atlantic ocean, as seen from Figure 14.1: Considering the sandstorm frequency for different areas of the Sahara desert as a measure of the source strength, a seasonal variation of a factor of about 2 can be seen (according to a compilation of observation data for the years 1925–1950 by Dubief, 1953). A period of increased sandstorm activity lasts from early spring until fall. Vertical wind data by SMN (1968) for the period 1951–1960 from Sal, Cape Verde Islands, clearly show favourable conditions for large scale transport especially in the summer season between May and October. During that time easterly winds prevail throughout levels up to 6000 m. For the remainder of the year the layer favorable for east to west transport is normally restricted to a shallow layer between 1500 m and 3000 m altitude. At higher levels strong westerly winds ('counter tradewinds') prevail. The transported mass of mineral dust is large during summer, as indicated by the turbidity coefficient  $B$  (for  $\lambda = 500 \text{ nm}$ ) which is a measure of the total aerosol mass in a vertical column for the particle size range between  $0.1 \mu\text{m} \leq r \leq 1.0 \mu\text{m}$ . These data are derived from a two-year series of measurements carried out at Sal by Jaenicke and Schütz (1977).

For a better understanding of the transport mechanism, a model of the Sahara dust transport over the Atlantic was developed. For comparison of the calculations with actual data the total aerosol size distribution with special regard to the mineral

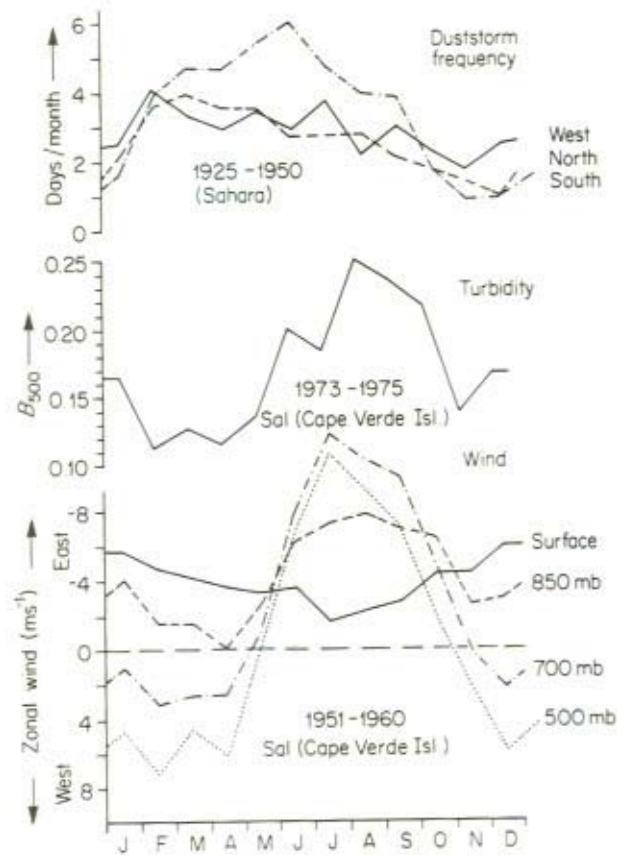


Figure 14.1 Comparison between mean annual frequency of sandstorms according to Dubief (1953), for different regions of the Sahara desert, vertical wind field over the Atlantic and atmospheric turbidity derived from measurements by Jaenicke and Schütz (1977). A possible explanation for the annual variation of turbidity which is a measure of the atmospheric dust load can be the superposition of the sandstorm frequency at the source area and the vertical wind field over the ocean

component was investigated in surface air of the NE-tradewind region over the Atlantic. To study the aerosol close to the source, measurements were carried out at Sal. Further investigations were performed onboard the German research vessel 'Meteor' while crossing the Atlantic from the Caribbean Sea to the West African coast at  $15^{\circ}\text{N}$  latitude. In this way it was intended to study the transport as a function of the distance from the source area.

## 14.2 TRANSPORT MODEL

For simulation of Sahara dust transport a two dimensional steady-state model (Schütz, 1977) was designed. The model considers east-to-west horizontal transport by zonal winds. Vertical transport is described by sedimentation and turbulent diffusion. Other transport processes such as subsidence and convection are assumed to balance each other. Removal of particles by precipitation is also not considered.

In order to properly describe flow conditions in the NE-tradewind zone, actual profiles up to 10 km altitude were used. The diffusion coefficient for vertical exchange was calculated from temperature and wind profiles (radio-sonde data from Sal were assumed to be representative of the total transport distance over the Atlantic). The starting point of the model was fixed at the West African coast. There a dust layer was assumed between 1500 m and 5000 m altitude with a constant vertical mixing ratio. The boundary layer up to 1500 m was assumed free of dust. This was justified because air mass trajectories never originate from the continent, and surface winds close to the African shore are westerly. The upper limit of the dust layer at 5000 m is confirmed by several aircraft observations near the African coast.

The model predicts the mixing ratio for mineral particles as a function of the air mass trajectory distance from the source area, altitude and particle size. Particle radii from 0.1  $\mu\text{m}$  to 20  $\mu\text{m}$  were considered. In order to study the size distribution as a function of the transport distance an initial distribution has to be assumed at the coastline. According to measurements of the mineral aerosol size distribution in the Libyan desert (Schütz and Janicke, 1974) an initial power function\* distribution with an exponent of  $\nu^* = 2$  seemed appropriate. These assumptions led to the following results.

## 14.3 RESULTS

### 14.3.1 Vertical mass distributions

Figure 14.2 shows how the Sahara dust plume develops during transport and how the vertical mixing ratio of the particles changes as a function of altitude and distance from the source. The mixing ratio is normalized to the initial mixing ratio.

\*Most aerosol size distributions for particles with radii larger than 0.1  $\mu\text{m}$  can be approximated by a power function:

$$\frac{dN}{d \log r} = n^*(r_0)(r/r_0)^{-\nu^*}$$

where

- $r$  = particle radius in  $\mu\text{m}$ ;
- $r_0$  = arbitrary chosen reference radius;
- $N$  = number of particles  $\text{cm}^{-3}$  larger than  $r$ ;
- $n^*(r)$  = differential number size distribution in  $\text{cm}^{-3}$ ;
- $\nu^*$  = exponent of the distribution.

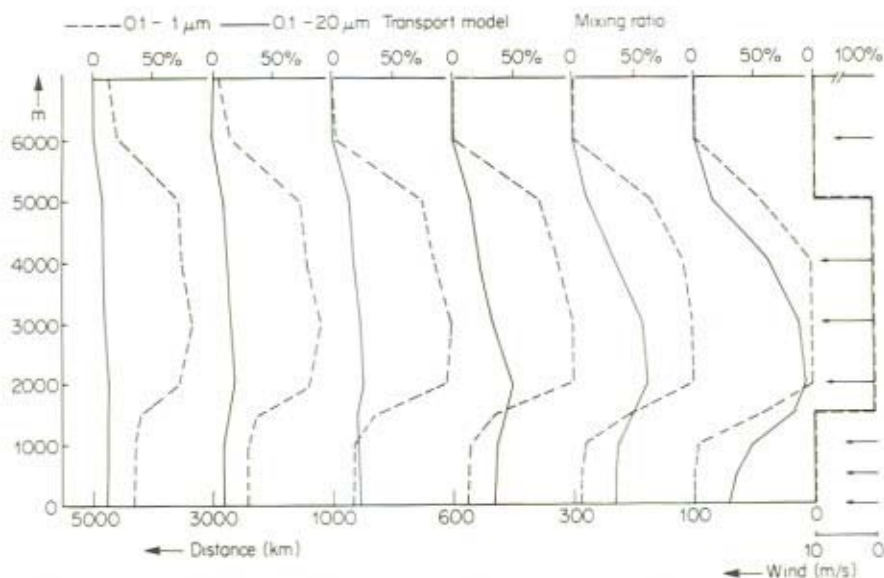


Figure 14.2 Vertical distributions of mineral dust for selected transport distances from the source. Vertical mixing ratios for the mass of mineral dust particles of the submicron range ( $0.1 \mu\text{m} \leq r \leq 1.0 \mu\text{m}$ ) and for the total mass ( $0.1 \mu\text{m} \leq r \leq 20 \mu\text{m}$ ) normalized to the initial mixing ratio at the source ( $x = 0 \text{ km}$ ). The vertical distributions of the submicron particles remain nearly unchanged up to large transport distances whereas those for the total mass show significant modifications up to approximately 1000 km distance. Thus most of the total mass is removed from the plume near the source but submicron particles are subject to long range transport

Obviously there is a different behavior for the submicron particles ( $0.1 \mu\text{m} \leq r \leq 1.0 \mu\text{m}$ ), which cause atmospheric turbidity, and those in the range of  $0.1 \mu\text{m} \leq r \leq 20.0 \mu\text{m}$ , which contain the total mineral mass. Up to 5000 km transport distance the submicron particles are only slightly removed from the plume. Their mixing ratio within the plume is only reduced to 70% of the initial value and at sea level their mixing ratio increases as the plume moves westward. These particles penetrate only very slowly from the elevated reservoir into the boundary layer by turbulent mixing and sedimentation. This clearly shows that these particles are subject to long-range transport.

In contrast, the vertical distribution of total aerosol mass ( $0.1 \mu\text{m} \leq r \leq 20 \mu\text{m}$ ) shows much more rapid variation with increasing transport distance. Due to the relatively large sedimentation velocities of giant particles ( $r \geq 1 \mu\text{m}$ ) most of the mass falls out of the plume within the first 1000 km. A constant vertical mixing ratio is nearly achieved at a distance of approximately 1000 km. Thus the dustfall area is practically restricted to the first 1000 km of transport. This agrees with earlier observations by Semmelhack (1934).

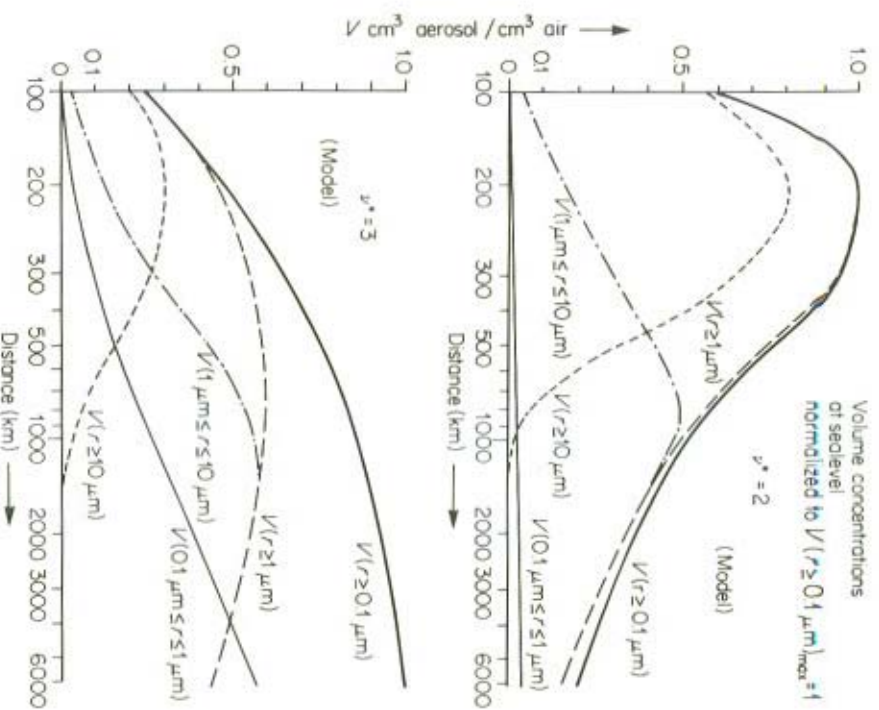


Figure 14.3 Volume concentration ratios at sea level for different particle size ranges as a function of the distance from the source. Model calculations for assumed initial size distributions with  $\nu^* = 2$  and  $\nu^* = 3$ . Except for particles with  $r \geq 10 \mu\text{m}$  the graphs indicate quite different volume concentration ratios for the size ranges considered when moving westward under the plume

#### 14.3.2 Volume and mass concentrations at sea level

In the previous chapter a general survey of the development of the plume was given. Now volume and mass concentrations at sea level for different particle size ranges as a function of the distance from the source will be discussed. Figure 14.3 shows calculated volume concentrations normalized to the maximum value of the total volume concentration  $V$  ( $r \geq 0.1 \mu\text{m}$ ) for several particle size ranges with transport distances between 100 km and 6000 km. The data plotted in Figure 14.3

are for power-function size distributions with  $\nu^* = 2$  and  $\nu^* = 3$  assumed for initial size distributions within the dust layer at the source.

Volume concentration ratios in the submicron range increase very slowly with increasing distance from the source, especially for an initial distribution with  $\nu^* = 2$ . Up to a transport distance of 6000 km these particles make up only a few percent of the maximum volume concentration (at 200 km). If an initial distribution with  $\nu^* = 3$  is assumed, however, considerably higher volume concentration ratios are reached with increasing distance from the Sahara. In this case the submicron particles may contribute more than 50% of the total volume for distances larger than 4000 km from the source area. But it should be pointed out that in both cases the concentrations of the submicron particles are comparatively low within the first hundreds of kilometres of transport. As mentioned above, this indicates that these particles reach the surface layer only by slow vertical mixing.

The ratios of the volume concentrations of the largest particles ( $r \geq 10 \mu\text{m}$ ) increase up to 200 km from the source and thereafter rapidly decrease with distance. At 1000 km from the source their values are roughly a few percent. At further distances their contribution to the total concentration is practically negligible. Independent of the assumed initial distribution, these particles, which sediment quickly, are deposited within 1500 km of the Sahara.

Giant particles in the intermediate size range ( $1 \mu\text{m} \leq r \leq 10 \mu\text{m}$ ) increase in relative values up to 1000 km, where a maximum of approximately 50% of the total volume is reached. For distances larger than 1000 km their volume concentration ratios decrease but still account for most of the mineral volume which is transported over larger distances. For  $\nu^* = 2$ , 90% of the total volume transported over distances larger than 1500 km consists of these particles. For  $\nu^* = 3$  the contribution of this particle range is smaller, because of rapidly increasing volume fractions of submicron particles at distances greater than 2000 km from the Sahara.

For verification of the model calculations a comparison with actual mass concentrations ( $M$ ) measured at sea level over the Atlantic ocean will be given. Data were collected during field studies of the NE-tradewind aerosol over the Atlantic as mentioned above. Figure 14.4 shows measured and calculated mass concentrations for the submicron and giant particles as a function of the distance from the source. As above, initial distributions with  $\nu^* = 2$  and  $\nu^* = 3$  will be distinguished. Calculated mass concentrations are normalized to  $M(0.1 \mu\text{m} \leq r \leq 20 \mu\text{m}) = 100 \mu\text{g m}^{-3}$  at a distance of 1000 km from the source. This value was selected from mean mass concentrations of our Atlantic data. From Figure 14.4 some important conclusions can be drawn about the shape of the initial assumed size distribution. Measured total mass concentrations agree reasonably well with the calculations using  $\nu^* = 3$ . For the submicron range, however, the model with  $\nu^* = 3$  predicts concentrations approximately one order of magnitude higher than observed. A better assumption for the initial distribution within the size range of  $0.1 \mu\text{m} \leq r \leq 20 \mu\text{m}$  would be to use  $\nu^* = 2$ . In that case the measured mass concentrations for both size ranges are better approximated by the model, as seen

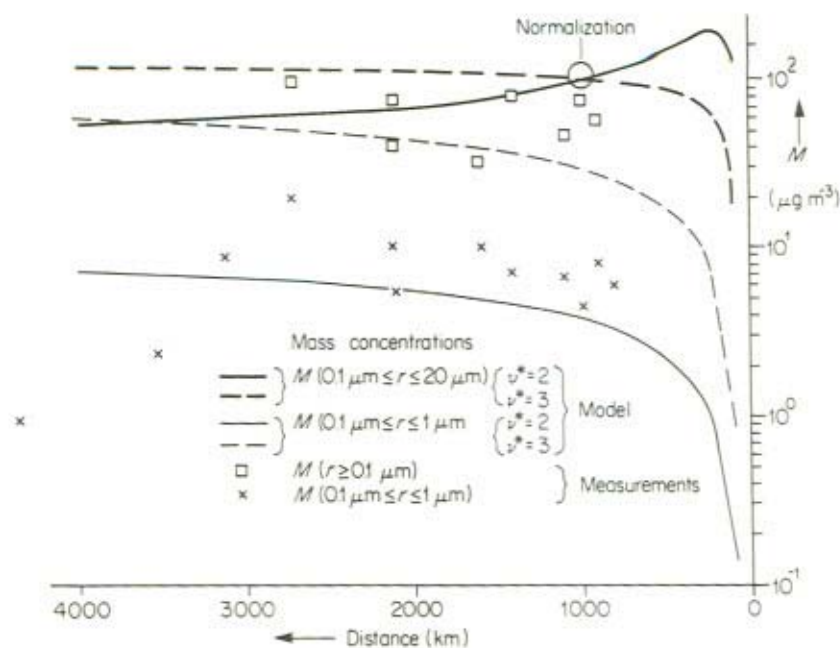


Figure 14.4 Mineral mass concentrations at sea level as a function of the transport distance from the Sahara. Comparison between calculated data [normalized to  $M(0.1 \mu\text{m} \leq r \leq 20 \mu\text{m}) = 100 \mu\text{g m}^{-3}$  at a distance of 1000 km] and data measured by the authors for the submicron and the total mass range. The measurements can best be described by the calculations when assuming an initial distribution at the source with  $\nu^* = 2$

in Figure 14.4. The assumption of  $\nu^* = 2$  at the source is confirmed by measurements of mean mineral size distributions in the size range  $r \geq 1 \mu\text{m}$  over the Libyan Sahara by Schütz and Jaenicke (1974). A similar value of  $\nu^* \sim 2$  has been obtained by Gillette *et al.* (1972) for soil-derived aerosol in Texas and Nebraska, which suggests that this value may be typical for soil-aerosol production in many regions of the globe. Figure 14.4 shows that neither the total sea-level mass nor its submicron fraction decrease significantly beyond 1000 km from the source. In contrast, significant variations in the mass concentrations have to be expected within the first 1000 km of transport. Unfortunately, no data are available to check this idea.

### 14.3.3 Volume distributions

One main goal of the investigation of the mineral dust transport in the NE-trade-wind region was the study of the development of the size distribution at sea level as

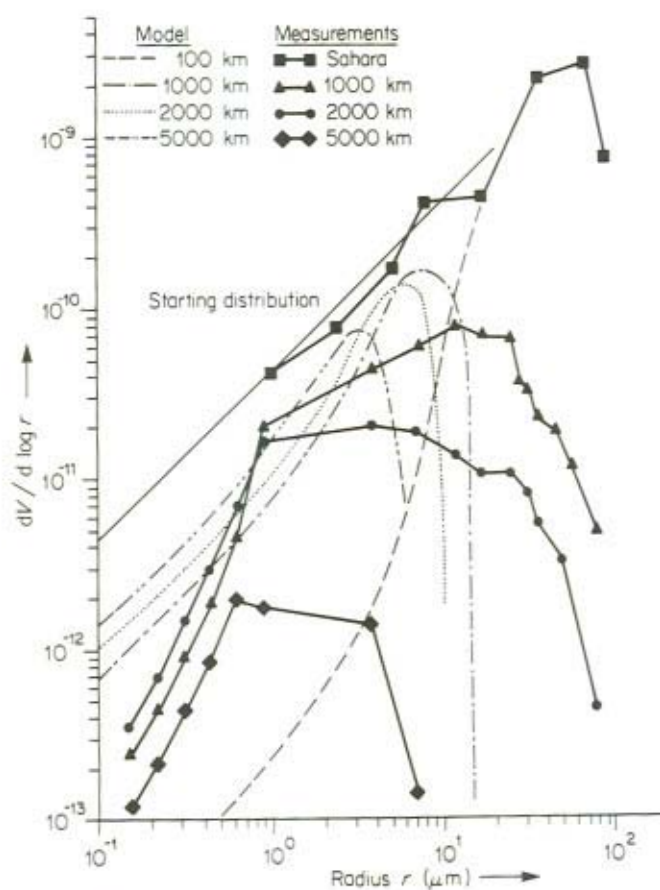


Figure 14.5 Mineral volume distributions at sea level for various distances from the Sahara. The dotted lines represent calculations assuming an initial distribution with  $\nu^* = 2$  at the source. Heavy lines (measurements) show mean volume distributions at the source and for selected transport distances over the Atlantic. Both measurements and calculations indicate a shift of the maximum of the distributions toward smaller particle radii

a function of the distance to the Sahara. For a better understanding of the measured size distributions across the Atlantic, a comparison with modeled distributions will be discussed. The calculations are based on an initial distribution at the source with  $\nu^* = 2$  according to the results achieved from Figure 14.4. The size distributions were then converted to volume distributions so that important variations in the giant-particle range could be more closely observed.

Figure 14.5 shows a comparison between volume distributions derived from measurements and calculations for selected distances from the source. From this Figure it is apparent that the assumed initial distribution at the source is a reasonably accurate representation of the actual distribution observed at the Sahara Desert site. When moving westward from the source, the model calculations indicate a shift of the maximum of the distributions towards smaller particle radii, and there is a general decrease in the maximum concentration. These results are in qualitative agreement with the measured size distributions. According to these data, the maximum of the volume distribution at the source is at  $50 \mu\text{m}$  radius and subsequently shifts to radii of approximately  $10 \mu\text{m}$ ,  $4 \mu\text{m}$ , and  $1 \mu\text{m}$  for transport distances of 1000 km, 2000 km and 5000 km respectively. Finally the model is not able to explain the comparatively high concentrations of particles of radii larger than  $10 \mu\text{m}$  observed during field measurements. These giant particles are probably agglomerates consisting of smaller particles which are formed during coalescence of precipitation and cloud droplets, followed by evaporation, which produces dry residues.

It is possible that the volume distribution observed over the Caribbean Sea, 5000 km from the Sahara Desert, may represent the background distribution of the mineral component of the atmospheric aerosol.

#### 14.4 CONCLUSIONS

The transport model offered the possibility to study some important features of Sahara dust transport within the NE-tradewind zone. From the calculations it clearly turns out that a very different behaviour for various particle size ranges must be expected when moving westward from the source. Submicron particles, which cause atmospheric turbidity, remain within the plume over large transport distances. Their removal from the plume, which mainly takes place by turbulent diffusion, is strongly affected by the tradewind inversion. This layer suppresses vertical exchange and leads to a delayed downward flux of these particles. Giant particles, however, remain unaffected by the inversion layer due to their high sedimentation velocities. Thus they are rapidly removed from the plume within relatively short distances from the source. Most of this particle fraction, which represents a considerable part of the mineral aerosol mass, will be deposited within the first 1500 km of transport.

A comparison between measured and calculated mass concentrations at sea level suggests  $\nu^* = 2$  as a reasonable value for the number size distribution in the form of a power function within the range  $r \geq 0.1 \mu\text{m}$ . This indicates a relatively large fraction of giant particles produced at the source and confirms earlier findings by the author in the Sahara desert. Furthermore this agrees well with data obtained by Gillette *et al.* (1972) for airborne soil particles over Texas and Nebraska and might indicate that the value of  $\nu^* = 2$  is significant for soil-derived aerosols close to the source.

Finally it can be pointed out that this model allows further applications, as is shown by Jaenicke (1979). His source strength estimates of the Sahara Desert and the budget studies of transported and deposited mineral mass over the Atlantic are based on this model.

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