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# Saharan dust in the Amazon Basin

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ABSTRACT

Saharan dust is shown to enter the Central Amazon Basin (CAB) in bursts which accompany major wet season rain systems. Low-level horizontal convergence feeding these rain systems draws dust from plumes which have crossed the tropical Atlantic under the large-scale circulation fields. Mass exchange of air between the surface and 4 km over the eastern Amazon basin is calculated using rawinsonde data collected during storm events. Mean concentrations of dust observed by aircraft over the western tropical Atlantic are used to calculate the amount of dust injected into the Basin. Individual storm events inject some 480,000 tons of dust into the northeastern Amazon Basin. Storm and dust climatology suggest that the annual importation of dust is in the order of 13 Mtons. In the northeastern basin, this may amount to as much as 190 kg $ha^{-1}$ $yr^{-1}$. Deposition of trace species, such as phosphate, associated with this dust ranges from 1–4 kg $ha^{-1}$ $yr^{-1}$. Uncertainties in these estimates are not believed to be greater than $\pm 50\%$ and may be as low as $\pm 20\%$. The deposition fluxes from Saharan dust are essentially identical to the CAB wet deposition fluxes from precipitation in the wet season; a result that implies that the major ionic composition of rain water in the CAB wet season may be strongly influenced by inputs of material originating on the African continent nearly 5000 km away. The total amount of Saharan dust calculated to enter the Amazon basin is 1/2 to 1/3 of that estimated to cross 60° W longitude between 10° and 25° N latitude. We conclude that part of the productivity of the Amazon rain forest is dependent upon critical trace elements contained in the soil dust originating in the Sahara/Sahel. This dependence should be reflected by expansions and contractions of the Amazon rain forest in direct relationship to expansions and contractions of the Sahara/Sahel. Turnover rates for nutrient species deposited with Saharan dust in the Amazon Basin suggest a time scale of 500 to 20,000 years. We believe the dependence of one large ecosystem upon another separated by an ocean and coupled by the atmosphere to be fundamentally important to any view of how the global system functions. Any strategy designed to preserve the Amazonian rain forest or any part thereof should equally concern itself with the inter-relationship between the rain forest, global climate and arid zones well removed from Amazonia.

## 1. Introduction

The tropical rain forests of the world are generally regarded as large ecosystems in relatively delicate nutrient balance. Balance is achieved by efficient cycling in a nutrient-limited environment (Jordan, 1985; Vitousek and Sanford, 1986). In the northeastern and parts of central Amazonia, where nutrient poor oxisols and ultisols are present and nutrient supply by rivers is limited, deposition of airborne soil dust particles is needed to achieve a nutrient balance (Jordan, 1985; Salati and Vose, 1984; Vitousek and Sanford, 1986). The amounts of aeolian influx have been estimated to be relatively high (in the order of millions to tens of millions of tons per year). In the case of some of the critical trace elements, this influx may be crucial to the health of the forest. Jordan (1985) and Vitousek and Sanford (1986), for example, have suggested that phosphorus may be a critical airborne element which could limit annual net primary production of the rain forest.

A substantial body of literature identifies the Sahara and sub-Saharan Sahel as the probable source region of dust found over a large fraction of the earth's surface. Saharan dust transported over distances of greater than 5000 km has been shown to reach areas in northern Europe (DeAngelis and Gaudichet, 1991; Reiff et al., 1986) and the middle east (Levin et al., 1980). In addition, there is considerable evidence mainly provided by Prospero and colleagues that Saharan dust reaches the eastern Caribbean (Prospero and Carlson, 1972; Talbot et al., 1990), southern North America (Savoie and Prospero, 1977) and the northeastern coast of South America (Parkin et al., 1972; Prospero et al., 1981; Prospero et al., 1987; Talbot et al., 1990).

There is also general agreement that transport of dust to the far western tropical Atlantic and the Caribbean occurs in the northeasterly trades at relatively low altitudes, mostly below 6–7 km (Prospero and Carlson, 1972; Jaenicke and Schütz, 1978; D'Almeida, 1986; Westphal et al., 1988; Bergametti et al., 1989). This layer of air, called the Saharan Air Layer (SAL), is situated most frequently between 850 and 700 mb (1.5 and 3 km) (Prospero and Carlson, 1972; Reiff et al., 1986; Bergametti et al., 1989).

Our results suggest that a considerable amount of the dust found in the Central Amazon Basin (CAB) is of Saharan origin. This Saharan dust is transported across the Atlantic under steady state (undisturbed) conditions in the 850 to 700 mb layer (Prospero and Carlson, 1972). However, we suggest that such steady state transport is not sufficient to bring the dust into the CAB. Synoptic scale weather systems, with associated organized low level convergence, are required to gather the dust into the Basin. Thus, dust events in the CAB are a function of synoptic scale systems coinciding with the existence of a dust plume in the far western tropical Atlantic. The role played by synoptic scale systems in producing pulses of Saharan dust in the CAB may also explain why Prospero et al. (1981) observed the maximum in dust concentrations in Cayenne, French Guiana to occur during the height of the wet season. Similarly, synoptic scale systems provide a mechanism in the far western Atlantic to inject dust across an active Intertropical Convergence Zone (ITCZ). Penetration of Saharan dust across an active ITCZ into the southern hemisphere has been deemed unlikely (Junge, 1979) because of wet removal of the dust.

Prospero and Carlson (1972) and Prospero et al. (1981) have made estimates of the annual amount of dust reaching a particular location. D'Almeida (1986) has also given estimates of the annual amount of particulate matter exported northward, westward and southward from the Sahara/Sahel. Uncertainties, however, remain in the estimates of the total amount of dust reaching such locations. An associated uncertainty also exists in the number and amount of trace elements delivered to a given location.

In the discussion which follows, aircraft sampling of aerosols, mass divergences calculated from rawinsonde stations and rain and dust storm climatology are used to calculate the storm and annual amount of dust brought into the Amazon Basin. A breakdown of the trace species concentrations present in the dust is also attempted. The resulting annual amounts of dust are compatible with those obtained by Prospero and Carlson (1972) across 60° W between 10 and 25° N latitude. The results obtained support the belief that the dust observed during the wet season in the central Amazon Basin is of Saharan origin. The storm convergence mechanism called upon to inject dust into the CAB provides a means to calculate the event, seasonal and annual amounts of dust imported.

If Saharan dust provides a major source of nutrients for the Amazonian rain forests, then a series of most important consequences follow. Reichholf (1986) has suggested that major fluctuations in rainfall over northern Africa during and following the pleistocene should be reflected by parallel expansions and contractions of the Amazon rain forest. Petit et al. (1981) have indeed reported evidence of increased continental aerosol concentrations during the pleistocene, attributed to increased size and activity of sand deserts located between 30° N and 30° S. Short term variations in the amount of particulate matter coming off West Africa have been related to the recent Sahelian droughts (Prospero and Nees, 1977, 1986). The possible response of the Amazon rain forest to variations in the airborne nutrient supply depends upon whether, how, what kind and how much dust is imported into the Amazon basin. The findings we present below to answer some of these questions are based upon a series of National Aeronautics and Space Administration (NASA) experiments carried out under the Division of

Atmospheric Chemistry's Global Tropospheric Experiment (GTE).

## 2. GTE Atlantic and Amazon Boundary Layer Experiment (ABLE)

The NASA GTE is attempting to document the chemical composition of the global troposphere by selecting and examining the atmosphere over important ecosystems. The Atlantic Boundary Layer Experiment (ABLE 1) (Gregory et al., 1986; Talbot et al., 1986) examined the troposphere over the open western tropical atlantic ocean in June 1984. The two Amazon experiments ABLE 2a and 2b, examined conditions over the relatively undisturbed tropical rain forest of the CAB in the dry, July–August 1985, and wet, April–May 1987, seasons (Harriss et al., 1988; 1990).

Field measurements made in the ABLE 1, 2a and 2b provide information on a range of interacting scales (e.g., space scales from 50 km to 5000 km) which appear essential to the understanding of both the chemistry and the dynamics of this fluid system (Fig. 1). The field experiments, associated observations and results are summarized in two special issues of the JGR devoted to ABLE 2a and 2b (JGR, 1988; 1990). A number of these results are used to present a mechanism to introduce Saharan dust into the CAB and to calculate the total importation of dust and associated trace species.

Sampling of atmospheric aerosols was conducted from the ground (Artaxo et al., 1990) and at various altitudes (0.2 to 6.0 km) from the NASA Electra research aircraft (Talbot et al., 1990). The ground-based sampling network was located on three of the towers shown in Fig. 1b at 45 m, 28 m and 2 m. Sampling duration ranged from 24 to 48 h. Samples were collected continuously from April 8 to May 14, 1987. The concentration of particulates and elements contained in soil dust (e.g., Si, Al, Fe) was determined on a daily basis.

Elemental concentrations were determined using particle induced X-ray emission (PIXE) analysis. Coarse ($>2\ \mu m$) and fine ($<2\ \mu m$) mode particle contributions were determined. Artaxo et al. (1990) found the following 22 elements in the ABLE 2b ground-based aerosol samples: Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Br, Rb, Sr, Zr, and Pb. Rain water analysis

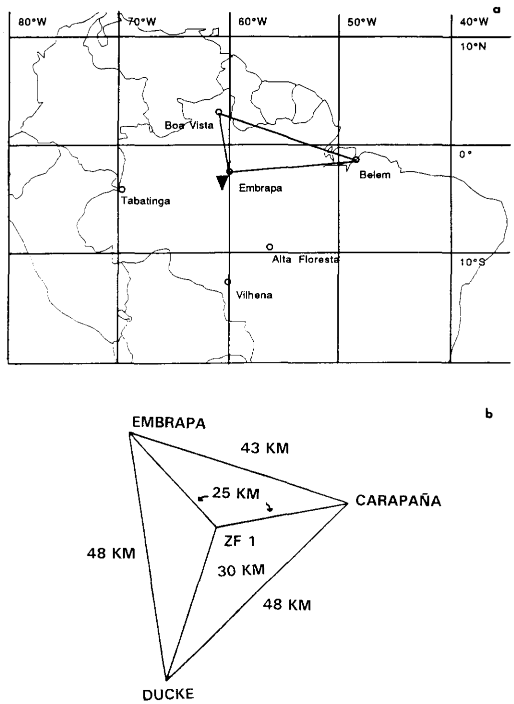


*Fig. 1.* Basin-scale rawinsonde network (a) and local mesoscale network (b) employed in the Amazon basin during ABLE 2B. Location of the mesoscale network is indicated by the darkened triangle in (a).

was performed on samples collected at 3 of the tower locations shown in Fig. 1b (Andreae et al., 1990). Rain water samples were collected on an event basis at each station.

Airborne (NASA Electra) sampling of aerosols consisted of collection on teflon filters and subsequent analysis of the water-soluble trace species using ion chromatography (Talbot et al., 1990). The constituents observed included Na, $NH_4$, K, Cl, $NO_3$, $SO_4$, $C_2O_4$, $CH_3SO_3$, HCOO, and $CH_4COO$ (Talbot et al., 1990).

The European Centre for Medium Range Weather Forecasting (ECMWF) global wind analyses are used for the computation of 10 day backward and forward isobaric trajectories. An overview of the ECMWF data assimilation system may be found in Hollingsworth (1987). The ECMWF analyses are available every 6th h with a horizontal resolution corresponding to 125 km at 19 vertical hybrid levels.

The 2-D trajectory method is a straightforward

Lagrangian following of air parcels in the analyzed wind field with wind components interpolated linearly in time every 6 h. The wind components are further interpolated, both horizontally and vertically (pressure), to the actual position of the parcel. The interpolated wind components are then used to track the parcel forward or backward over 6 h in 15-min increments.

Horizontal wind fields were compiled using ECMWF global data together with commercial aircraft and satellite wind observations (T. Krishnamurti, personal communication). The data at 850, 500, and 200 mb are used to determine the streamline fields over the tropical Atlantic, Africa, and South America during the ABLE 2b experiment.

Satellite imagery from the European Meteosat are used to provide coverage of the tropical Atlantic from northern Africa to the coast of South America including the arid region of northeast Brazil.

Ground-based rawinsonde measurements, obtained 4 times daily, were made in a basin scale network (1000–1500 km apart) shown in Fig. 1a. Local meteorological measurements used in this study include rawinsondes from the three corner stations of the mesoscale network in Fig. 1b (approximately 50 km spacing) together with rainfall measurements made on the towers at 5 m above the canopy.

Aerosol optical thickness values deduced from the Advanced Very High Resolution Radiation (AVHRR) satellite measurements (Rao et al., 1988) were not available during any of the ABLE missions. We refer to post field experiment aerosol optical thickness data to confirm the frequency and geographic extent of Sahara dust outbreaks.

## 3. Analysis and results

Ground-based measurements of aerosol concentration and composition during ABLE 2b indicate the occurrence of several large pulses containing both terrestrial and marine aerosols (Fig. 2a). Three maxima were centered around April 12–14 (experimental days 12–14), April 29–May 1 (experimental days 29–31) and May 5–8 (experimental days 36–40).

Aerosols associated with these pulses had relatively high concentrations of alkali and alkaline earth elements in the atmospheric mixed layer of the CAB (Talbot et al., 1990). Amazonian soils, however, are highly weathered and exhibit deficits of these elements. This finding suggested a non-local source region for the dust, which Talbot et al. (1990) believe to be the Sahara. Pulses of Saharan dust were also observed at Barbados during ABLE-2b (Talbot et al., 1990). These pulses, with concentrations at the surface reaching 180 $\mu g\ m^{-3}$, appeared at Barbados 1 to 2 days before Saharan dust was seen in the CAB.

The temporal variation of major mineral aerosol

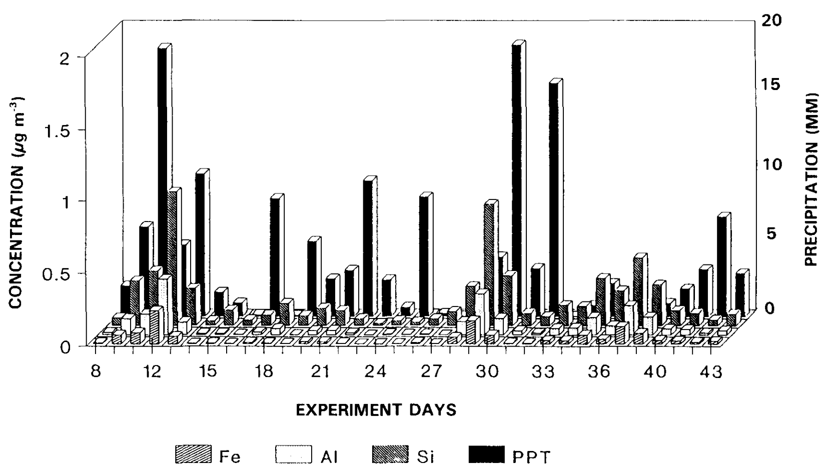


*Fig. 2.* Time series of ground-based concentrations of terrestrial elements (Fe, Al, Si) measured at Ducke tower with mesoscale network rainfall. (PPT)

constituents (e.g., Fe, Al, Si) shown in Fig. 2, are compared with the mean regional mesoscale (4 station) rainfall in Fig. 2. Both aerosols and rainfall occur in distinct pulses. The two major pulses in Si coincided with the two major rain events. The third, weaker aerosol pulse preceded a weaker rainfall event by about 48 h. Other rain events show little or no association with increases in dust. On days with little or no rain, however, very low concentrations of dust are observed.

Analysis of the rainfall during ABLE 2b (Greco et al., 1990; Garstang et al., 1990; Swap, 1990) showed that more than 80% of the rain was due to large (linear scales of 1000 km or larger) organized synoptic scale systems.

Wet season rainwater chemistry associated with large systems compared to small or local rain systems is different. The highest concentrations of $SO_4^{2-}$ and $Cl^-$ as well as higher pH values occur in large organized rain systems compared to local rain showers (Andreae et al., 1990). The presence of marine constituents (e.g., $Na^+$ and $Cl^-$) in these large rain systems suggest that they are ingesting low level air from over the western tropical Atlantic. Higher pH values in rain water, however, have also been found to be associated with Sahara dust (Löye-Pilot et al., 1986). Therefore, marine chemical constituents and continental components from African regions south of the Sahara may contribute to the rainwater composition of large rain systems in the CAB.

High concentrations of mineral aerosols occurring in close association with large rain events requires an explanation because wet removal would suggest the opposite result. We propose below that low level convergence covering a large area and preceding such large rain systems by 24 to 72 h is responsible for increasing the dust concentrations in near coincidence with the production of rain from these weather systems. This explanation requires the presence of a Saharan dust plume in the far western tropical Atlantic at the time that the synoptic scale weather system is organizing on the northeastern South American coast. First, we show from trajectory analysis that Saharan dust can reach the eastern and central Amazon Basin. Secondly, we calculate mass convergence in the low troposphere preceding the weather system and will show that this convergence can concentrate the dust from the preexisting plume residing over the western tropical Atlantic. Finally, we show that measured values of concentrations in the oceanic dust plume allow the calculation of both the total mass of dust and the mass of the associated chemical constituents transported into the Amazon Basin.

### *3.1. Streamline and trajectory analysis*

The large subtropical anticyclones are indicators of the nature of the lower tropospheric fields of motion linking western Africa and eastern South America. The position of the West African Subtropical High (WASH) with ridging over the central tropical Atlantic has been shown to influence low level flow across the Atlantic into the Amazon Basin (Talbot et al., 1990). Fig. 3 shows that, with the WASH centered in a prescribed area of West Africa, flow at 500 mb extends across the Atlantic and into the Amazon Basin. Each of the three concentrated pulses of soil dust into the CAB shown in Fig. 2 followed a 4–7 day period of the WASH so established over West Africa (Talbot et al., 1990). Meteosat visible images (not shown) confirm that, during such periods of dominance by the WASH, fair weather extends across the low latitude north Atlantic. Under a slowly changing large-scale anticyclonic field, the streamlines approach trajectories. The absence of deep convection or other forms of strong vertical motion along the path provide conditions which are near optimal for the calculation of trajectories.

Two-dimensional horizontal isobaric trajectories were calculated at 975, 950, 925, 900, 850, 800, 700, and 600 mb based upon the 6 h ECMWF global wind analysis. The 2-D trajectory calculations at multiple levels over 10 days were used to produce an envelope to bound the possible path taken and as an indication of the approximate origin or end point of the air parcels. Visible satellite imagery and the large scale wind fields in the 5–7 day period prior to a soil dust event in the CAB suggest near steady state conditions with little or no deep convection in the region of dust transport (Talbot et al., 1990). In the absence of deep convective clouds, vertical motions in the lower troposphere are confined to large scale subsidence in the order of 400 m $day^{-1}$ (Riehl, 1954; Riehl et al., 1951). Forward trajectories were calculated from two locations:

15° N latitude 10° E longitude in the Sahel, and

20° S latitude 15° E longitude in the Namib.

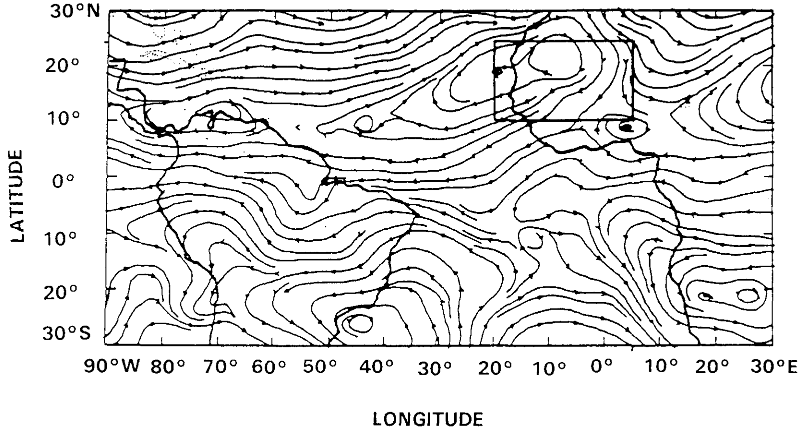


*Fig. 3.* 500 mb streamlines on 17 April 1987 illustrating the West African Subtropical High and associated wind flow across the Atlantic Ocean and into the Amazon Basin.

Backward trajectories were calculated from

0 latitude 60° W longitude in the CAB.

Three 10-day periods were chosen, two to coincide with the two major dust events seen in the CAB and one to coincide with a period of very low dust concentrations in the CAB (Fig. 2). The results of these calculations are discussed below.

*3.1.1. Dust event of 12 April–14 April.* Backward trajectories starting on 12 April 1987 (Figs. 4a, b) and 14 April 1987 (Figs. 4c, d) and forward trajectories starting on 4 April 1987 (Fig. 5) suggest that air parcels between 800 and 700 mb (Figs. 4b, 4d and 5b) originate from a region near Lake Chad. Air below 800 mb is traced back to the eastern Atlantic and the West African coast (Figs. 4a, c). Air below 800 mb originating (Fig. 5a) near Lake Chad does not leave the west coast of Africa after 10 days of travel time. Air above 700 mb is either not traced back to Africa (Fig. 4b) or does not reach the Sahel in the backward trajectory calculation. In the 10-day forward calculation (Fig. 5b), air at 600 mb heads towards, but does not reach the mouth of the Amazon.

Backward and forward trajectories were also calculated for the dust event of 29 April–1 May 1987 and for a low dust concentration day, 26 April 1987. We discuss our findings from these trajectory calculations without showing the graphical results. The backward trajectories starting on 29 April 1987 and 1 May 1987 and forward trajectories starting on 21 April 1987 show results similar to the April 12–14 event. Backward trajectories at 800 to 700 mb once again end up near Lake Chad. Above 800 mb and below 700 mb, however, parcels show a diverse set of pathways. Forward trajectories with the calculation beginning on 21 April 1987 just west and north of Lake Chad do not show any connection to the Amazon Basin. Backward trajectory results suggest that the point of origin chosen for the calculation is too far north and east. Trajectories for the low dust case show no connection to the Amazon Basin.

10-day forward trajectories were also calculated for three separate dates: 4, 16 and 21 April 1987 to determine whether dust could be coming from the southern hemisphere deserts of the Namib and Kalahari. No such connection was found.

While the trajectory calculations carried out as part of this paper do not rule out any other source of soil dust, we believe that the results show support for the contention that the Sahara/Sahel is the primary source. We find no evidence in the trajectory calculations that would support a South American location as a source region in the April/May time of year. None of the backward trajectories calculated from the CAB point (0° latitude, 60° W longitude) approach the dry zone of northeastern Brazil. Transport from the Namib/Kalahari, as well as from NE Brazil, into the Amazon basin may well, however, occur during astral spring and summer.

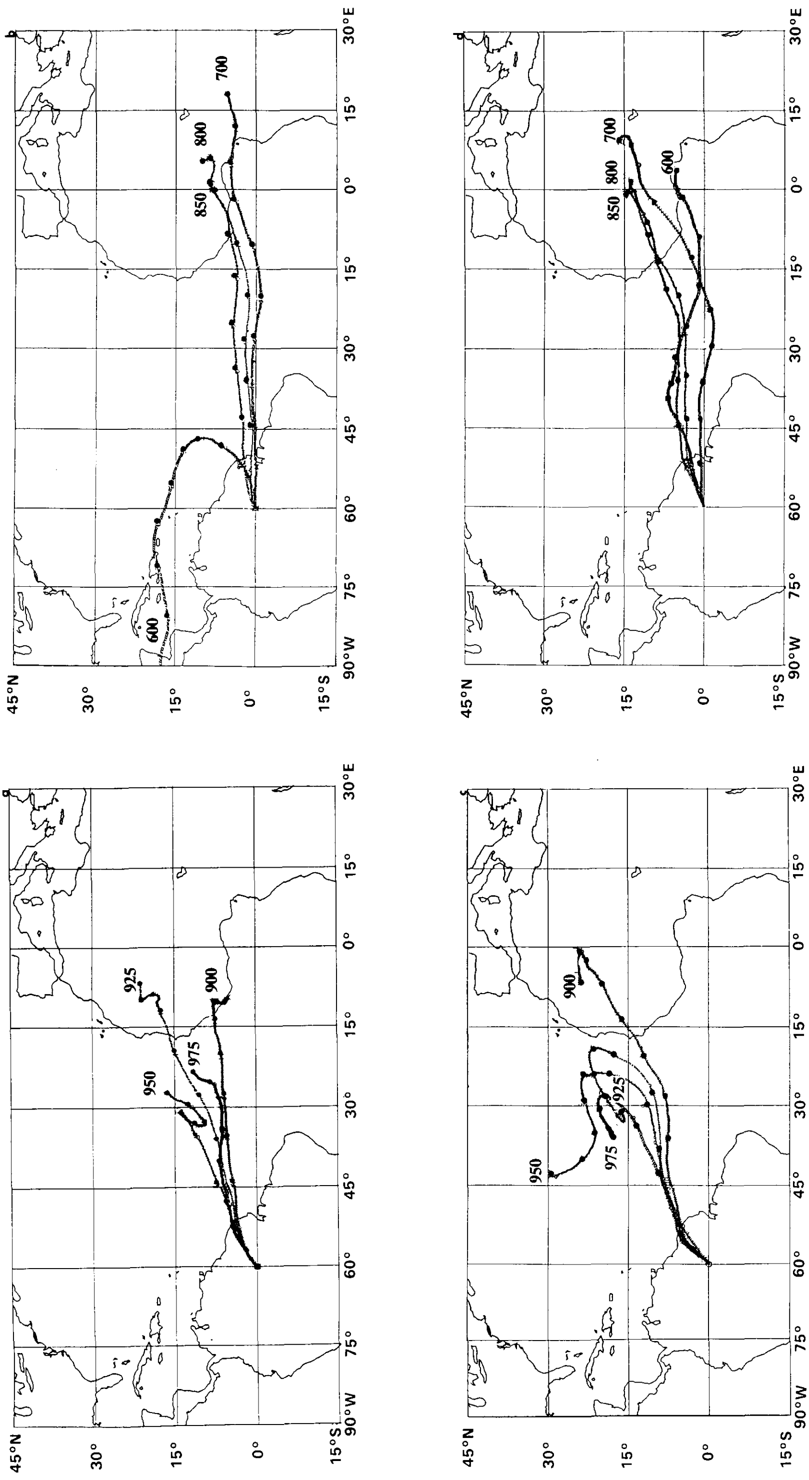


*Fig. 4.* 10-day backward isobaric trajectories beginning on 12 April 1987 (a) and (b) and 14 April 1987 (c) and (d).

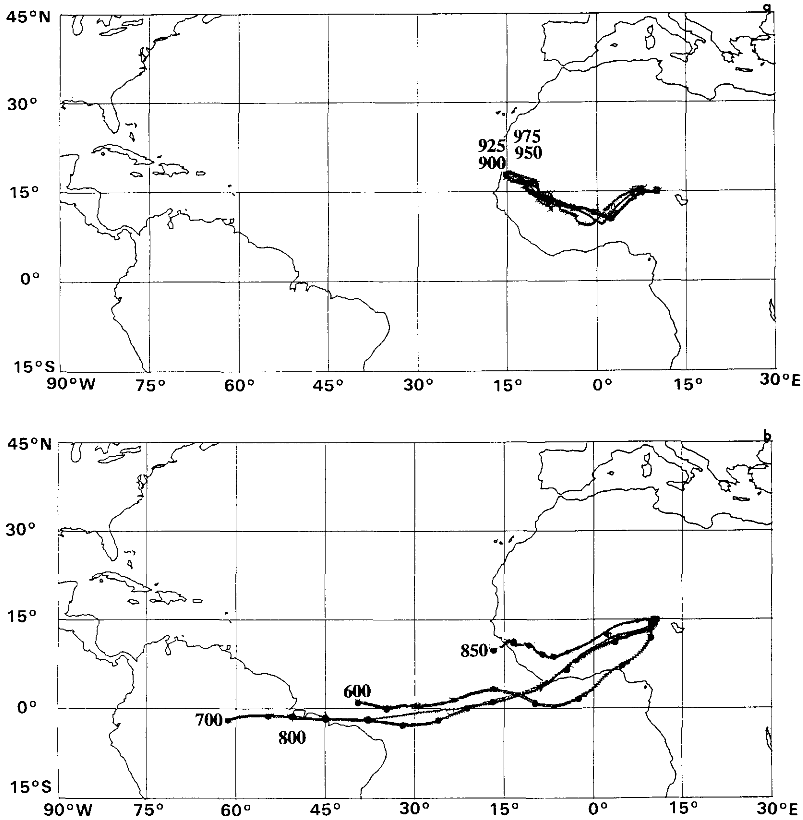


*Fig. 5.* 10-day forward trajectories beginning on 4 April 1987.

### *3.2. Horizontal mass divergence calculations*

The large triangle in Fig. 1a shows the relative location of three of the six basin scale rawinsonde network stations operated during ABLE 2b and designed to describe large-scale meteorological conditions over the entire Amazon Basin. The line from Boa Vista to Belém is nearly parallel to the northeast coast of South America. This line is also approximately normal to low level inflow into the Amazon Basin under conditions which favor both the transport of dust across the Atlantic and the development of synoptic scale weather systems in the Amazon Basin. The Belém, Boa Vista and Embrapa triangle over the northeastern Amazon Basin is thus positioned to capture any enhanced mass inflow into the Basin, drawing lower tropospheric air from over the western tropical Atlantic.

Rawinsonde data from the basin-scale stations were used to calculate horizontal divergence for the Belém, Boa Vista and Embrapa triangle by employing a line integral method utilizing the wind components normal to each leg of the triangle (Brummer, 1978). The horizontal divergence calculated for the triangle serves to determine the amount of air and, with measured aerosol concentrations, the amount of dust imported into the triangle volume as a function of the circulation of the synoptic scale storm system.

Fig. 6 shows the experiment time series of horizontal divergence at 850 mb and 700 mb. The rawinsonde network was not fully functional until 15 April 1987. The dust event of 29 April–1 May 1987 is captured by this time series and is used below to calculate total mass inflow into the volume above the triangle. The divergence signal in Fig. 6 shows a major perturbation about

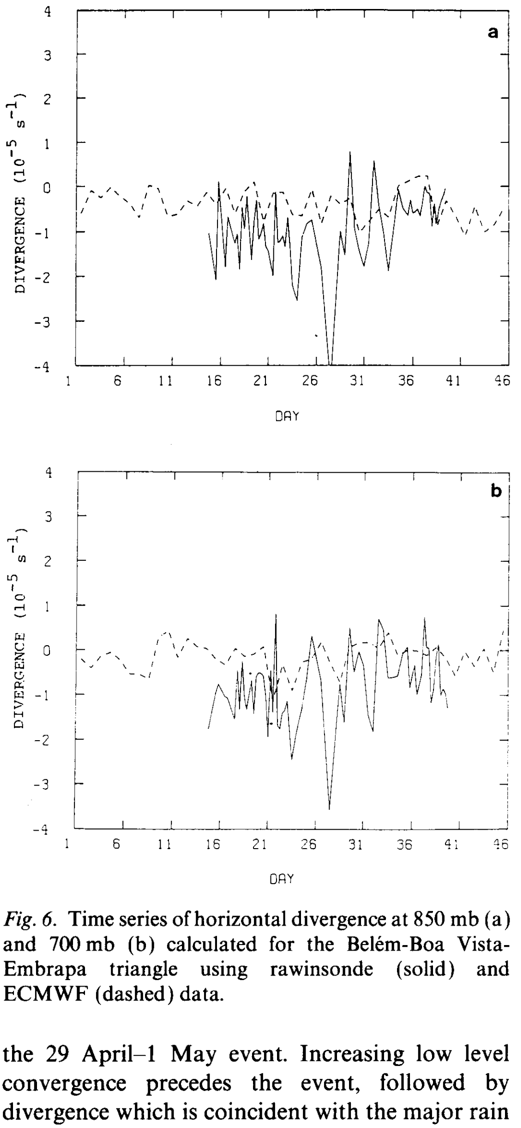


*Fig. 6.* Time series of horizontal divergence at 850 mb (a) and 700 mb (b) calculated for the Belém-Boa Vista-Embrapa triangle using rawinsonde (solid) and ECMWF (dashed) data.

the 29 April–1 May event. Increasing low level convergence precedes the event, followed by divergence which is coincident with the major rain pulses.

Divergence calculations for the triangle were repeated based solely upon ECMWF data. The results of this calculation are also shown in Fig. 6. While the ECMWF data captures much of the temporal variation in the signal, divergence is an order of magnitude lower than that obtained from the calculations based on the soundings.

Divergence calculated for the smaller mesoscale triangle shown in Fig. 1b (Scala et al., 1990) yield divergence values an order of magnitude higher ($10^{-4}$ $s^{-1}$) than those obtained from the large scale triangle network soundings. Such a hierarchal increase in divergence ($10^{-6}$, $10^{-5}$, $10^{-4}$ $s^{-1}$) proceeding from the large scale flow fields, as represented by the ECMWF, to the synoptic fields large scale triangle (Fig. 1a) to the mesoscale (mesoscale triangle soundings, Fig. 1b) is consistent with other work in the tropical atmosphere (see for example the GARP Atlantic Tropical Experiment results such as Frank, 1978). We, therefore, use a 48-h mean convergence of $2.0 \times 10^{-5}$ $s^{-1}$ as representative of the mass inflow into the volume bounded by the surface to 4 km and the sides Boa Vista to Belem to Manaus.

### 3.3. *Calculation of mass transports of Saharan dust into the Amazon Basin*

The area of the large triangle in Fig. 1a is approximately $4.0 \times 10^{11}$ $m^2$. The volume of air from the surface to 4 km over the triangle is $1.6 \times 10^{15}$ $m^3$. If the mean divergence over 48 h preceding the dust event is $-2.0 \times 10^{-5}$ $s^{-1}$, then the amount of air exchanged during this time is $(-2.0 \times 10^{-5}\ s^{-1})(1.728 \times 10^5\ s) = 3.5$ times the original volume. In contrast, with large-scale flow in the absence of an organized synoptic scale weather system (divergence $= 10^{-6}$ $s^{-1}$), the exchange rate would be an order of magnitude less, or only 1/3 of the low level volume would be exchanged in 48 h. Under synoptic scale forcing, the volume of air contained below 4 km over the triangle is exchanged 3.5 times in 48 h equalling $(3.5)(1.6 \times 10^{15}\ m^3) = 5.6 \times 10^{15}$ $m^3$ of air.

Under northeasterly inflow into the Amazon Basin, we may assume that all of this exchange occurs across the side of the triangle parallel to the coast. Fig. 7 shows the dust plume laying off the NE coast of South America. Fig. 8 shows a Saharan dust plume immediately east of Barbados (60° W, 13° N) as observed by downward looking airborne lidar (Browell, personal communication). The plume lies between 1.5 and 4.2 km. In the presence of such a dust plume, the air being brought into the basin-scale triangle by the storm system will contain large amounts of dust. Talbot et al. (1986) showed that these dust plumes contained up to 400 $\mu g\ m^{-3}$, with a mean value of 51 $\mu g\ m^{-3}$ for the surface to 3.7 km layer. A weighted mean for the layer between 1.5 and 4 km from Prospero and Carlson (1972) gives a value of 45 $\mu g\ m^{-3}$. We take a mean value of 50 $\mu g\ m^{-3}$ for the dust concentration in such a plume between

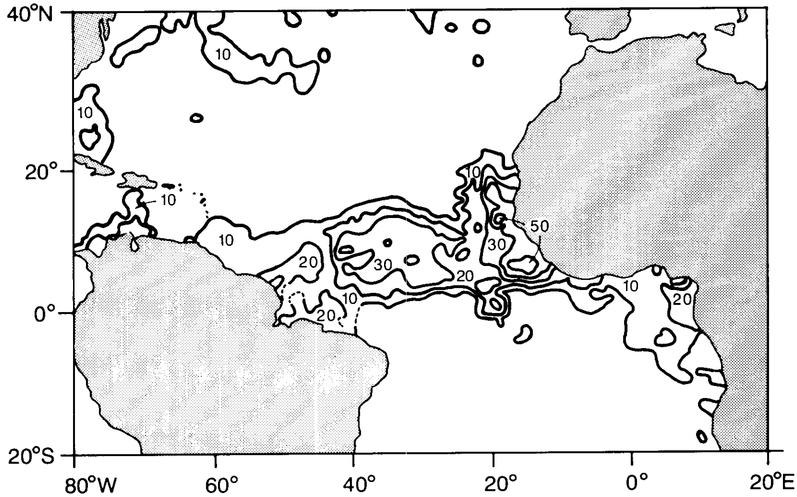


*Fig. 7.* Aerosol optical depth ($\tau$) on 21 April 1988 showing a dust plume between western Africa and the northeastern coast of Brazil. Values for $\tau$ derived at NOAA/NESDIS using satellite radiance values obtained from the AVHRR. Contour intervals are multiplied by 100.

the surface and 4 km over a continuous period of 48 h. Using this mean concentration, we calculate the mass of dust entering the volume in 48 h to be:

(the volume of air exchanged in 48 h)
(mean concentration)

$$(5.6 \times 10^{15}\ \mathrm{m^3})(5.0 \times 10^{-5}\ \mathrm{g\ m^{-3}}) = 2.8 \times 10^{11}\ \mathrm{g}\ \text{or}$$

280,000 tons per storm system.

A given storm may have a convergence field which acts on the dust plume for longer than 48 h. However, this may be counteracted by the fact that a mean concentration of 50 $\mu$g m$^{-3}$ may be high for the entire duration of the inflow. Thus, we feel that 48 h and 50 $\mu$g m$^{-3}$ are representative of the average dust event.

The calculation above assumes the dust enters across the side of the triangle (Fig. 1a) parallel to the coast. In fact, the dust will enter across the entire NE coast of South America. Aerosol optical depth data from the Advanced Very High Resolution Radiometer (AVHRR) presented in (Fig. 7) shows that the length of coastline across which the dust is transported extends from Sao Luis, Brazil (44°30′W longitude, 2°30′S latitude) to the Gulf of Paria (63°0′W longitude, 10°30′N latitude), a total distance of 2500 km. The linear distance of the triangle side to the coastline is 1:1.7. We thus increase our above estimate by 1.7:

$$(2.8 \times 10^5)(1.7) = 4.8 \times 10^5\ \text{tons/storm system.}$$

Greco et al. (1990) have shown that 80% of the CAB rainfall during the wet season is produced by organized synoptic scale weather systems. The average amount of rainfall in the CAB during the 6 months (December–May) of the CAB wet season coincident with Saharan dust outbreaks is about 1600 mm (Villa Nova et al., 1976; Marques-Filho et al., 1981). Swap (1990) shows that the average amount of rain per synoptic scale system is 20 mm. Thus, approximately 60 synoptic scale weather systems occur in the 6-month wet season or approximately 10 systems a month. Other evidence (Madden and Julian, 1972) show a 5-day periodicity in the equatorial tropics or 6 systems a month.

The wet season for the eastern Amazon basin (EAB) is approximately 2 months longer than the CAB wet season. The EAB wet season lasts from December to July (Villa Nova et al., 1976), and with approximately 2000 mm of rain falling during this period. If 80% of the EAB rain is also delivered by organized synoptic scale systems, approximately 80 storms occur in the 8-month

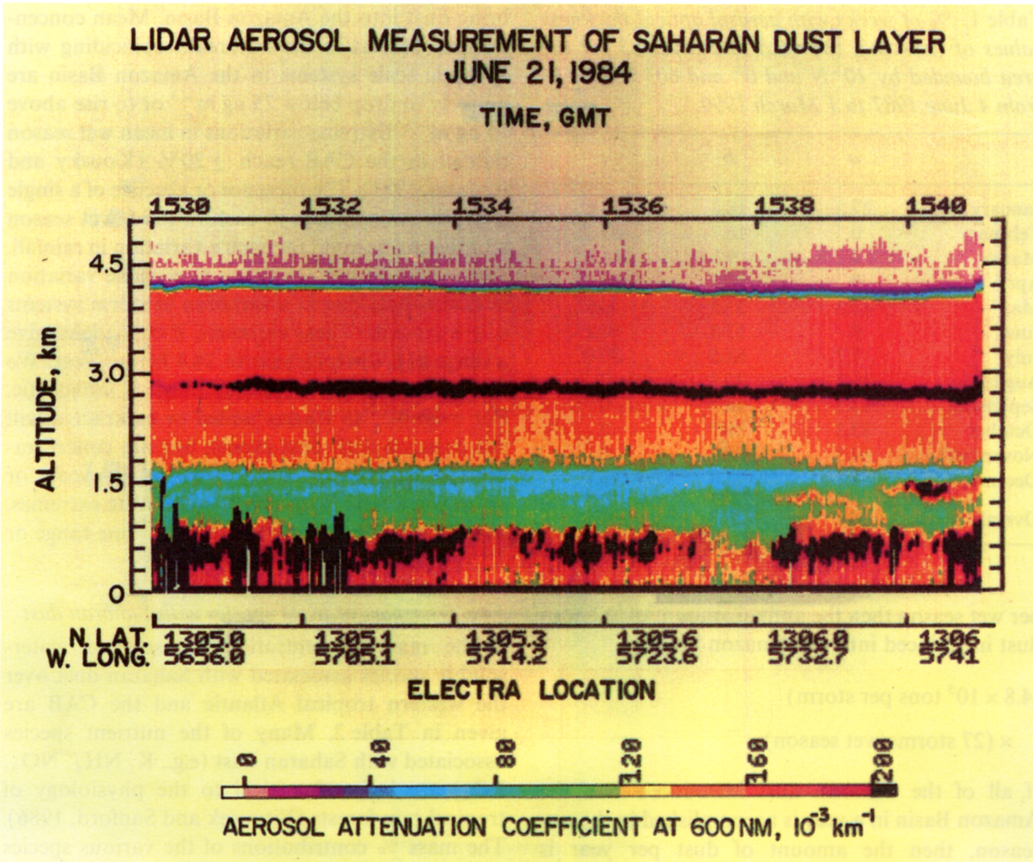


*Fig. 8.* Lidar-measured aerosol attenuation coefficient near Barbados on 21 July 1984 (courtesy of E. Browell, personal communication). The dust plume is seen between 1.5 km and 4.2 km.

wet season (10 systems a month). These numbers are supported by Cohen (1989) who reported an average annual value of 67.5 synoptic scale instability lines in the EAB during these months between 1979 and 1986. Cohen's numbers are confined to "instability lines" and do not include all synoptic scale systems.

Aerosol optical thickness measurements made from the AVHRR equipped satellite over a 32-month period from 4 June 1987 to 1 March 1990 are used to obtain a measure of the number of weeks in which Saharan dust outbreaks are present off the NE coast of South America. Table 1 shows that 34.1 % of the weeks during the 32 months have aerosol optical thickness values of at least 0.3 within the area bounded by 10° N–0°, 60° W–40° W. Values of 0.3 or greater are representative of heavy aerosol outbreaks (Carlson, 1979). Table 1 also shows that heavy dust outbreaks are seen from December to July. This corresponds to the height of the wet season for eastern and northeastern Amazon Basin (Villa Nova et al., 1976) and to the period of increased coastal squall line activity (Cohen, 1989).

Based on the results of rainfall per system and the aerosol optical depth analysis, 34.1 % of the 80 or 27.3 synoptic scale systems have the potential to carry dust into the eastern Amazon Basin during the extended wet season of December–July. If we round off the number of dust bearing storms to 27

Table 1. *% of weeks with aerosol optical thickness values of (a) < 0.2, (b) < 0.3 and (c) ≥ 0.3 for the area bounded by 10° N and 0° and 60° W–40° W from 4 June 1987 to 1 March 1990*

| | *a* | *b* | *c* |
|---|---|---|---|
| January | 27.2 | 18.2 | 54.6 |
| February | 0 | 16.7 | 83.3 |
| March | 9.1 | 9.1 | 81.8 |
| April | 0 | 14.3 | 85.7 |
| May | 12.5 | 37.5 | 50.0 |
| June | 0 | 53.8 | 46.2 |
| July | 7.7 | 61.5 | 30.8 |
| August | 66.7 | 33.3 | 0 |
| September | 83.3 | 16.7 | 0 |
| October | 83.3 | 16.7 | 0 |
| November | 64.3 | 35.7 | 0 |
| December | 58.3 | 25.0 | 16.7 |
| Overall | 36.2 | 29.7 | 34.1 |

per wet season then the annual amount of Saharan dust introduced into the Amazon Basin is

$(4.8 \times 10^5$ tons per storm)

$\times$ (27 storms/wet season).

If all of the Saharan dust introduced into the Amazon Basin in a year is accomplished in the wet season, then the amount of dust per year is *13.0 Mtons/year*.

Prospero and Carlson (1972) have estimated the annual transport of Saharan dust through a wall extending from 10° N latitude to 25° N latitude along 60° W longitude to range between 25 and 37 Mtons per year. D'Almeida (1986) has estimated annual westward transport immediately off West Africa to lie between 45 and 53 Mtons per year. Estimates of the total annual West African source strength for westward transport vary from 80 Mtons per year (Prospero and Carlson, 1972) to 260 Mtons/year (Jaenicke and Schütz, 1978) with 190 Mtons per year having been reported by D'Almeida (1986).

Our results suggest that the amount of dust that enters the Amazon basin is between one half and one third of the amont of dust found by Prospero et al. (1981) to cross the 60th meridian between 10 and 25° N. The major uncertainties in our calculations are the mean concentration (50 $\mu g\ m^{-3}$) and the number of synoptic scale systems (27) which bring dust into the Amazon Basin. Mean concentrations of dust in the outbreaks coinciding with synoptic scale systems in the Amazon Basin are unlikely to drop below 25 $\mu g\ m^{-3}$ or to rise above 75 $\mu g\ m^{-3}$. Extreme variations in mean wet season rainfall in the CAB reach $\pm 20\%$ (Kousky and Kagano, 1981). The presence or absence of a single synoptic scale system in each of the 8 wet season months can account for such a variation in rainfall. Thus, a maximum or minimum possible variation in dust supply due to a variation in storm systems is $\pm 8$ systems. These extremes, if coincident, give a range of 4.4 Mtons/year to 24.4 Mtons/year. We believe that such an extreme range is unrealistic. For example, all storms added or subtracted will not coincide with dust events; nor are concentrations of dust likely to go down in dry years or up in wet years. Both effects reduce the extremes. A more realistic range is half the extreme range or 8.5 to 18.5 Mtons/year.

### 3.4. *Transport of trace species with Saharan dust*

The mass concentrations of selected water-soluble species associated with Saharan dust over the western tropical Atlantic and the CAB are given in Table 2. Many of the nutrient species associated with Saharan dust (e.g., K, $NH_4$, $NO_3$, $PO_4$) are believed critical to the physiology of tropical rain forests (Vitousek and Sanford, 1986). The mass % contributions of the various species range from tenths of a percent to several percent.

Mass concentrations of Na and Cl are enhanced over the CAB compared to their levels in the Sahara air layer over the western tropical Atlantic (Table 2). This apparent enrichment is presumably due to entrainment of sea salt into dust-containing air masses that are advected inland from the South American coast. The sea salt concentration over the CAB is on the order of 0.5 $\mu g\ m^{-3}$ during periods influenced by the injection of marine air (Talbot et al., 1990). Besides Na and Cl, $NH_4$ and $SO_4$ appear to be enriched 2-fold and $NO_3$ 3-fold over the CAB compared to the Sahara air layer over the western tropical Atlantic. We attribute these differences to inputs of nitrogen-rich biomass burning emissions along coastal Africa (Delmas, 1982). The levels of $NH_4$, $NO_3$, and $SO_4$ associated with Saharan dust over the tropical Atlantic appear to be strongly influenced by African biomass burning products during the winter-to-spring time of the year (Savoie et al.,

Table 2. *Mass concentrations (%) of selected trace species associated with Saharan dust over the Western Tropical Atlantic and the Central Amazon Basin*

| Species | Average (%) | Range (%) |
|---|---|---|
| (a) *Western tropical Atlantic*[a] | | |
| Na | 0.37 | 0.24 –0.85 |
| K | 0.17 | 0.10 –0.33 |
| $NH_4$ | 0.18 | 0.01 –0.27 |
| Cl | 0.32 | 0.19 –0.50 |
| $NO_3$ | 0.51 | 0.21 –1.5 |
| $SO_4$ | 1.29 | 0.35 –3.0 |
| $PO_4$ | 0.037 | 0.017–0.071 |
| (b) *Central Amazon basin*[b] | | |
| Na | 1.1 | 0.42–1.8 |
| K | 0.29 | 0.12–0.46 |
| $NH_4$ | 0.44 | 0.08–0.91 |
| Cl | 1.9 | 1.3 –2.6 |
| $NO_3$ | 1.6 | 0.20–2.6 |
| $SO_4$ | 2.4 | 0.22–3.7 |
| $PO_4$ | N/A | N/A |

[a] From Talbot et al. (1986).
[b] From Talbot et al. (1990).

1989). Our ABLE 1 measurements over the western tropical Atlantic were conducted during summertime and exhibit minimal influence from African biomass combustion products; a dramatic seasonal signal in this source appears in the annual record of aerosol composition at Barbados (Savoie et al., 1989). Thus, Saharan air intrusions into the CAB during the wet season appear to reflect combined chemical inputs from mineral aerosol, sea salt, and possibly biomass burning products.

The annual rates of supply of trace species were estimated assuming that all the dust entering the Boa Vista/Manaus/Belem triangle is deposited within that area. In assessing this assumption, it should be noted that Manaus lies more than 1300 km inland from the NE coast of South America. If all the Saharan dust introduced into the triangle (Fig. 1b) in a year was effectively deposited in that area, its deposition flux would be:

$$\frac{13 \times 10^9 \text{ kg yr}^{-1}}{(1.7)(4.0 \times 10^7 \text{ ha})} = 190 \text{ kg ha}^{-1} \text{ yr}^{-1}.$$

This value, 190 kg $ha^{-1}$ $yr^{-1}$, is on the high end of other reported Saharan dust depositional rates; 13 kg $ha^{-1}$ $yr^{-1}$ at Miami, Florida (Prospero et al., 1987) and 77 kg $ha^{-1}$ $yr^{-1}$ in the French Alps (DeAngelis and Gaudichet, 1991).

Using the mass concentrations of selected trace species associated with Saharan dust over the CAB (Table 2) and our above estimate of dust deposition to the Amazonian ecosystem, we find that most species are deposited at a rate of 1–4 kg $ha^{-1}$ $yr^{-1}$ (Table 3). These deposition fluxes are essentially identical to the average wet deposition fluxes measured at two stations within the triangle area during the ABLE 2B experiment (Table 3). This result suggests that precipitation scavenging is the principal removal mechanism of Saharan dust associated material from the atmosphere during the CAB wet season. During the CAB wet season, the average residence time of aerosols in boundary layer air relative to precipitation washout is 0.25–1 day (Andreae et al., 1990). Our analysis suggests that the major ionic composition of precipitation (e.g., $NH_4$, $NO_3$, $SO_4$) in the CAB wet season may be strongly influenced by inputs of material originating on the African continent nearly 5000 km away. This transcontinental bio-

Table 3. *Comparison of deposition fluxes (kg $ha^{-1}$ $yr^{-1}$) of selected trace species associated with intrusions of Saharan dust and precipitation in the Amazonian wet season (December–May)*

| | Dust Intrusions[a] | | Precipitation[b] | |
|---|---|---|---|---|
| Species | average | range | average | range[c] |
| Na | 2.1 | 0.80 –3.4 | 1.7 | 0.73–2.9 |
| K | 0.55 | 0.23 –0.87 | 1.3 | 0.41–2.3 |
| $NH_4$ | 0.84 | 0.15 –1.7 | 0.71 | 0.38–1.4 |
| Cl | 3.6 | 2.5 –4.9 | 2.9 | 1.4 –5.1 |
| $NO_3$ | 3.0 | 0.38 –4.9 | 1.4 | 0.90–3.7 |
| $SO_4$ | 4.6 | 0.42 –7.0 | 1.8 | 1.2 –3.1 |
| $PO_4$ | 0.07[d] | 0.032–0.14[d] | 0.04[e] | 0.01–0.12[e] |

[a] Calculated using mass concentrations reported in Table 2.
[b] Based on measurements reported in Table 1 from Andreae et al. (1990).
[c] Based on upper and lower quartile concentrations observed at two sites within the triangle area (Andreae et al., 1990).
[d] Estimated using average mass concentration (see Table 2) reported by Talbot et al. (1986).
[e] Based on unpublished data from ABLE 2b (R. Talbot and M. Andreae, personal communication, 1987).

geochemical link appears to be severed during the dry season when the large-scale meteorological regime which favors transport of Saharan air masses into the CAB migrates to the north. The aerosol and precipitation chemistries in the CAB dry season support such a scenario (Talbot et al., 1988; Andreae et al., 1988). Long-range transport of aerosol-associated species to the CAB appears to explain the higher wet season precipitation fluxes of Na, Cl, and K compared to the dry season. It also seems to be responsible for the similar seasonal precipitation fluxes of $NH_4$, $NO_3$, and $SO_4$ despite a five-fold contrast in rainfall amounts. Our estimate of long-range chemical inputs to the CAB are significantly lower than Reichholf's (1986), who suggests at least 2 orders of magnitude higher dust transport to the western tropical Atlantic atmosphere than any reported estimate.

Table 4 compares our deposition fluxes to reported annual internal fluxes (the amount of nutrients internally recycled) and standing stock values (the total ecosystem amount of a nutrient) for the Amazon Basin. Inputs of K and P associated with Saharan dust aerosols represent from a few tenths to 6% of the annual nutrient turnover due to litterfall, and from a few thousandths to a few tenths of a percent of the total ecosystem standing stock. The nutrient influx of these and other trace elements into the EAB and CAB does not appear important on short time scales ($10^1$–$10^2$ years). However, with respect to the long-term geochemical mass balance of the Basin, Saharan dust and associated aerosols are important as an outside source of elements that help replenish those lost from the system. This importance is amplified in a tightly constrained nutrient system such as the EAB and CAB.

The time required for the imported K and P to be equal to the amount of their respective Amazonian standing stocks is estimated using our deposition fluxes to evaluate the potential biogeochemical importance of Saharan dust inputs to the Amazon rainforest. Dividing the standing stock of K in the Amazon oxisol rainforest, $\sim 380$ kg ha$^{-1}$ (Jordan, 1985), by our maximum and minimum values of K influx (Table 3), we arrive at values ranging from 440 to 1700 years. The same calculation for P, using a standing stock value of 220 kg ha$^{-1}$ for the CAB (Golley et al., 1975) results in values ranging from 4700 years to 20,000 years. These calculations do not account for losses from the system, such as the Amazon River outflow (Gibbs, 1972). Hydrologic loss values (Franken and Leopoldo, 1984) of P from the CAB vary from an order of magnitude less than our deposition values to the same order of magnitude.

These results suggest that if Saharan dust aerosol is a principal source of these trace species to the EAB and CAB, then the effect on the biogeochemical cycling would be on the long term ($10^2$–$10^3$ years). Other possible mechanisms may play additional roles in this seemingly storm event driven system. The accumulation of nutrients in rain water stored in epihytes may be one such mechanism. Increased tree falls in tropical rain forests are noted during the wet season (Oldeman, 1972; Brokaw, 1985). Large trees heavily loaded with epiphytes may therefore be prime candidates to fall during the CAB wet season. Tree fall is most likely to occur in the synoptic scale storms called upon to gather the dust into the Basin. Downdrafts from deep convective clouds in these storm systems reach speeds of 20 to 25 m s$^{-1}$ (45–55 mph). The creation of gaps in the rain forest at the time of maximum soil dust influx may

Table 4. *Range of values for depositional influx of P and K due to Saharan dust and associated aerosols compared to and expressed as %s of annual internal flux from litterfall and total ecosystem nutrient amount*

| | Depositional input (kg ha$^{-1}$ yr$^{-1}$) | Internal flux from litterfall (kg ha$^{-1}$ yr$^{-1}$) | Input as % of litterfall (min–max) | Standing stock (kg ha$^{-1}$) | Input as % of standing stock |
|---|---|---|---|---|---|
| P | 0.011–0.047 | 1.4– 4.1[a)] | 0.27–3.4 | 220[b)] | 0.005–0.021 |
| K | 0.23 –0.87 | 13 –21[a)] | 1.1 –6.7 | 378[c)] | 0.061–0.23 |

[a)] Proctor (1984).
[b)] Klinge (1976).
[c)] Golley et al. (1975).

be an important component in the utilization of small amounts of trace elements.

## 4. Summary and conclusions

We conclude that Saharan dust penetrates the eastern Amazon Basin and is detected in the Central Basin. The dust is delivered in intermittent pulses which occur in association with major pulses in rainfall. Since these large rain events are due to organized storm systems with horizontal scales of up to a few thousand kilometers and time scales of days, we conclude that part of the mechanism driving the storm system is responsible for the accumulation of dust.

Low-level (up to 4 km) horizontal negative divergence associated with the storm system is shown to be sufficient to draw dust into the Amazon Basin. Previous work together with results provided here show that Saharan dust easily reaches the western tropical north Atlantic. Mean flow into the Basin can neither concentrate the dust nor deliver it in the aperiodic fashion observed. Storm systems are shown to be sufficiently frequent to draw upon existing dust plumes. The presence of Saharan dust off the northeast coast of South America is also shown to coincide with the high frequency of storms. Not all rain events in the CAB are accompanied by dust, but all of the dust events we observed occurred in association with rain events.

Observations of the horizontal extent, vertical depth and concentrations of dust permit an estimate of the amount of dust introduced into the Amazon Basin in a given storm event. Storm climatology yields an estimate of 13 Mtons/year of dust introduced into the Amazon Basin. In the northeastern basin, this may amount to as much as 190 kg $ha^{-1}$ $yr^{-1}$ of dust. The amount of trace species supplied with this dust ranges from a few kg $ha^{-1}$ $yr^{-1}$ to less than 1 kg $ha^{-1}$ $yr^{-1}$.

The total amount of Saharan dust calculated to enter the Amazon Basin is one half to one third of that estimated by others to cross 60° W longitude between 10° and 25° N latitude (Prospero and Carlson, 1972). It is two orders of magnitude less than is implied by Reichholf (1986) who has estimated quantities of trace species needed by the rain forest on nutrient poor soils. This large discrepancy may be due to an underestimate in the total amount of soil dust supplied to the Amazon Basin if, as we have, one confines the calculation to the Sahara as the only source. The discrepancy may also be due to an overestimation of the necessary nutrient influxes and a simultaneous underestimation of the efficiency in recycling nutrients in this ecosystem.

Whatever the resolution of the above paradox is, we conclude that part of the Amazon rain forest is dependent upon soil dust which originates in the Sahara/Sahel region of western Africa. We concur with conclusions drawn by others that such a dependence must be reflected by expansions and contractions of the Amazon rain forest in direct relationship to expansions and contractions of the Sahara/Sahel. We hypothesize that such fluctuations in the size of the rain forest are on time scales which lie between about 500 and 20,000 years. Evidence for such a coupled response must be present in the records of the pleistocene pluvial periods. Such a dependence of one large ecosystem upon another separated by an ocean is of fundamental importance to our view of the role of these ecosystems in the global atmosphere. A view of the role of Amazonian rain forest in the global system must take this coupled process into account. Any strategy designed to preserve the Amazonian rain forest or any part thereof should equally concern itself with the interrelationship between the rain forest, global climate and acid zones well removed from Amazonia.

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