Modeling the atmospheric distribution of mineral aerosol: Comparison with ground measurements and satellite observations for yearly and synoptic timescales over the North Atlantic

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Modeling the atmospheric distribution of mineral aerosol: Comparison with ground measurements and satellite observations for yearly and synoptic timescales over the North Atlantic

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Abstract. We present here a 3-year simulation (1990 to 1992) of the atmospheric cycle of Saharan dust over the Atlantic with an off-line three-dimensional transport model. The results of the simulation have been compared with selected relevant measurements. Careful attention has been paid to the spatial and temporal consistency between the observations and the model results. Satellite observations of optical thickness and the model show a closely similar latitudinal shift and change of the aerosol plume extent from month to month over 3 years. This is explained by the dominant role of the large-scale transport, well described by the European Centre for Medium-Range Weather Forecasts winds, a sufficiently consistent description of aerosol physics along with a detailed prognostic source function. A feature not captured perfectly by the model is the winter maximum in observed optical depth, which is south of the satellite observation window. This underestimate in the very southern tropical region in winter suggests that additional aerosol sources become important, such as Sahelian dust and carbonaceous aerosols from biomass burning, not included in our simulation. However, spring and autumn simulated optical thickness is 50% less than that observed, while it is only 30% less in summer and winter. This is found for both the subtropical and the tropical Atlantic Ocean, which points to a general underestimate by the model, not just because of aerosol sources missing in the Sahel region. Another seasonal feature is discussed for Sal Island where measurements suggest that low-level dust transport in winter is replaced by a pronounced high-level Saharan dust layer in summer. The model reproduces this pattern except that there is also significant low level transport in summer, associated mainly with peculiar simulated dust transport events from the western Sahara. On a synoptic scale the frequency of dust outbreaks over the North Atlantic and of major dust deposition events in Spain and a dust vertical profile measured by a lidar over the Azores region are reproduced by the model.

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1. Introduction

Determination of the climatic impact of mineral aerosol requires the knowledge of their spatial and temporal distribution, together with their chemical composition and size distribution [*Tegen and Lacis*, 1996; *Claquin et al.*, 1998]. Data retrieval from satellites can be used to estimate the column abundance of aerosol over oceans. However, the aerosol loads over land, the size distribution of the particles, and the altitude at which aerosols are transported have so far not been obtained with sufficient temporal and spatial coverage using passive remote sensing. This complete set of information can only be derived from global models at this point.

Aerosol models have thus been developed to investigate the global distribution of aerosol components, and they provide a means for studying the interactions be-

tween aerosols and climate. Such models require an accurate description of (1) the aerosol sources, (2) the meteorology, and (3) the atmospheric cycle of aerosols. Up to now, few simulations of mineral aerosol have been carried out on a global scale [*Joussaume*, 1990; *Genthon*, 1992; *Tegen and Fung*, 1994; *Dentener et al.*, 1996; *Tegen and Miller*, 1998].

Following the work of *Schütz* [1979], *Lee* [1983], *Westphal et al.* [1988], *Ellis and Merrill* [1995], and *Ničović and Dobričić* [1996], we examined the processes that govern the long-range transport of mineral dust and the influence of the size distribution during transport. We have developed a parameterization of the atmospheric aerosol cycle for inclusion in an "off-line" three-dimensional atmospheric transport model. It includes a description of the main processes responsible for the transport and deposition of aerosols, namely, gravitational settling, removal by precipitation, and evolution of the aerosol size distribution away from the source [*Schulz et al.*, 1998; *Guelle et al.*, 1998a].

We focus this paper on a validation of a multiyear simulation of Saharan dust. We use an advanced prognostic parameterization of the desert dust uplift which presents the advantage of having previously been validated independently [*Marticorena and Bergametti*, 1995; *Marticorena et al.*, 1997]. Concurrently, atmospheric circulation is prescribed starting from the analyzed fields from the European Centre for Medium-Range Weather Forecasts (ECMWF). In this way, our parameterization of the aerosol physics should be mainly responsible for any deficiencies in our simulation. However, any discrepancies found by comparison with observations might still require a review of the quality of the meteorological fields and the source description.

A challenge in the validation of simulated mineral aerosol distributions stems from the sporadic nature of desert dust events. Indeed, these episodes are responsible for most of the atmospheric dust load produced by a desert area. It is therefore important not to confine the validation procedure to yearly or seasonally averaged measurements. We have compared our simulations of Saharan dust to relevant long-term observations. These observations include concentration and deposition measurements at the surface and dust optical depths which provide information on the integrated atmospheric column loading. Some of these measurements integrate several aerosol components such as Sahelian dust and carbonaceous aerosols, which are not included in our simulation. The discussion on the model versus observations comparison therefore has to take into account the possible interference of such aerosols.

This paper is organized as follows: section 2 and section 3 describe the atmospheric model and the data sets used in the comparison, respectively. Section 4 presents the results, and section 5 includes the discussion and conclusions that can be drawn from this comparison.

2. Model Description

The model used in this study is the off-line transport model TM2z [*Heimann*, 1995; *Ramonet*, 1994], in which *Schulz et al.* [1998] have included a module to

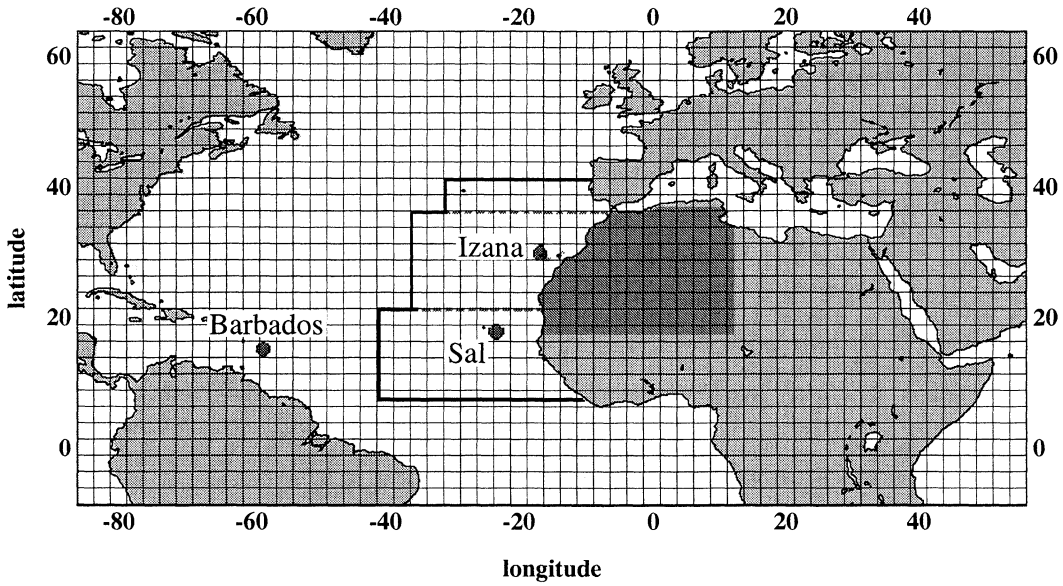


Figure 1. Simulation domain and location of the available measurements over Africa and the North Atlantic. The grid depicts the model resolution; the dark area over Africa indicates the source region used in this study. We have indicated the three Atlantic stations where daily long-term measurements of Al have been carried out. The Atlantic region limited by the bold solid line and the western coast of Africa indicates the Meteosat window for which satellite-derived dust optical depth remains accurate. This region has been partitioned into three regions (delimited by the bold dashed lines). In the remainder of the text, we call the subtropical region the area including Izaña and tropical region the area including Sal Island.

describe some of the aerosol physics, namely, the treatment of the size distribution evolution and a sedimentation scheme as well as diagnostic computations such as the computation of dust optical thickness. The model has a horizontal resolution of $2.5° \times 2.5°$ and a vertical resolution of 9 sigma levels (mean pressure levels: 959, 894, 797, 635, 470, 323, 202, 110, and 40 mbar). The input of the model consists of ECMWF-analyzed 12-hourly fields which permit a realistic description of the meteorology.

The main process responsible for large aerosol removal far from the source regions is scavenging by precipitation. To account for this process, we have included in the model a parameterization of wet deposition of aerosols by both convective and synoptic rains, accounting for the size-dependent aerosol removal below the cloud base [*Guelle et al.*, 1998a]. This parameterization has been validated through a comparison between observations and simulations of ^{210}Pb aerosol [*Guelle et al.*, 1998a, b].

For the source formulation we have used the model developed by *Marticorena and Bergametti* [1995] which takes into account both the size of the erodible loose particles and the surface roughness lengths of the soil to determine the threshold wind friction velocities and then the horizontal flux of dust particles. The vertical flux is then determined according to clay content of the soil. It has been validated for the large source area described in Figure 1 through the use of infrared satellite imagery [*Marticorena et al.*, 1997], and it has been shown to reproduce dust event frequencies better than the more simple formulations previously used in global mineral aerosol simulations [*Marticorena et al.*, 1999]. The dust source fluxes have been calculated off-line apart from the transport model from 6- hourly ECMWF fields of wind speed at 10 m in a $1° \times 1°$ horizontal resolution and have then been regridded onto the TM2z grid.

In this work we use the spectral scheme developed by *Schulz et al.* [1998] to compute the aerosol mass and number. We initially impose a size distribution for the dust that is representative of the material injected in the atmosphere over source regions. This distribution is made up of three lognormal modes [*Shettle*, 1984], and the most important of them has its mass median diameter at 2.5 μm. The initial geometric standard deviation of 3.2 [*Shettle*, 1984] has been reduced to 2.0 according to recent observations and sensitivity studies [*Balkanski et al.*, 1996; *Schulz et al.*, 1998]. After injection into the atmosphere, the dust size distribution evolves and is computed for each grid box of the model and at every time step. We therefore keep track of mass and number concentrations in both space and time.

We now have a transport model of mineral aerosol for which all major processes relative to the source and sinks have been independently validated. This reduces the chances of compensatory effects between the different parameterizations that could bias the results.

3. Data sets and Methods

Model simulations were conducted for 3 years from 1990 to 1992, and we compared the results to long-time series of measurements we could access for the corresponding period.

3.1. Satellite-Derived Optical Depths

In order to compare Meteosat-retrieved optical depths [*Moulin et al.*, 1997a, b] to the modeled ones, satellite pixels were first regridded onto the TM2z grid and then averaged over each model $2.5° \times 2.5°$ grid square. We indicate in Figure 1 the validity limits of the Meteosat window used for comparison with model output. When over 80% of the Meteosat pixels are covered by clouds, neither the satellite data nor model values of optical depth for the corresponding grid boxes are considered representative, and thus they are not retained for further analysis [*Schulz et al.*, 1998].

As the model computes both the aerosol mass and the aerosol number concentrations with the spectral scheme, the computation of the model optical depth is done in the following way: for each grid box, the specific extinction cross section at 550 nm ($\sigma^{\star}_{550}$) is extracted from a pretabulated matrix. The entries in this matrix are the mass median diameter and the standard deviation of the size distribution. The computation of $\sigma^{\star}_{550}$ was done following Mie theory for mineral aerosol particles of density 2.65 g m^{-3} with a refractive index of 1.5-0.01i [*Ignatov et al.*, 1995; *Moulin et al.*, 1997b].

The contribution of sulfate aerosols to the observed total optical depth was retrieved by using sulfate concentrations from the MOGUNTIA model [*Langner and Rodhe*, 1991], with values ranging between 0.02 and 0.04 [*Moulin et al.*, 1997a]. Uncertainties in the sulfate fields do not prevent us from deriving a reasonable optical depth because sulfate is a small to very small component compared with mineral dust or carbonaceous aerosols over our study region [*Li et al.*, 1996; *Chiapello et al.*, 1999]. Moreover, the quantitative comparison of optical depths in this paper is done for January 1990 to June 1991 to eliminate uncertainties due to contributions from the Mount Pinatubo aerosol to the observed signal.

Sea salt and carbonaceous aerosols also influence the observed optical depth. Even though the sea salt mass relative to other aerosol components is substantial, the sea salt contribution to the optical depth is thought to be weak, with a mean and maximum value of 6% and 20%, respectively, observed at Sal [*Chiapello et al.*, 1999]. In fact, the bulk of sea salt mass is in large particles whose concentrations decrease sharply with altitude [*Blanchard and Woodcock*, 1980].

In comparison with sea salt, the mass of carbonaceous aerosol is small, but its contribution to the optical depth is more important owing to scattering properties of these particles. *Chiapello et al.* [1999] found a mean and maximum contribution to total optical depth

of 12% and 39%, respectively. Since these two aerosol types are not accounted for in the satellite dust optical depth retrieval algorithm, the model including only mineral dust is likely to underestimate the observed aerosol optical depths (AOD).

Finally, when we present seasonally or monthly averaged optical depths, we retain model output only for the days when a measurement has been reported as valid. In particular, we screen the model output to exclude on any given day all those locations where clouds appear on the Meteosat picture. This filtering procedure ensures that the analyzed satellite picture and the model output are fully consistent in time and in space.

Satellites do not yet provide accurate quantitative information on the dust loading over the continents. This is the reason why some networks of ground-based Sun photometers have recently been developed, such as the North African one [*D'Almeida*, 1987] and the worldwide AERONET network [*Holben et al.*, 1998]. Unfortunately, these measurements were carried out mainly in the early 1980s, have been reinstalled in the late 1990s, and do not match our simulation period.

3.2. Aerosol Ground Concentrations

3.2.1. Atlantic sites. Aerosol data from ground stations at three islands were used for the comparative studies because dust concentrations are available for those sites over periods of several to many years. These sites are the Spanish Meteorological Observatory on Izaña (Tenerife, 28.3°N, 16.5°W), Sal Island (Cape Verde, 16.7°N, 22.9°W), and Ragged Point (Barbados, 13.2°N, 59.4°W) (see Figure 1).

Comparable sets of measurements also have been made at Bermuda and Mace Head (Ireland) [*Arimoto et al.*, 1995], but the influence of dust is much less pronounced at those sites, and therefore we did not study them in depth. Furthermore, the altitudes of the three sites used for the comparisons are well suited for studies of the transport of dust out of Africa. The Izaña observatory is at an elevation of 2360 m above sea level, which ensures that free tropospheric air is sampled most of the time at this site, and the two other sites are situated close to sea level. Hence we are able to determine whether the model can capture the differences in transport between the surface and free tropospheric layers.

Model level 3 spans 1.2 to 2.6 km and encompasses the height of the Izaña observatory. Since Tenerife, the island on which Izaña is located, is small in relation to the surface area of the model column, its topography does not influence the flow in the lowest sigma levels of the model. Hence we compared measurements at Izaña with the mean concentration for model level 3.

Another important aspect of this comparison is the latitude and the distance of the sites from the Saharan sources, i.e., Izaña and Sal Island are situated a few hundred kilometers from the nearest source regions, but at different latitudes, whereas Barbados is located ~5000 km downwind from these sources. Barbados is ideally situated for studies of the long-range transport of the dust, and in fact that site has been the focal point for dust studies dating back to the mid-1960s [*Prospero and Carlson*, 1980].

Izaña is likely less influenced than Sal Island by low-latitude source regions. The northeast trade winds prevent dust from reaching the Canary Islands in winter. *Coudé-Gaussen et al.* [1987] have characterized the Moroccan sources as being responsible for the dust observed over the Canaries in spring. *Bergametti et al.* [1989] indicate that dust in the summer also comes from the Gao region, which is included in our source model. More southern source regions not included in our source description (Sahel and sub-Sahel) are less active in summer owing to precipitation which stimulates vegetation growth and inhibits dust deflation. However, these source regions should influence winter dust concentrations at Sal Island. Finally, we note that Barbados is known for major dust transport during the summer, which is when the sources from the sub-Saharan region are rather inactive.

At all three sites (Izaña, Sal, and Barbados), aerosols were sampled daily on bulk filters that efficiently collect particles below 10-μm diameter. Samples were then analyzed by instrumental neutron activation (*Arimoto et al.* [1995] for Izaña and Barbados) or by X ray fluorescence spectrometry (*Chiapello et al.* [1997] for Sal) to determine elemental concentrations. The error in these determinations is estimated to be ~10%, mainly due to uncertainties in flow volumes.

Mineral aerosol concentrations are not measured directly; rather, it is the aerosol aluminum concentration, an excellent tracer for mineral dust, that is determined. Different minerals in soils vary in Al mass content, the lowest values reported being 6% for Sahelian soils [*Herrmann*, 1996], and the richest soil in aluminum contained over 10% Al [*Gomes*, 1990]. *Schütz and Rahn* [1982] have shown that for relatively small size particles (diameter of <20 μm) the variations of aluminum content were much less than those for larger particles. As the simulated size range is centered around 2.5 μm, we adopted the global mean Al content in mineral dust of 8% compiled by *Taylor and McLennan* [1985] in our model comparisons.

Concentration measurements were started on a continuous basis since the late 1960s at Barbados, since April 1989 at Izaña, and lasted with interruptions from December 1991 to December 1994 at Sal. Hence we are able to compare observations and model results for the 3 years of the simulation at Izaña and Barbados and from December 1991 through August 1992 at Sal. Some daily values are missing either because the concentrations were below the detection limit or because of problems with the sampling equipment or bad weather. However, a large number of daily measurements exist for this 3-year period: 491 measurements

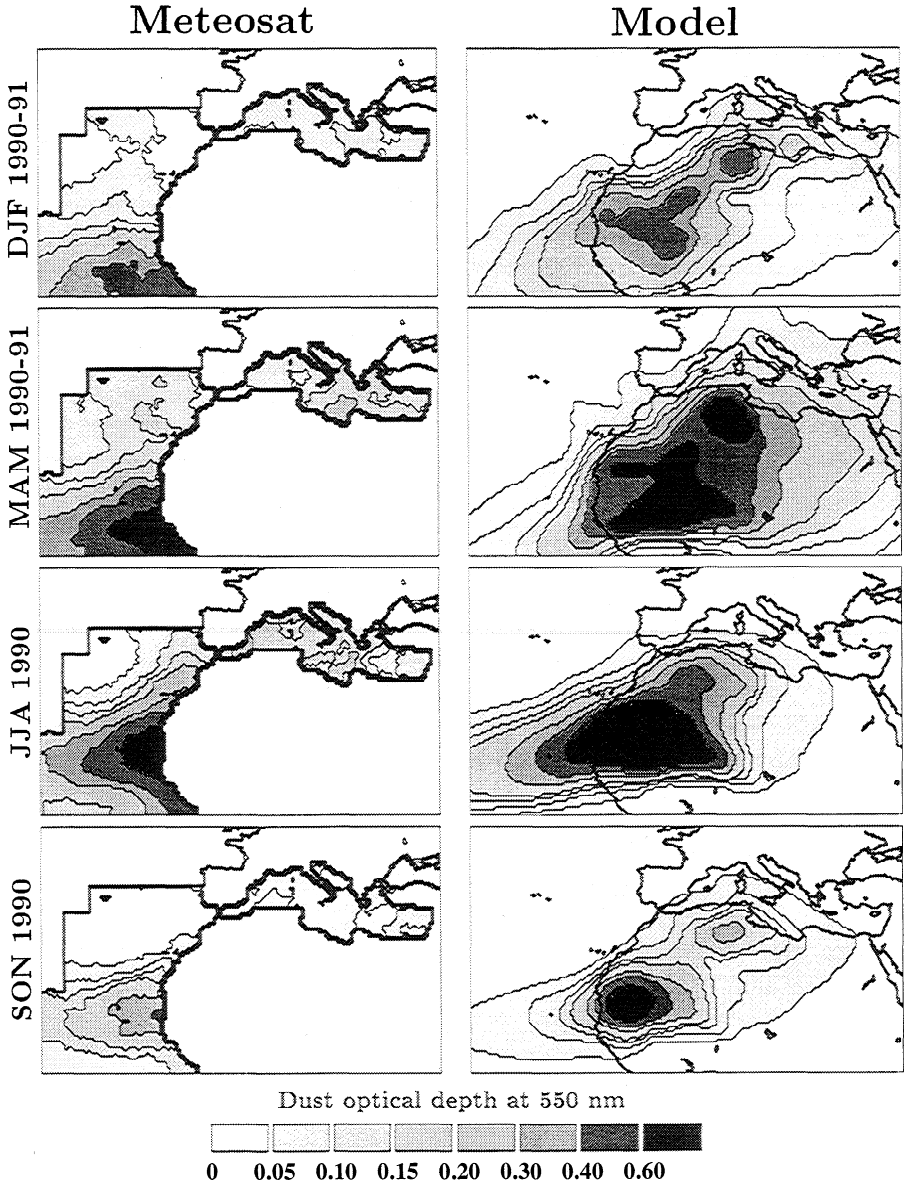


Figure 2. Seasonally averaged dust optical depths at 550 nm measured with Meteosat (left column) and simulated by the model (right column) for the pre-Pinatubo period January 1990 - June 1991. DJF: December, January, February. MAM: March, April, May. JJA: June, July, August. SON: September, October, November.

were made at Izaña, 935 measurements were made at Barbados, and 199 measurements are reported for Sal Island. Model results are averaged only for those days with valid observations.

3.2.2. North American sites. Numerous ground stations measuring aerosol concentration have been developed over the United States in the Interagency Monitoring of Protected Visual Environments (IMPROVE) network. Daily aerosol samples are performed twice a week in order to collect particles with diameters of less than 2.5 μm ($PM_{2.5}$) and particles with diameters of less than 10 μm (PM_{10}). Elemental composition of these particles is determined by using a combination of X ray fluorescence and Proton-Induced X ray Emission, allowing us to retrieve soil dust concentrations from Al, Ca, Fe, Si, and Ti contents [*Malm et al.*, 1994].

Perry et al. [1997] have determined the occurrence of North African dust over the United States from these data. Six years of data were analyzed over the Virgin Islands, which are known to be affected by African dust. The analysis criteria distinguished between North African soil dust and local soil dust. The first of these two criteria is a minimum threshold of 3 $\mu g\,m^{-3}$ on the $PM_{2.5}$ concentration, and the second is a minimum Al/Ca ratio of 3.8. If both of these criteria are reached at a given station, the dust is considered to be of North African origin.

Perry et al. [1997] have applied these criteria to all

the IMPROVE network measurements in order to study the occurrence and spread of African dust events over the United States. These data are useful for studying the long-range transport of mineral aerosol over the North Atlantic. Whereas the Barbados station provides data over a long-time period at a single point, the IMPROVE network provides data on the large-scale spread of the African dust plumes over an extended remote area. To simulate such transport is a rigid test on a synoptic scale of model assumptions on removal and dispersion.

4. Results and Discussion

4.1. Seasonal Pattern of Dust Transport

4.1.1. Large-scale extent of the dust plume. Seasonally averaged aerosol optical depths from Meteosat and from the model are presented in Figure 2. For a quantitative comparison we have averaged in Table 1 the AOD in two regions, the subtropical Atlantic region centered around Izaña and the tropical region around Sal Island.

The AODs derived from Meteosat show several salient features with respect to dust [*Moulin et al.*, 1997c]. Mean optical depths greater than 0.5 extend over a large region offshore of West Africa. The maximum AODs are observed in spring and summer, whereas AODs reach their minimum value in the fall period and are noticeably lower in winter. Another particular feature of the mineral aerosol transport over the North Atlantic consists in a marked latitudinal shift of the dust plume.

Strong spatial gradients in AOD can be observed which mark the position of the plume. Despite the fact that the model underpredicts the observed AOD and that the simulation plume has a slightly different shape, it reproduces these gradients well (Figure 2). The reproduction of the gradients indicates that the dispersion and removal of mineral dust are well described in the model. We would like to stress that the choice of source formulation, aerosol physics, transport conditions, and satellite data retrieval has been done very much independent from each other. Considering that all these choices may influence the deviation of simulated from observed AOD, we find the underprediction of seasonal AOD of up to 50% (Table 1) to be small.

Table 1. Seasonal Average (January 1990 - June 1991) of Observed and Modeled Aerosol Optical Depth in the Marine Cloud-Free Area for Two Regions and Deviations per Season and Region of the Simulation From Satellite Observation.

	Season			
	Winter (DJF)	Spring (MAM)	Summer (JJA)	Fall (SON)
	Subtropical Region			
$AOD_{meteosat}$	0.088	0.159	0.172	0.090
AOD_{model}	0.089	0.085	0.128	0.053
$\frac{AOD_{model}}{AOD_{meteosat}}$, %	101	53	74	59
	Tropical Region			
$AOD_{meteosat}$	0.312	0.469	0.402	0.261
AOD_{model}	0.222	0.246	0.275	0.144
$\frac{AOD_{model}}{AOD_{meteosat}}$, %	71	52	68	55

See Figure 1 for a description of the regions.

The seasonal differences in the shape of the plume and the latitudinal shift are associated with a seasonal migration of the main sources and a change in the atmospheric circulation. This is due to the different circulation system occurring over Africa between summer and winter periods. We have plotted in Figure 3 the mean circulation for the four seasons, both at the surface (first model layer) and in altitude (fourth model layer). We see that in winter and spring, northeasterly winds dominate over a large part of the western Sahara and Sahel, bringing dust far enough south, which penetrates Atlantic air at very low latitudes.

On the other hand, westerly summer surface winds prevent African dust transport toward the Atlantic, which should occur mainly in altitudes above the trade wind inversion in the Saharan Air Layer. We see that the corresponding winds have strong east-west components, which explains why the dust stays at higher latitudes in summer. The model reproduces well the mean position of the plume in summer and fall and with less accuracy the southward transferred aerosol plume in spring and winter.

The remaining discrepancies between simulated and observed dust plume extent might be grouped in three problems based on the seasonally averaged comparison: (1) especially in winter the model misses the very southern part of the aerosol plume (Figure 2); (2) however, the largest absolute AOD differences are found in spring and autumn (Table 1); and (3) finally, in spring and summer observed AODs in the small region of the Atlantic Ocean close to the western Sahara (ex-Spanish Sahara) are smaller than simulated AODs.

In the tropical region, three distinct contributions to the optical depths are expected over the Atlantic: mineral aerosol produced over the Sahara, mineral aerosol produced in the Sahel zone, which is bordering the Sahara between 16°N and 17°N [*Milich and Weiss*, 1997], and carbonaceous aerosols produced from biomass burning and domestic fires over savanna regions, of which the northern border may reach 15°N [*Cooke et al.*, 1996]. Whereas Saharan dust is permanently produced during the year, the last two components have a marked seasonality. The burning season coincides with the driest months (from November through March) over the sub-Saharan region with a south-to-north migration during that period. Dust emissions from the Sahel peak from January to May and are much less abundant the rest of the year, while biomass burning occurs in the

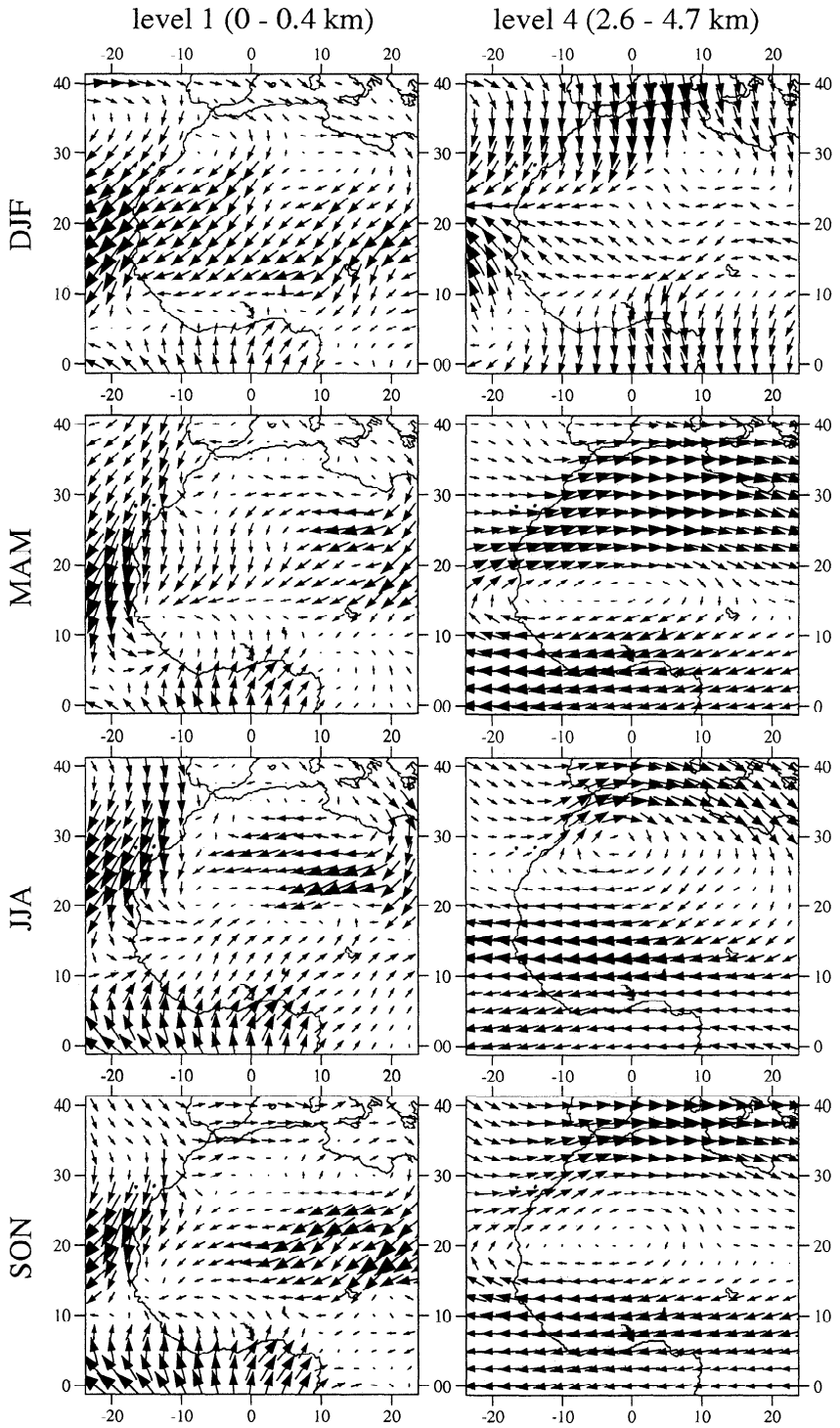


Figure 3. Mean seasonal circulation over West Africa according to ECMWF wind fields at the surface (0-400 m, left column) and in altitude (2.6-4.7 km, right column).

region from November to March. This seasonality of the aerosol over the sub-Saharan region has been evidenced from data of visibility measured at several stations by *N'Tchayi Mbourou et al.* [1997].

Assuming significant influences from sources of Sahelian areas and biomass burning, which are not included in the model, one would expect the model to underestimate optical depths over latitudes downwind of the Sahel region. This is exactly what Figure 2 shows. On the other hand, as the Sahel and biomass burning contributions are weak in summer, we find improved agreement between the observed and simulated optical depths for that season. But even so there is a noticeable contribution from the source formulation used in our model (Figure 2) to low-latitude AOD.

Furthermore, the simulated deviation in AOD from

observed values (Table 1) does not fully support the hypothesis that the discrepancies are mainly due to missing aerosols from biomass burning and Sahelian dust uplifting: (1) the largest deviations are not in winter, but rather in spring and autumn, and (2) the deviations in spring, summer, and autumn are not larger in the tropical than in the subtropical areas. Only in winter do the deviations in the two regions differ, supporting the hypothesis that there is some other aerosol missing in the model. In conclusion, if one would like to bring the model in closer agreement with the absolute values of AOD, one would need to increase the overall transport of dust also from the Sahara.

The local discrepancy close to the western Sahara might suggest a local source in the model to be overestimated. However, as will be pointed out later, it might also be due to local meteorological phenomena in this coastal region, which are not well captured either by the ECMWF fields or by the transport model.

4.1.2. Position of the plume and its seasonal variation. The strong latitudinal shift of the dust plume mentioned above is largely due to the position of the intertropical convergence zone (ITCZ), which is displaced to the south during the Northern Hemisphere winter compared with its summertime position [*Barry and Chorley*, 1987, p. 277]. We examine in this section the ability of the model to reproduce quantitatively this seasonal migration, a feature which has always been poorly resolved by general circulation models [*Joussaume*, 1990; *Tegen and Fung*, 1995]. To pinpoint the position of the plume in a quantitative way, the mean optical depth from Meteosat and from the model were averaged zonally by month over the Meteosat window depicted in Figure 1. From these two data sets we compute the latitude where the optical depth was at a maximum over the selected region.

Figure 4 shows the position of the optical depth maxima for the 3 years of the simulation for all seasons except winter. The winter months are not shown for the following reasons: first, it is when the observed maxima are very often located below the southern limit of the Meteosat window; second, the winter aerosol plume is clearly affected by two other aerosol contributors that we have not modeled at this point, the Sahelian and the carbonaceous aerosols.

For the other months, the latitude of the plume maximum is well represented. For most of the months shown, the model reproduces the position of the plume to better than ±2°. A closer inspection revealed that this simulated latitudinal shift is not due to a corresponding shift in location of our model source, but rather it is due to an accurate description of the atmospheric circulation in ECMWF fields. The high seasonal amplitude of the latitudinal shift is closely tracked by the model. Positions of the maxima as far south as 10°N in spring and fall are captured by the model despite the southern limit of our source description at 16°N. Even the interannual shift of the position of the AOD maximum from 20.5°N in August 1990 to ~18°N in August 1991 and 1992 is well captured.

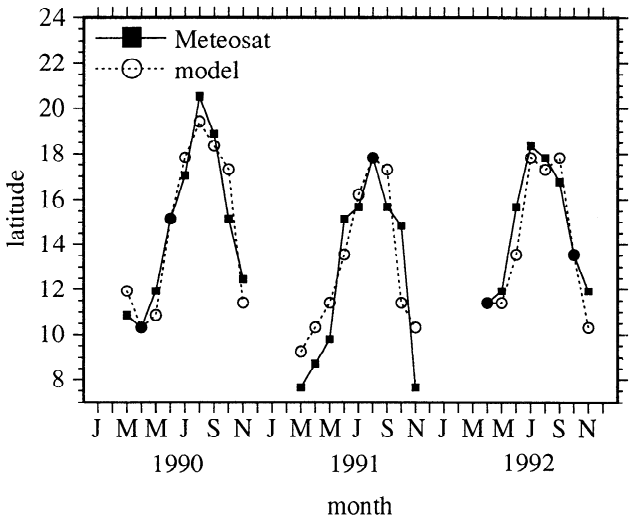


Figure 4. Monthly position in latitude (degrees) for the nonwinter months of the 3 years of simulation of the maximum in zonally averaged dust optical depth as determined from Meteosat imagery and predicted by the model over the Meteosat window described in Figure 1.

4.2. Monthly Variations of Mineral Dust Concentrations

Of equal interest is whether the model reproduces accurately the seasonal variations of aerosols observed at ground stations. We present in Figure 5 the monthly variations of Al concentrations at the three sites where long-term measurements of aluminum exist. In Figure 6 we also present the optical depths at Sal and Izaña, which are located in the Meteosat window.

We note here that for a comparison with observations on shorter time scales the presence of other types of aerosols might become more important. It can be seen from daily satellite-derived data that a background in AOD is present over the Atlantic region throughout the year. This is consistent with the analysis made at Sal Island in winter by *Chiapello et al.* [1999] which showed that for low AODs, carbonaceous aerosols, sea salt, and sulfate gain importance. Although the contribution of sulfates has been subtracted [*Moulin et al.*, 1997b], Meteosat-derived AODs include mineral aerosol together with carbonaceous matter and sea salt contributions. These aerosols produce a mean background of 0.03 in optical depth at 670 nm at Sal in winter [*Chiapello et al.*, 1999]. Hence for the purpose of comparison we have added a constant optical depth of 0.03 to the simulated values in all the figures presented from now on. This value of 0.03 may not reflect the aerosol background over the subtropical region, which is less influenced by carbonaceous aerosols but which experiences greater sea salt concentrations during the year (S.

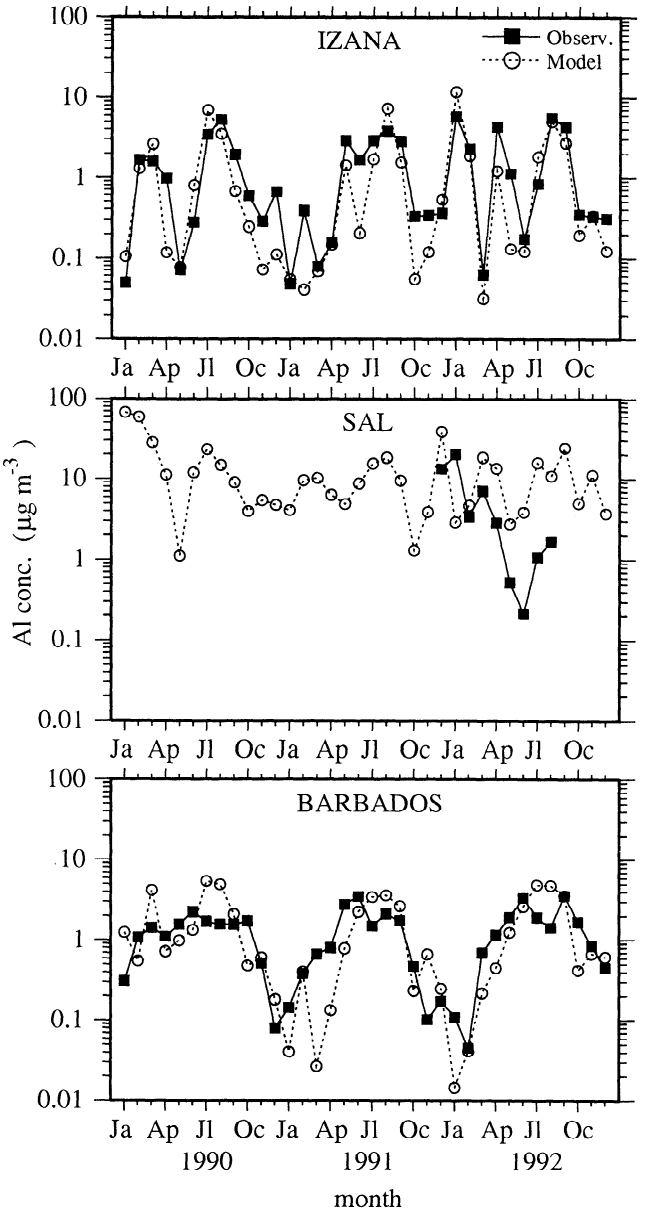


Figure 5. Comparison between monthly Al concentrations (in micrograms per cubic meter) observed and simulated at the three Atlantic stations for the 3 years of simulation.

L. Gong, personal communication, 1998). However, this is the only estimate of the different contributions to the total aerosol over this region of which we are aware.

The observed seasonal variation of surface Al concentrations is well reproduced both at Barbados and Izaña, although both stations show quite different patterns of dust fluctuations from month to month. At the altitude of Izaña the maximum Al concentrations are predicted to within a factor of 2. The fewer surface concentration data from Sal suggest an overestimate of surface concentrations by the model in Sal in summer. We defer discussion of this feature to the next section.

Both the seasonal variation and the amplitude of the AOD at Izaña and Sal Island are sufficiently reproduced. However, discrepancies show up especially for the spring months both in Sal and Izaña. The discrepancy between model and simulation at Izaña seems to be larger for the AOD than for surface Al concentrations. While AOD is constantly underpredicted from March to June in both years, simulated Al concentrations scatter around observed values. This would be consistent with the idea that light extinction is also due to other types of aerosol than just dust simulated here. An analysis of the daily Meteosat images in the 30×30 km resolution revealed that most of the mean spring AOD results from a permanent aerosol background (the minimum value of daily Meteosat AODs is 0.1 from April to June 1991 at Izaña) together with some small-scale puff events (see, e.g., Figures 3a and 3b of *Coudé-Gaussen et al.* [1987]) which cannot be resolved at the model resolution. We cannot determine the nature of this background aerosol, which could be both anthropogenic and/or long-range transported dust.

4.3. Vertical Distribution of Mineral Dust

Though important for radiative calculations, it is difficult to validate the vertical distribution of mineral

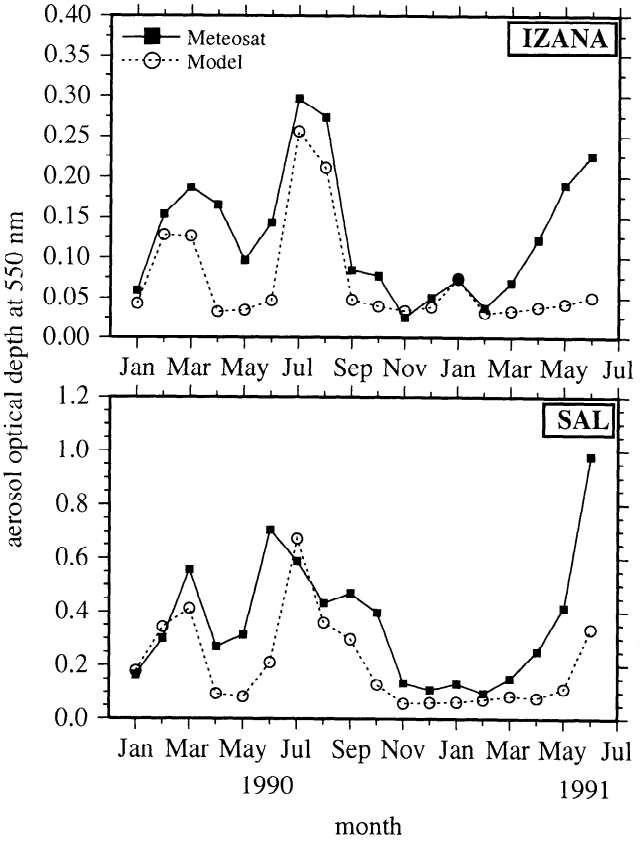


Figure 6. Comparison between monthly aerosol optical depths at 550 nm observed by Meteosat and simulated over Izaña and Sal for the pre-Pinatubo period of simulation (January 1990 - June 1991). The modeled optical depths have been increased by a background value of 0.03.

aerosol simulated by the model since very few measurements exist. Several arguments support the hypothesis that the model simulates dust transport correctly from lower to elevated layers. First, there is agreement between the observed and simulated Al concentrations at Izaña's free troposphere measurement site. Second, sensitivity studies by *Schulz et al.* [1998], who used an earlier model version, showed that long-range transport can only be reproduced if the convection scheme correctly injects dust into higher altitudes. Third, Figure 2 together with Figure 3 shows that the important dust export in summer is correlated to easterly winds at higher altitudes. Finally, as will be discussed below, we demonstrate on a synoptic scale agreement with a lidar measurement of a dust vertical profile near the Azores, which showed an elevated dust layer.

Low-level transport is more likely effected by local sources and mesoscale transport patterns. The analysis made at Sal by *Chiapello et al.* [1995] is based on surface concentration data. It suggests that a transport in the lowest layers of the atmosphere happens just in winter, whereas in summer numerous earlier studies showed a transport in the dry Saharan air layer above the trade wind inversion [e.g., *Prospero and Carlson*, 1980]. Comparison with the Al concentrations at Sal in Figure 5 suggests that the model reproduces the near-ground transport in wintertime. However, while the summertime AOD is slightly underestimated, the summer surface concentrations are considerably overestimated.

The seasonal evolution of the profile seems to miss one component, the absence of dust at the surface in summer. A possible explanation is illustrated with Figure 7, which shows the predicted vertical profiles of Al

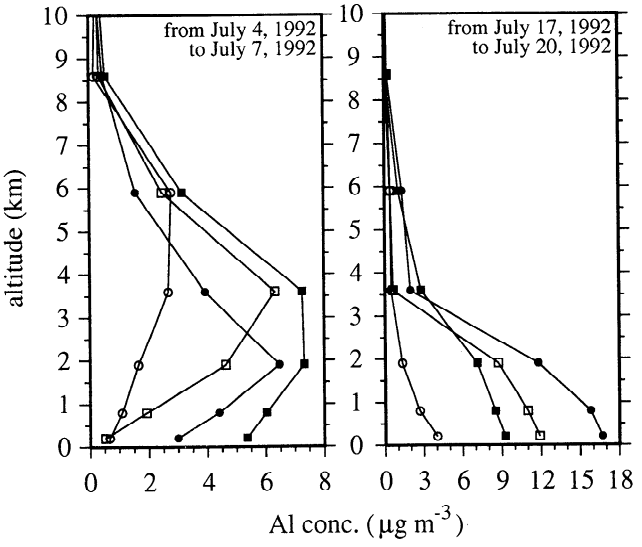


Figure 7. Vertical profiles of Al concentrations (in micrograms per cubic meter) simulated in 1992 for (left) 4 consecutive days during a first dust event from July 4 to July 7 and (right) 4 consecutive days during a second dust event from July 17 to July 20.

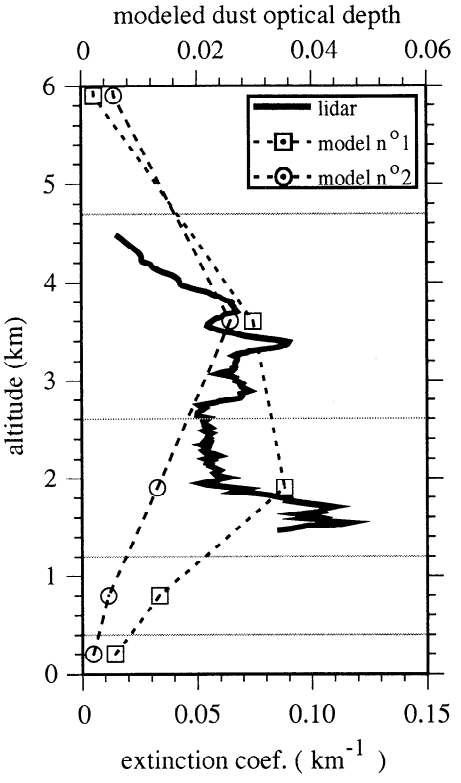


Figure 8. Comparison between the vertical profile of extinction coefficient (km^{-1}) measured by the lidar on June 17, 1992, at coordinates 35.6°N, 23.8°W and the vertical profiles of optical depth simulated the same day for the corresponding model column (profile 1), and for the column located 2.5° to the north (profile 2). The lidar data have not been plotted below 1.4 km because of the presence of a stratocumulus layer. The horizontal dotted lines indicate the borders of the vertical model layers.

concentration at Sal Island for 4 consecutive days of two distinct dust events in July 1992. The first event (left panel) has its origin in two source regions located in Mauritania and Mali, approximately at the same latitude as Sal Island. We see that the model transports most of the mineral aerosol at an altitude between 1 and 5 km, in agreement with some lidar observations made over the Atlantic in summer (see, e.g., *Talbot et al.* [1986], *Swap et al.* [1992], *Karyampudi et al.* [1999]).

The source of the second dust episode (right panel of Figure 7) is located in the western Sahara. We see this time a transport in the low layers of the atmosphere. This is due to the surface winds generated by the Azores High which entrain the dust produced over this region toward Sal Island. Therefore the reasons for the overestimate of summer surface concentrations at Sal resulting from such western Sahara dust episodes are either an overestimate of dust erosion in this region or a misrepresentation by the model of the transport above the marine boundary layer. We have already mentioned above that the western Sahara seems to be responsible for a simulated local discrepancy to Meteosat observed AOD over the adjacent coastal At-

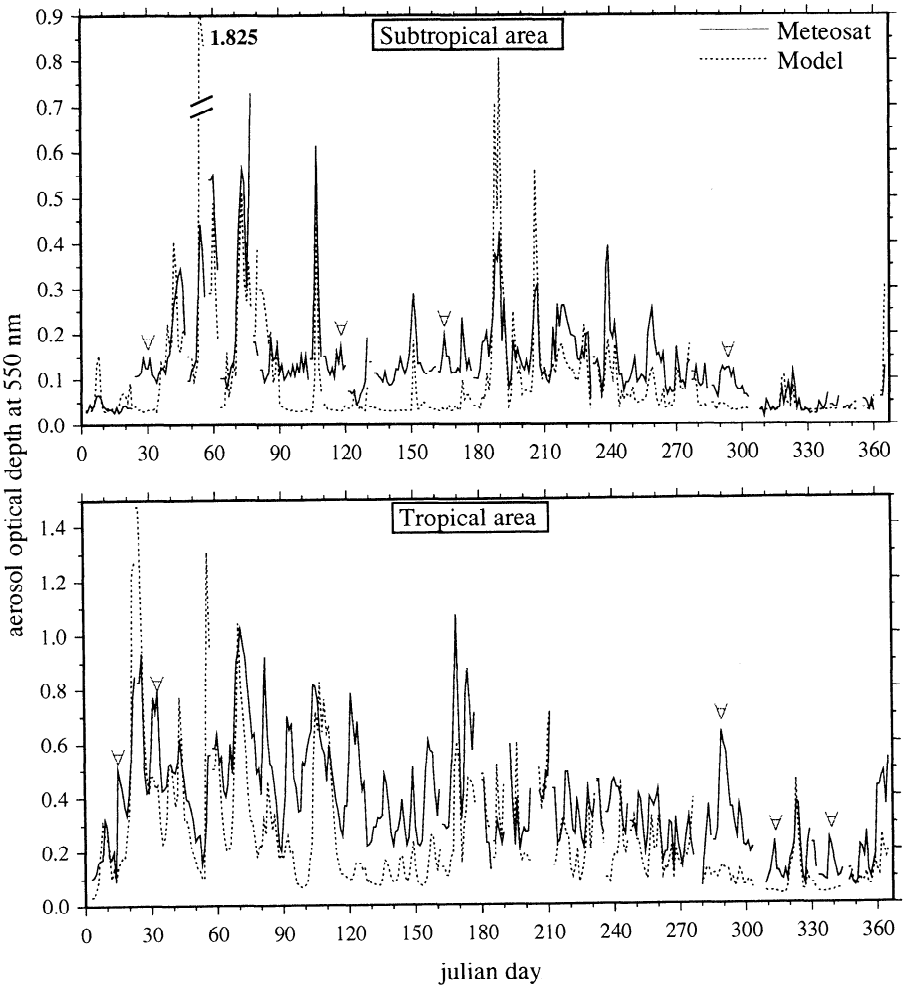


Figure 9. Comparison between observed (Meteosat) and modeled daily values of aerosol optical depths at 550 nm averaged over the subtropical and tropical regions (as defined in Figure 1) for year 1990. The modeled optical depths represent simulated dust optical depths raised with a background value of 0.03. The symbols highlight observed peak values which are not or are weakly simulated by the model.

lantic regions. Whether this is a transport or source problem could not be resolved with TM2z owing to its poor vertical resolution.

The only dust vertical profile measured between 1990 and 1992 over the Atlantic that we are aware of has been done during the SOFIA/ASTEX campaign over the Azores on June, 17, 1992 [*Chazette et al.*, 1997]. This corresponds to a dust event the origin of which has been traced to Morocco on June 13 by back trajectories. The model simulates this dust event, starting from Morocco, spreading northward toward the Mediterranean, where it is deviated toward the Atlantic by a low located over Gibraltar, to reach the Azores region on June 17. The AOD simulated by the model near the Azores is 0.1, in exact agreement with the Meteosat-derived value for that area.

We have plotted in Figure 8 the vertical profile of the extinction coefficient measured by the lidar at 35.6°N, 23.8°W together with the simulated vertical profile of AOD at 550 nm for the corresponding grid box (profile 1) and as a sensitivity test for the grid box 2.5° to the north. The lidar profile shows a group of thin dust layers between 2.6 and 4 km and another below 1.8-km altitude. Profile 1 shows that the model reproduces a maximum AOD in the two model levels including these observed dust layers. Moreover, the predicted profile simulated 2.5° to the north (profile 2) reproduces a maximum AOD only in the fourth model layer, indicating a considerable change in vertical profile just one grid box apart. A balloon radio sounding was done on the measurement site (P. Chazette, personal communication, 1999) which revealed that the lower dust is at an altitude where easterly winds prevailed, whereas the highest dust is at an altitude with southerly winds. The difference between the two modeled profiles thus indicates that the model reproduces the shear between the two air masses carrying dust to the measurement point on slightly different trajectories.

4.4. Daily Representation of the Dust Modeling

Since dust events are sporadic in nature, long-time series are required to characterize the transport to a particular location. To compare episodes simulated by the model with Meteosat observations, we averaged the daily observed and simulated AODs over the subtropical and tropical regions. The results are presented in Figure 9.

Most of the sporadic dust events are captured by the simulation even though the amplitudes of the simulated events often are less than those observed. One can discern from Figure 9 that strong dust transport events over the subtropical zone often are reproduced with more accuracy than the small events. As was mentioned above, an aerosol background appears to become important in spring and is partly responsible for the underestimate. However, the agreement existing on a daily scale indicates that the prognostic source used in the model is correct in the timing of most of the dust uplift over Africa and, furthermore, that the meteorological fields from the ECMWF closely track the meteorological situation present.

Those events that were detected by Meteosat but not simulated by the model at all are indicated in Figure 9. These peaks were analyzed individually through a careful examination of daily satellite images in the visible channel. For the subtropical zone, these relatively small peaks are either the result of artifacts from the cloud detection algorithm or are caused by patchy aerosol clouds. For the 28 clear dust events occurring over this region, the model underestimates 16 of them (57%). More than 80% of these events have their amplitude simulated by the model within a factor of 2.

In the tropical region five dust peak events have been termed unpredicted events against 61 simulated dust outbreaks. They all took place in winter or fall when aerosol plumes arrived over the ocean at latitudes south of 10°S. Such plumes are evident in Meteosat images, but their sources are likely to be well south of our source area.

Among the 61 remaining observed and predicted dust events, 45 are underestimated by the model, and 65% of the events have their amplitude predicted within a factor of 2. This slightly poorer score compared with that over the subtropical area is most probably due to the aerosols (Sahelian and carbonaceous) not simulated in this study.

4.5. Long-Range Transport Over the Atlantic

Perry et al. [1997] have studied several dust events spreading over the United States in the summers between 1992 and 1995. They discuss the occurrence of a huge mineral aerosol plume in July 1992 which covered about 2.4×10^6 km^2 of the North American continent on July 8 (date of the maximum spatial extent). Since we have shown previously that the model was able to simulate individual dust events, we have studied how the model behaved at reproducing such a remote transport episode.

We have carried out a simulation over the period June-July 1992, enlarging the area presented in Figure 1 to 130°W in order to fully include the United States. We present in Figure 10 the simulated dust surface concentrations from June 20 to July 11 for the days where measurements at the IMPROVE stations were available. Of particular interest is the 3 μg m^{-3} isoline which corresponds to the $PM_{2.5}$ concentration African dust criterion. We see in Figure 10 the progression of the simulated dust plume, which reaches Florida on June 24, spreads over the southeastern U.S. on July 1, and reaches the central part of the U.S. on July 4. As was observed by *Perry et al.* [1997], the maximum spatial extent of the dust plume is simulated on July 8.

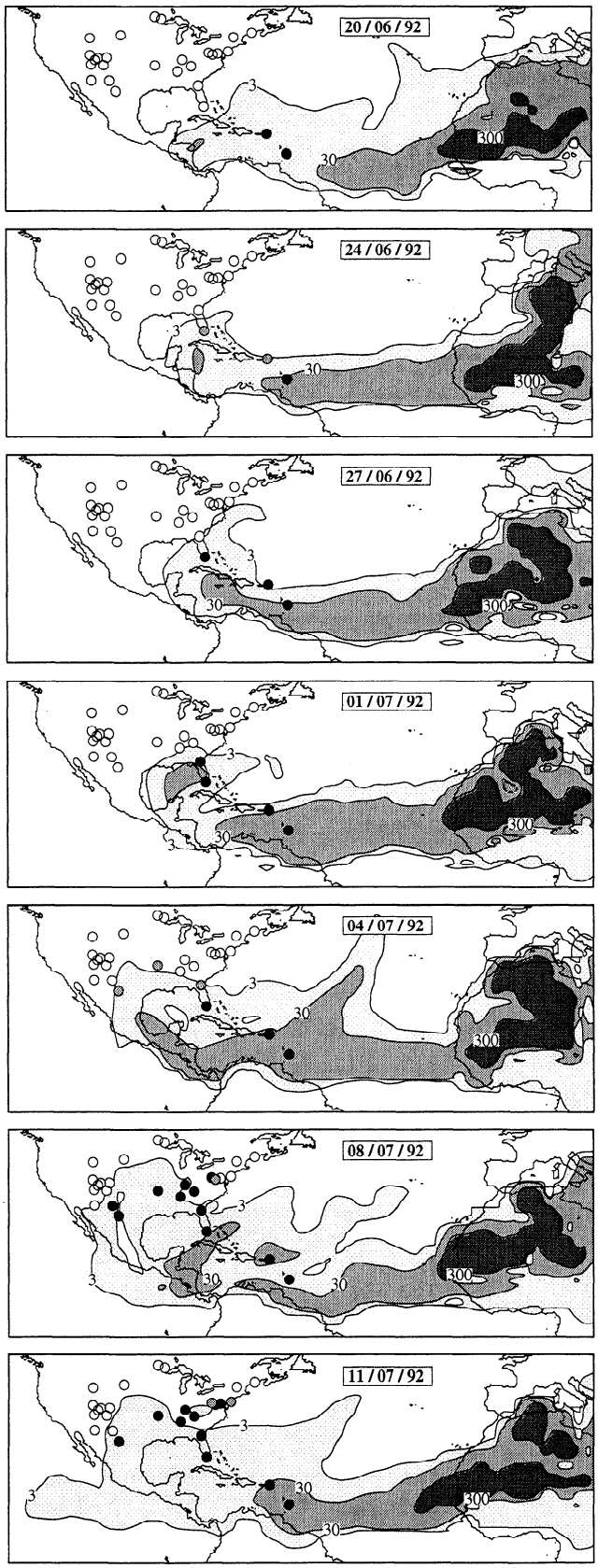
The character of the circles representing the locations of stations indicates the extent of the observed dust plume. These circles are solid when the two criteria are fulfilled for indicating the presence of African dust, and the circles are open when no criterion is satisfied (absence of African dust). We have also plotted as gray circles stations which probably experience African dust when only one criterion is satisfied. For instance, on June 24 we have $PM_{2.5} = 3.1$ μg m^{-3} but Al/Ca = 3.3 at the Virgin Islands, indicating probably that the Al/Ca criterion is too exclusive in that case. On the other hand, we have Al/Ca = 4.6 but $PM_{2.5} = 2.5$ μg m^{-3} at the Everglades station, indicating that there is likely African dust but in smaller concentration than the required value of the $PM_{2.5}$ criterion. Most of the gray circles presented correspond to the latter case, with very high Al/Ca ratio but $PM_{2.5}$ around 2 μg m^{-3}.

We see that for every day the 3 μg m^{-3} isoline includes most of the solid and gray circles (African dust observed) and excludes most of the open circles (no African dust observed). This reveals that the model, coupled with ECMWF fields, is able to simulate the mineral aerosol transport over long distances.

4.6. Deposition of Mineral Dust

Few long-time series studies of deposition have been made over the study region. We chose a data set of weekly deposition measurements taken over northern Spain by *Avila et al.* [1997]. The observations have been taken over the entire period of the simulation, and they are denoted by solid squares in Figure 11. We are aware of other measurements of deposition [*Dulac*, 1986; *Bergametti*, 1987; *Loÿe-Pilot and Martin*, 1996; *Sala et al.*, 1996; *Guerzoni et al.*, 1997]; however, these other data sets either do not extend over the period of our simulation, or they are for regions of the Mediterranean Sea influenced by dust sources from East Africa that are not included here. The measurements by *Avila et al.* [1997] are dependent on the occurrence of both

dust and rain, and the results indicate that the model reproduces all such observed events. The amounts deposited are reproduced satisfactorily except for two particular events, one at the end of March 1991 and the other in October 1991. In the March event, the reason for underestimating this peak in deposition could not be established, but for the October event, the measured amount of precipitation at the site was 169 mm, whereas the ECMWF analysis predicted only 17 mm. This order of magnitude difference in precipitation largely explains the discrepancy between observed and predicted deposition.



5. Conclusions

We simulated the atmospheric cycle of Saharan dust over the North Atlantic for 3 years using a global three-dimensional transport model. To reduce the possible deficiencies introduced by the meteorological fields and the dust source, we have used the analyzed fields from ECMWF and a detailed prognostic formulation of the mineral aerosol source.

To evaluate the model's ability to reproduce the observed distributions of mineral aerosol, we used a large set of measurements that were available and reliable over the simulation area, i.e., satellite-derived optical depths, aluminum surface concentrations at three North Atlantic sites, soil dust ground concentrations over the United States, a vertical profile of aerosol extinction, and deposition fluxes. Particular attention was paid to ensure the best time and space coincidence between observations and model results. Moreover, this comparison has not been restricted to yearly averages, but rather has included daily data.

The model was generally able to reproduce all these observations, from seasonal cycles to single dust events and from short to long distances. The model was able to show that emissions from the Sahara Desert alone can explain a large part of the seasonal latitudinal shift of the aerosol plume over the North Atlantic. There are several arguments at hand which suggest that the seasonal change in atmospheric circulation, described correctly by ECMWF fields, is responsible for the agreement with observations and for this latitudinal shift: the coincidence of daily AOD fluctuations between simulation and satellite observations is the direct consequence of an accurate description of the timing of dust uplift and transport. Such coincidence in the tropical region is of special significance, because it is due to transport from source regions north of 16°N, which is the southern limit of the source area we have used in our simulation. The ECMWF wind fields themselves suggest a significant different transport from season to

Figure 10. Mineral aerosol concentrations simulated at the surface for the period June 20 to July 11, 1992. Isolines are 3, 30, and 300 $\mu g m^{-3}$. Circles indicate the location of IMPROVE stations measuring aerosol surface concentration. Circles are open when no African dust criterion (see text) is satisfied (no African dust); they are gray or solid when one criterion or two criteria are satisfied (African dust), respectively.

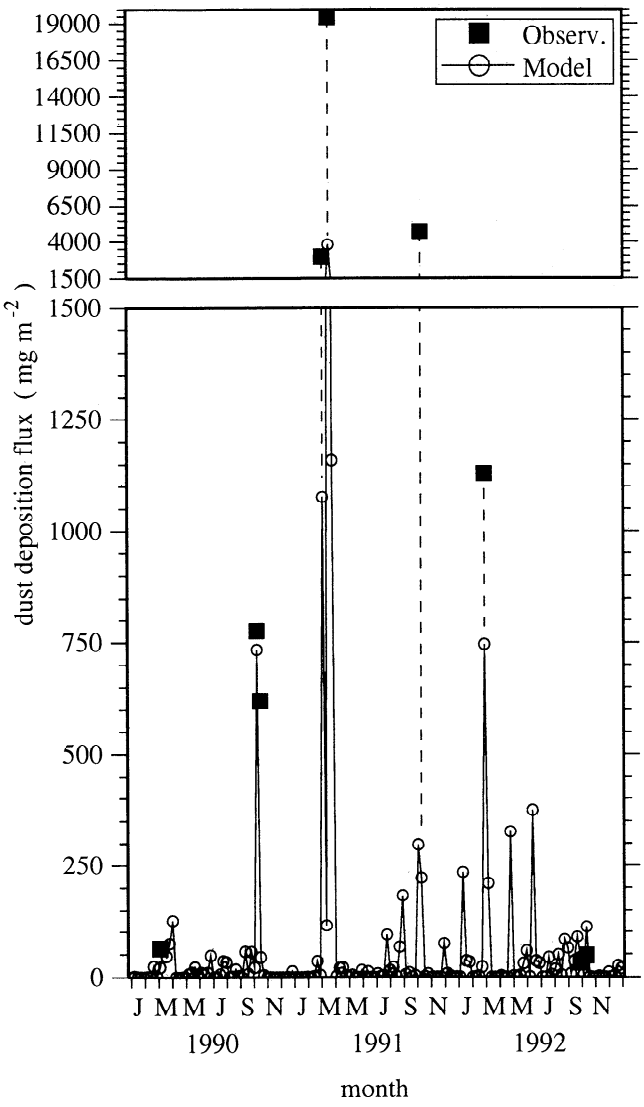


Figure 11. Comparison between observed and modeled weekly dust deposition fluxes (in milligram per square meter) at La Castanya (northeastern Spain) for the 3 years of simulation. The Y axis is divided into two different linear scales to display both low and high values.

season. Finally, there is no outstanding discrepancy between simulation and observations in winter. Rather, we find peculiar discrepancies for each season, which require taking into account multiple sources of small error in the simulation.

The comparison between observed and modeled AODs has shown that our simulation underestimates by 50% the high spring values. We also miss the aerosol maximum in winter, which is observed by Meteosat at the southern edge of the satellite window. Although sources not accounted for, such as Sahelian and carbonaceous aerosols, are likely to be responsible for this discrepancy over the tropical region, the model is not able to reproduce the high aerosol background over the subtropical region in spring. This indicates a more general bias in the source and/or transport model.

The use of different types of data such as surface concentrations together with columnar dust mass loading (optical depth) has also shown some limitations in the model. Although it reproduces rather well the summer AOD over the North Atlantic, the model strongly overestimates the surface dust concentrations at Sal Island. We suspect that the western Saharan source is likely to be responsible for the discrepancy between observations and model results at Sal. However, it will be important to determine how much of this discrepancy is due to poor vertical resolution of the model in the lower troposphere and in the marine boundary layer.

The model reproduced with reasonable agreement the vertical profile of dust measured over the Azores region, but a more general study of the vertical distribution needs to be done with the use of numerous lidar measurements of the Lidar In-space Technology Experiment (LITE). This will allow us to fully validate the parameterizations of the atmospheric dust cycle used in our model, with the ultimate goal of including this dust parameterization in a general circulation model. A further step will also consist in simulating the Sahelian, the carbonaceous, and sea salt aerosols in order to quantitatively determine the different contributions of these species to the total aerosol extinction over large areas.

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