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Detection of mineral dust over the North Atlantic Ocean and Africa with the Nimbus 7 TOMS

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Abstract. It has recently been found that the ultraviolet measurements obtained with the Nimbus 7 total ozone mapping spectrometer (TOMS) instrument can be used to retrieve information on the distribution of aerosols over oceanic and continental surfaces. Here we examine the use of the derived TOMS aerosol index (AI) for the detection of absorbing aerosol in terms of mineral dust aerosol over the North Atlantic Ocean and North Africa. Specifically, we compare the TOMS AI with the time series of daily aerosol measurements made in the boundary layer at Sal Island (Cape Verde), Barbados, and Miami and in the free troposphere on Tenerife (Canary Islands); these sites are frequently impacted by African dust events. At Tenerife, over the time period 1988–1992, TOMS detected 80% of the African dust events that yielded daily average dust concentrations greater than $20 \mu\text{g m}^{-3}$; at Barbados and Miami, TOMS detected 65% and 44% respectively of the events over the period 1979–1992. If we exclude events during which some of the TOMS data are missing and also short (1-day) dust events, TOMS detected 99% of the events at Tenerife, 97% at Barbados, and 81% at Miami. TOMS was also successful in detecting the “low altitude” African dust events recorded at Sal during the winter season. Over Africa we compare the TOMS AI data with ground-based measurements of aerosol optical thickness (AOT) obtained during field experiments in Senegal and Niger; these yield a nearly linear relationship between the TOMS AI and the AOT. Discrepancies between ground-based measurements (in terms of dust concentrations or AOT) and TOMS AI can be attributed to a number of factors: variations in the physical properties of the aerosol; the sensitivity of the TOMS response to the altitude of the aerosol layer; or the coarse spatial resolution of the TOMS pixel. Nonetheless, our results clearly show that the TOMS AI provides a remarkably accurate picture of mineral dust distributions in the atmosphere over both continental and oceanic regions.

1. Introduction

Aerosol particles present in the atmosphere affect climate directly by interacting with solar and terrestrial radiation and indirectly by their effect on cloud microphysics, albedo, and precipitation [Intergovernmental Panel on Climate Change (IPCC), 1994; Andreae, 1995]. Uncertainty in aerosol science (amount, optical properties, and geographical distribution) is contributing to a large uncertainty in predicting anthropogenic climate change [Penner *et al.*, 1994; Schwartz and Andreae, 1996; Kaufman *et al.*, 1997]. One of the major problems in assessing the radiative forcing due to tropospheric aerosols is related to the fact that the various aerosol species exhibit high temporal and spatial variability because of their short lifetime in the troposphere (days to weeks) compared with greenhouse gases. As a consequence, ground-based measurements of aerosols, necessarily limited in number and sparse, are not sufficient to

furnish a global view of their spatial distributions and time variations. Remote sensing of aerosols from Earth-satellite systems constitutes the appropriate tool in order to provide comprehensive information on the aerosol spatial and temporal distributions. As an example, Meteosat observations in the visible wavelengths have been used to retrieve the desert aerosol optical thickness (AOT) over the tropical North Atlantic Ocean (NAO) and the Mediterranean [Jankowiak and Tanré, 1992; Dulac *et al.*, 1992; Moulin *et al.*, 1997a,b]. Global AOT distributions are also available from the advanced very high resolution radiometer (AVHRR) polar-orbiting satellite over the world ocean [Husar *et al.*, 1997]. Because optical thickness can only be retrieved over surfaces that have a relatively low and constant albedo using these techniques, these observations are limited to ocean regions. Detection of aerosols is especially difficult over land surfaces, which have complex and variable radiative properties in the visible spectrum.

Here we present results from a new approach for detecting UV-absorbing aerosols in the atmosphere based on the spectral contrast between the 340- and 380-nm channels of the total ozone mapping spectrometer (TOMS) instrument. Because the UV surface reflectivity is typically low and nearly constant over both land and water [Eck *et al.*, 1987; Herman and Celarier, 1997], the TOMS method can be used for the detection of aerosols over continents as well as oceans [Herman *et al.*, 1997]. Radiative transfer calculations show that the TOMS spectral contrast is very sensitive to absorbing aerosols such as desert-mineral dust, smoke and soot aerosol from biomass burning and forest fires, as well as volcanic ash clouds [Torres *et al.*, 1998].

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The association of the TOMS spectral contrast signatures with specific types of absorbing aerosols has been largely based on the matching of the temporal and spatial variability of the TOMS aerosol index (AI) with known sources of absorbing aerosols, for example, specific volcanic eruptions, forest fires, and large dust events [Seftor *et al.*, 1997; Herman *et al.*, 1997]. Hsu *et al.* [1996] demonstrated that TOMS can detect and track smoke and soot aerosols generated by biomass burning in South America and that TOMS can be used to distinguish between absorbing aerosol particles (smoke and dust) and nonabsorbing aerosols (clouds and haze).

The global patterns of TOMS AI yield a striking picture of the distribution of the sources of absorbing aerosols and their transport paths [Herman *et al.*, 1997]. However, to date, there are only two other publications that compare the TOMS AI with Sun photometer optical depths [Torres *et al.*, 1998; Hsu *et al.*, in press, 1999] and none that link quantitative measurements of aerosol-mass concentrations to the temporal record of the TOMS AI. Since radiative transfer calculations from Torres *et al.* [1998] have shown that the TOMS response is not only related to the aerosol content (in terms of aerosol optical depth or concentration) but also strongly influenced by the altitude of the aerosol layer, it seems particularly important to assess how this altitude effect affects the TOMS retrieval of aerosol contents. In this context we use long-term daily ground-based measurements of mineral dust concentrations made at different sampling stations of the NAO (Sal Island, Tenerife, Barbados, and Miami) to test the performance of TOMS in detecting African dust events over oceanic regions in terms of both occurrence and intensity. Over the African continent, we use AOT measurements performed during field experiments in Niger and Senegal to assess the ability of TOMS to retrieve the aerosol content over land.

2. Presentation of the Data Set

2.1. The TOMS Aerosol Index Product

The TOMS instrument flew on the Nimbus 7 polar-orbiting satellite from November 1978 to May 1993; during its 14.5-year lifetime, TOMS made measurements almost every day over most of the Earth's surface. Its spatial resolution is 50x50 km at nadir and 150x250 km at extreme off-nadir. The Nimbus 7 TOMS instrument was designed to provide accurate global estimates of total-column ozone from the measured amount of backscattered UV radiance in six 1-nm-wide wavelength bands (313, 318, 331, 340, 360, and 380 nm). At the three longest wavelength bands (340, 360, and 380 nm), gaseous absorption is weak, and the backscattered radiation is primarily controlled by molecular scattering, surface reflection, and scattering from aerosol and clouds.

The algorithm for TOMS detection of aerosols and clouds from the backscattered ultraviolet radiance measurements in the 340- to 380-nm range is based on the residue theory, which is described in detail by Herman *et al.* [1997] and Torres *et al.* [1998]. Briefly, the residue at the wavelength $\lambda=340$ nm can be defined as

$$r_{340} = -100 \log_{10}[(I_{340}/I_{380})_{\text{meas}} - (I_{340}/I_{380})_{\text{calc}}] \quad (1)$$

where I_{meas} is the measured backscattered radiance at a given wavelength and I_{calc} is the radiance calculated at that wavelength using a modified version of the Lambert equivalent reflectivity

(LER) atmospheric model from Dave [1978] [McPeters, 1996]. The algorithm yields nearly zero residue values at all TOMS wavelengths in the presence of clouds.

The residue method is based on the principle that for a fixed 380-nm radiance the I_{340}/I_{380} spectral contrast is largest for nonabsorbing aerosols and clouds and decreases with increasing absorption. UV-absorbing aerosols produce smaller contrast than predicted by the pure Rayleigh scattering atmospheric model; consequently, dust and smoke will yield positive residues. Nonabsorbing aerosols (e.g., sulfate aerosols and sea-salt particles) produce greater contrast and negative residues. In the present paper and that of Torres *et al.* [1998] the values of the residue (positive and negative) are referred as the aerosol index (AI). The AI as defined here is also related to the reflectivity difference at 380 and 340 nm ($R_{380}-R_{340}$) used in a previous work [Hsu *et al.*, 1996]. Because below 0.5-value units of the AI the measure may contain a ground signal or noise [Herman *et al.*, 1997], we will consider this value as the threshold for TOMS detection of absorbing aerosols. The TOMS AI data set used for this study is gridded on a 1° latitude by 1.25° longitude grid.

The detection of absorbing aerosols is based on perturbations of Rayleigh scattering from below the aerosol layer. Thus a low-lying aerosol layer will have a relatively small affect on the upwelling UV, and, in fact, it may not be detectable by TOMS; conversely, the same layer in the upper troposphere would have the maximum affect. As a consequence, the TOMS AI is most sensitive to aerosols at high altitudes, aerosols that would most likely be subject to long-range transport; on the other hand, TOMS is least sensitive to aerosols in the boundary layer, aerosols that are least likely to have a long lifetime in the atmosphere.

2.2. The Ground-Based Aerosol Measurements

2.2.1. African dust events record over the NAO. During much of the year, large quantities of dust are carried by winds from sources in North Africa across the west coast and over the NAO [Prospero, 1996a, b]. The daily progress of individual dust outbreaks can be observed in visible satellite imagery as the dust clouds move across the ocean to the Caribbean [Ott *et al.*, 1991]. The seasonal pattern of African dust transport and the very large spatial scale of these events is clearly revealed in satellite-derived AOT distributions [Husar *et al.*, 1997] and the AI distribution of absorbing aerosols [Herman *et al.*, 1997]. Long-term aerosol measurements from the Cape Verde Islands [Chiapello *et al.*, 1995; Chiapello, 1996] and Canary Islands [Arimoto *et al.*, 1995] in the eastern NAO as well as Barbados [Prospero and Nees, 1986] and Miami [Prospero *et al.*, 1987] in the western NAO show that the tropospheric aerosol content is strongly dominated by African soil dust [Prospero, 1996a, b]. As a consequence, this region is ideal for testing the performance of TOMS in detecting mineral dust.

The Barbados sampling station (13°17'N, 59°43'W) provides the most extensive long-term record, with aerosol measurements made continuously since the late 1960s [Prospero and Nees, 1986]. The samples are collected from the top of a 20-m-high tower located on a 30-m-high promontory at Ragged Point on the east coast of the island. In Miami (25°75'N, 80°25'W), continuous sampling of aerosols started in the middle 1970s; the samples were collected at the top of a 16-m tower erected on the roof of a three-story building at the Rosenstiel School, located on a coastal site on Virginia Key, east of the mainland. At both stations, bulk aerosol particles are collected on a daily basis with

high-volume samplers ($45 \text{ m}^3\text{h}^{-1}$) on Whatman-41 filters. The filters are essentially 100% efficient for the collection of mineral dust [Savoie, 1984; Pszenny *et al.*, 1993].

In the eastern Atlantic region, on Tenerife (28.30°N , 16.48°W), Canary Islands, aerosol samples have been collected at Izana Observatory since 1988 as a part of the Atmosphere/Ocean Chemistry Experiment (AEROCE) [Arimoto *et al.*, 1995]. Izana Observatory is located on a mountain ridge at an altitude of 2360 m; it is only 300 km to the African coast and is thus ideal for studying aerosol properties relatively close to the sources. The samplers at Tenerife only operate during the night (around 0800 pm to 0800 am), when a downslope wind circulation is in effect; during the day, orographic upslope winds bring local materials to the sampling site. Thus, during the night, we sample air from the free troposphere with little likelihood of contamination from local sources. The equipment and procedure are the same as those at Miami and Barbados.

The filters are extracted with water; the mineral dust concentration is determined by ashing the extracted filter at 500°C for 14 hours and weighing the residue. At these sites, computer-based systems are used to control the aerosol sampling with respect to wind direction; the pumps are activated only when the wind is coming off the ocean and at speed greater than 1 m s^{-1} . The AEROCE samples are analyzed by instrumental neutron activation analysis; the mineral dust concentration is estimated by assuming that aluminum content of the dust is the same as that in average crustal material, about 8% [see Arimoto *et al.*, 1995].

The Sal Island ($16^\circ45'\text{N}$, $22^\circ57'\text{W}$) aerosol sampling station has been operating since December 1991 [Chiapello *et al.*, 1995]. Daily bulk aerosol samples are collected on $0.4\text{-}\mu\text{m}$ -pore-size Nuclepore filters at a flow rate of about $1 \text{ m}^3 \text{ h}^{-1}$. The sampling site is located at the top of a 25-m-high tower situated at an altitude of 100 m, 5 km from the eastern coastline of the island. Samples are analyzed by X ray fluorescence spectrometry [Chiapello *et al.*, 1997]; the mineral dust concentration is then estimated by assuming that the silicon content of the dust is the same as average crustal material, 33% [Bowen, 1966].

2.2.2. Measurements of aerosol optical thickness over Africa. Over the African continent, only a limited set of ground-based aerosol measurements is available for the period prior to May 1993, when Nimbus 7 TOMS ceased operation. The automatic Sun photometer network currently in operation [Holben *et al.*, 1998] started to function in mid-1993 and could not be used for comparison with the Nimbus 7 TOMS product. Instead, we use aerosol measurements performed in Senegal during two field experiments (1986 and 1987) and in Niger (1992) during the Hydrologic Atmospheric Pilot Experiment (HAPEX). The measurements of AOT made at M'Bour, Senegal (14.3°N , 16.9°W), in the spring of 1986 and 1987 are described by Tanré *et al.* [1988] and Jankowiak and Tanré [1992]. Briefly, the AOT measurements were done in the spectral range 400–2200 nm with a portable radiometer from the Laboratoire d'Optique Atmosphérique, Lille, France [Tanré *et al.* 1988], from April 28 to May 20, 1986, and April 1 to May 3, 1987. The goal of these experiments was to characterize the optical properties of desert aerosols in order to validate satellite monitoring algorithms. The site at M'Bour was chosen because it is directly in the path of African dust outbreaks and it is far enough from Dakar (80 km to the south) to avoid local anthropogenic aerosol components [Tanré *et al.*, 1988]. The strategy of the HAPEX experiment is described by Goutorbe *et al.* [1994]. Briefly, the experiment

combined remote sensing and ground-based measurements with hydrological and meteorological modeling in order to improve the description of the land-atmosphere interactions in the Sahel region. The radiation measurements of the AOT were made on a site located 50 km east of Niamey (13.32°N , 2.30°E) from August 24 to October 7, 1992, with a portable radiometer similar to the one used in M'Bour.

3. TOMS Detection of African Dust Over the NAO

3.1. Annual Variations of the TOMS Aerosol Index Over the NAO

Figures 1a, 1b, 1c, and 1d present the monthly averages of the positive values of the TOMS-derived AI from 1988 to 1992, for the pixels corresponding to Sal Island, Cape Verde (i.e., the box centered at 16.5°N , 23.125°W), Tenerife, Canary Islands (28.5°N , 16.875°W), Barbados (13.5°N , 59.375°W), and Miami (25.5°N , 80.625°W), respectively. We selected the positive values of the TOMS AI in order to examine only the effects of absorbing aerosol on the TOMS response and to compare the AI values with the mineral dust concentrations measured at the sampling stations. The averaged frequency of positive values of the TOMS AI over this 5-year period is 70% at Sal Island, around 50% at Tenerife and Barbados, and 36% at Miami. At Sal Island, there are only 9 months of data, from December 1991 to August 1992. For the four other stations, mineral dust concentration measurements were available for the 5 years of comparison.

The highest AI values appear at Sal, Cape Verde Islands (with maximum between 2.5 and 3), followed by Tenerife (maximum between 1 and 2), Barbados (maximum between 0.8 and 1.3), and Miami (maximum between 0.5 and 0.8). Similarly, the highest monthly mean dust concentrations are obtained at the two sites closest to Africa, Sal, and Tenerife, both within 500 km of the coast; conversely, the lowest concentrations are observed at Miami, the most distant station from Africa. Moreover, Sal Island is located on the main path of the Saharan dust transport over the NAO, whereas Tenerife is at the northern edge of the main area of dust transport; this is consistent with the higher AI values at Sal Island relative to Tenerife. Similarly, Barbados AI values are greater than Miami AI values because Barbados lies in the main dust transport path.

The Tenerife station is at an altitude of 2400 m, well above the marine boundary layer (MBL) and in the region of the troposphere where Saharan dust is usually transported (i.e., in the Saharan air layer (SAL)). Thus we would expect the dust measurements made at this site to serve as a good test data set of the TOMS AI measurements. On an annual basis, the maximum monthly mean dust concentrations are consistently seen in the summer months, although prominent peaks can be seen in other months as well, but not in any consistent pattern. Both the dust-load data and the AI data track one another closely. Note that during the summer the relative height of the AI peaks and the dust concentration peaks track one another with consistency. This suggests that the radiative properties of the dust and the dust altitude distribution do not vary much from summer to summer in this region. This consistency is due in part to the fact that, as previously stated, the Tenerife station is at an altitude that lies within the SAL that characterizes the summer dust transport. In contrast, during the winter season, the AI and dust concentration values do not appear to track one another with the same

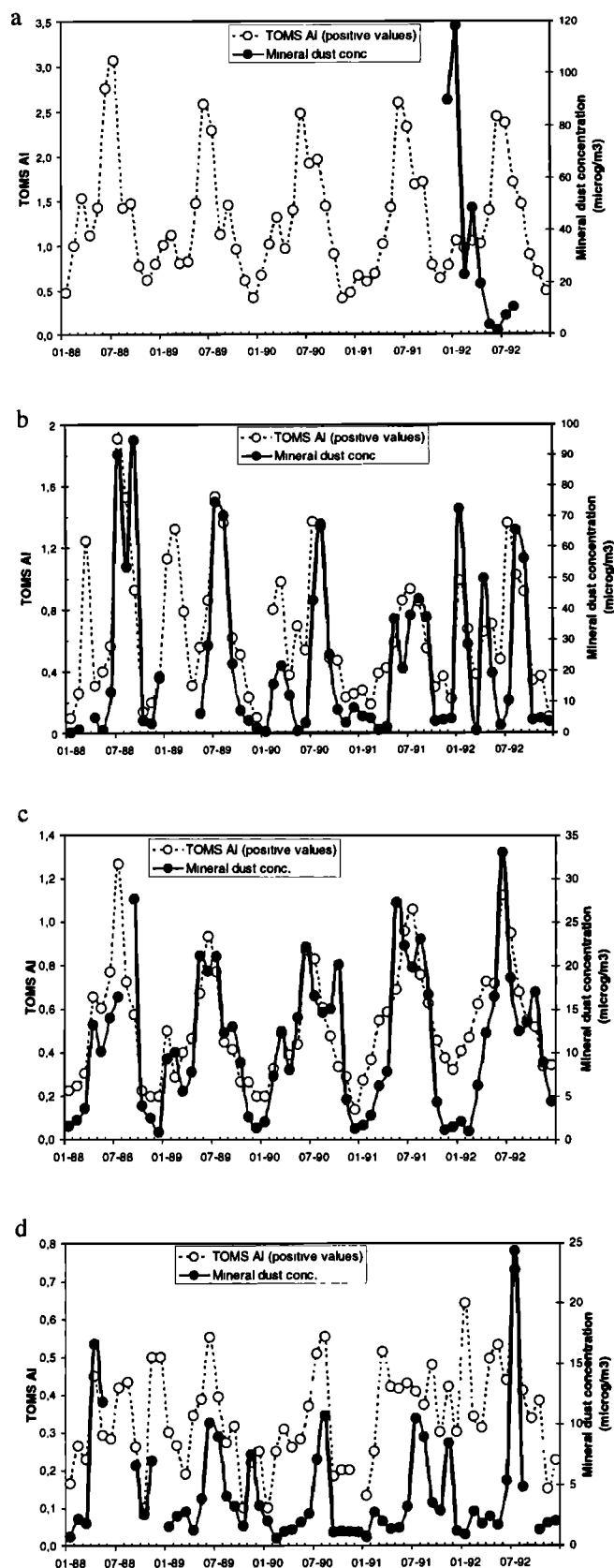


Figure 1. Time series of monthly averages of the positive values of the total ozone mapping spectrometer (TOMS) aerosol index (AI) and of measured mineral dust concentrations from 1988 to 1992 for (a) Sal Island, Cape Verde Islands; (b) Izana Observatory, Tenerife, Canary Islands; (c) Barbados, West Indies; and (d) Miami, Florida.

consistency as during the summer; however, the amount of winter dust data is insufficient to make a firm statement on this issue.

The monthly averages of the positive AI values at Sal Island show a clear and consistent pattern, with a maximum in summer (June–July) and a minimum in autumn and early winter (November–December). In contrast, mineral dust concentrations reach a maximum during winter [Chiapello *et al.*, 1995]. These differences can be explained by the seasonal change in the altitude of the dust transport. In winter the dust events sampled at Sal Island are transported at low altitude in the trade wind layer [Chiapello *et al.*, 1995]. In contrast, the summer transport occurs in the SAL at much higher altitude, typically above about 1.5 km and extending to 5–6 km [Carlson and Prospero, 1972; Karyampudi and Carlson, 1988; Westphal *et al.*, 1988]; the dust concentrations in the SAL can be many times greater than in the underlying MBL [Prospero and Carlson, 1972]. Consequently, this high-altitude summer transport of dust has a minimal impact on the concentrations measured at ground level at Sal Island. As previously stated, the TOMS AI is more sensitive to high-altitude aerosol layers and goes to zero as the layer height nears the ground [Torres *et al.*, 1998]. As a result, the seasonal modulation at Sal Island of the monthly mean AI time series is due in part to the seasonal change in the meteorology of dust transport. Given this limitation, the persistence of high concentration dust events at Sal Island in winter provides an opportunity to characterize the response of TOMS to “low altitude” aerosol layers.

At Barbados, the time series of monthly averages of TOMS AI closely matches that of mineral dust, with maximum values during the summer months and minima during the winter. The agreement is surprisingly good considering that the dust measurements are made at ground level while the main transport takes place above the MBL. The close tracking of the Barbados dust data and TOMS AI suggests that the concentration and physical properties of the dust in the MBL at Barbados are closely correlated with those of the main dust transport that takes place in the free troposphere. Consequently, this site is ideal for monitoring long-range African dust transport.

The Miami dust data do not track the TOMS AI as closely as at the other sites. This is not surprising, given the great distance from the sources and the variable meteorological conditions in Miami. During the summer, Miami lies under the influence of a strong, large-scale, southeasterly trade wind air flow; African dust is often transported into the region under such conditions, sometimes at very high concentrations [Prospero *et al.*, 1987]. In contrast, during the winter and spring, south Florida is under the influence of a steady northeasterly flow, interrupted by the passage of cold fronts; under these conditions, the winds often carry substantial concentrations of pollutants from eastern and central North America. As seen in Figure 1, in general, high summer dust concentrations are matched by high values of the TOMS AI. High AI values are also noted in the winter and spring; these values could reflect the influence of other absorbing aerosol components (e.g., black carbon or soot particles) that are associated with polluted air masses that come from the north.

3.2. Comparison of Daily Mineral Dust Concentrations With TOMS AI

In this section we compare the daily mineral dust concentration measured at each site with the TOMS AI value obtained on the same day. In making this comparison, it should be remembered that the mineral dust sample is collected over a nominal 24-hour period (except at Tenerife, where the sampling

time is reduced to 12 hours). In contrast, the TOMS AI value is obtained from an instantaneous satellite measurement made during the overpass, which occurs at about 1130 LT. At all sites except Tenerife, samples are changed in the morning; at Tenerife, sampling is only carried out at night. Thus the TOMS data are obtained relatively early in the daily aerosol sampling period at all sites except Tenerife, where the TOMS measurements are completely outside the sampling period. Consequently, under changing meteorological conditions, there could be a large difference between the mean dust concentration and the AI value reported for that day. This is particularly true for African dust events, which typically begin with a very rapid increase in dust concentration.

3.2.1. Sal Island. At Sal Island, Cape Verde, the comparison of the recorded African dust events and the TOMS AI is limited in time, since the sampling started recently, in December 1991, and there have been interruptions of the sampling often lasting for several months (due to logistical problems). As previously stated, the most intensive African dust events as measured at ground level occur in winter in association with low-altitude transport in the trade wind layer [Chiapello *et al.*, 1995]. Consequently, we limit our comparison to winter events. In Figure 2 we show the daily variations of the mineral dust concentrations in January, the month of maximum mineral dust concentrations at Sal in 1992, along with the daily TOMS AI values for the corresponding pixel. During January, two very intense African dust events were observed. In the first one, from January 2 to 9, the mineral dust concentrations are higher than $100 \mu\text{g m}^{-3}$, with maximum dust values around $450 \mu\text{g m}^{-3}$ (from January 4 to 6). The corresponding TOMS AI values remain higher than 1.1 during this period. From January 6 to 8 they reach values higher than 2 (with a maximum of 2.9 on January 8). The second event is less intensive, with a maximum around $250 \mu\text{g m}^{-3}$ on January 15. The TOMS AI maximum for this event occurs on January 14, with a value of 2.1. During the second part of January, two other African dust events of much moderate intensity occur, from January 20 to 22 and from January 25 to 28. The first one is characterized by concentrations around $50 \mu\text{g m}^{-3}$ on January 20 and 21, with AI values of 1 and 0.6. During the

second event the mineral dust concentration reaches $60 \mu\text{g m}^{-3}$ on January 27, along with a value of 1.1 for the TOMS AI.

There is a relatively good correspondence between the peaks in the dust concentration time series and that of AI. This agreement is observed for the very intensive events early in the month and also for the moderate ones later in the month. Nonetheless, there are significant differences in the phasing of the individual peaks and also the ratio of the respective values. In the first major event in early January, the peak value in AI lags behind the peak dust concentration by as much as several days; in the subsequent dust event, the peak dust concentration appears to lag behind the peak AI value. Furthermore, the ratio of the peak values changes from event to event. The changing ratios might be attributed to a number of factors, including variations in the altitude and thickness of the dust layer. As previously stated, in winter at Sal Island, dust transport occurs primarily at low altitudes; thus the ground-based aerosol concentrations are more likely to be representative of the vertically integrated dust content. Nonetheless, because of the sensitivity of TOMS to the height of the dust layer, variations in the thickness of the layer could result in substantial differences in the time series of AI values compared with dust concentrations measured at the surface.

3.2.2. Tenerife. Because of its location close to the African coast and the elevation of the sampling site, the Tenerife data serve as a good test of the consistency of the TOMS response to mineral dust during the summer when dust is primarily transported above the MBL. Tenerife is located on the northern edge of the main transport plume during much of the year [Husar *et al.*, 1997]. As a result, aerosol concentrations are highly variable depending on the day-to-day synoptic conditions. Although large dust events can occur at any time of year, the frequency of events is much greater in midsummer when the islands lie on the north edge of the plume. Figure 3 presents the daily variations of the mineral dust concentrations measured at Tenerife for the year 1988, along with the daily values of the TOMS AI for the corresponding pixel. Both the mineral dust concentrations and TOMS AI are at their lowest levels from October to March. Very intensive African dust events were

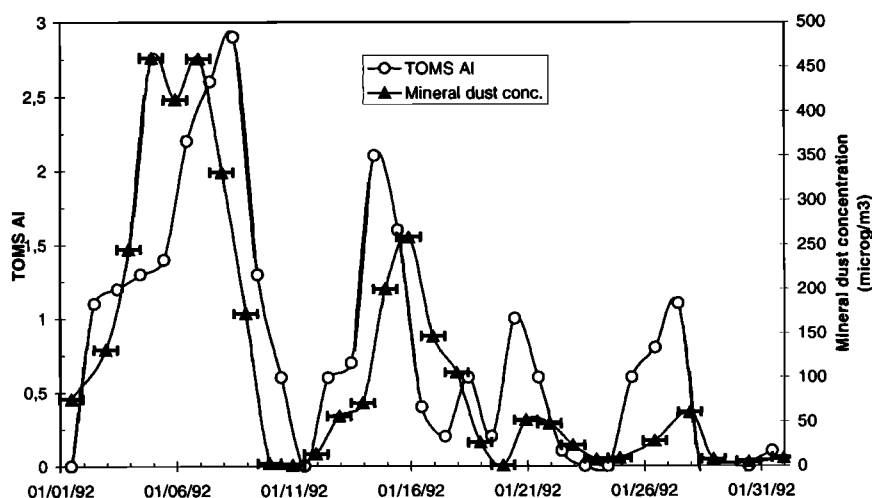


Figure 2. Time series of daily values of the TOMS aerosol index and mineral dust concentrations at Sal, Cape Verde Islands, during the month of January 1992. The symbol marking the TOMS AI value is placed at the time of the TOMS overpass. The length of the horizontal bar marking the dust concentration indicates the duration of the aerosol sample. The TOMS overpass occurred at about the time that the aerosol sample was changed each day.

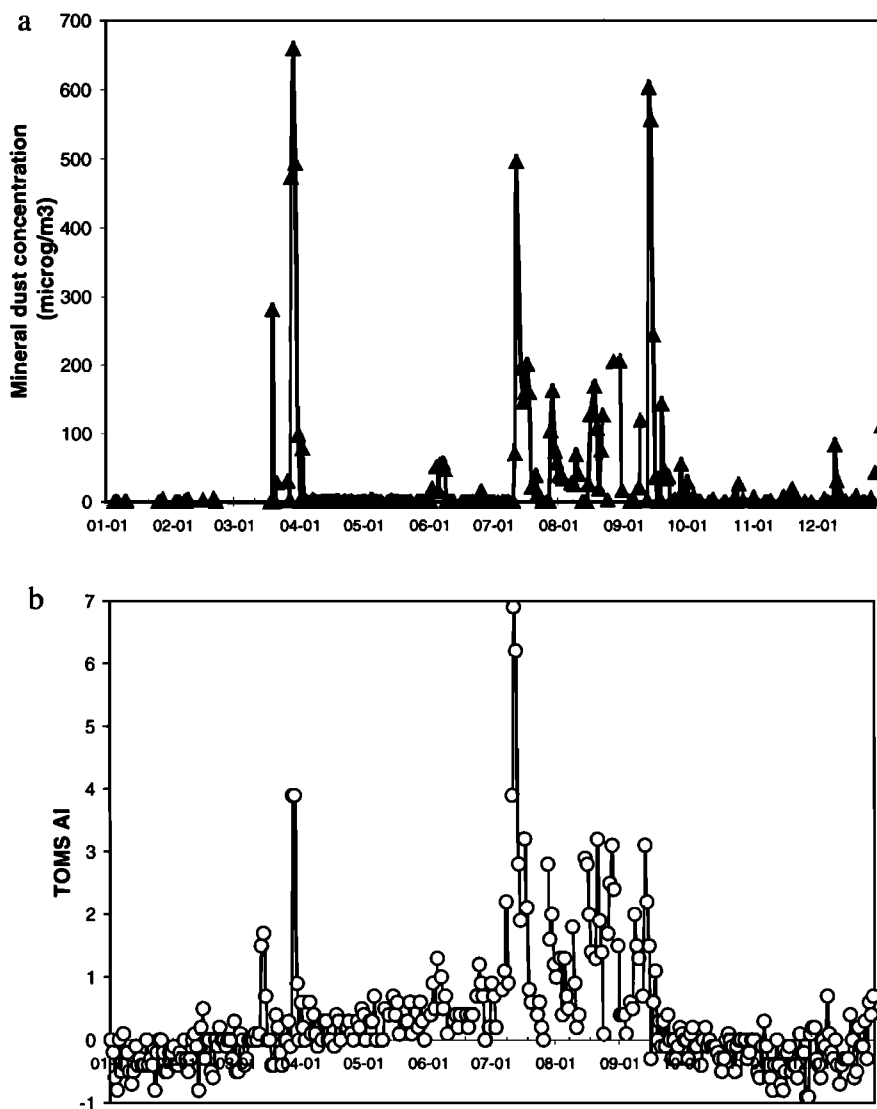


Figure 3. Time series of daily values of (a) the mineral dust concentration, and (b) the TOMS aerosol index, at Izana, Tenerife, during 1988.

observed during the year, with dust concentrations as high as $500 \mu\text{g m}^{-3}$. The year 1988 is typical in that most of the dust events occur during summer (July–September); the TOMS AI also exhibits the highest values during the same period.

Three extremely intense dust events (concentrations greater than $400 \mu\text{g m}^{-3}$) occurred in 1988 (Figure 3a): one at the end of March, another in mid-July, and the third one in September. Figure 4 shows the daily mean dust concentrations along with the TOMS AI for each of these events. The TOMS AI closely follows the day-to-day variations in the dust concentration under these very dusty conditions. However, it should be noted that the dust concentration and AI scales are different for each event (see also Figure 3). Thus the highest dust concentration levels do not necessarily correspond to the highest values of the TOMS AI: The most intensive dust event is observed on March 29 (mineral dust concentration around $650 \mu\text{g m}^{-3}$) and corresponds to an AI ranging between 3.5 and 4, whereas on July 12 the TOMS AI reaches 7 for a dust concentration of about $500 \mu\text{g m}^{-3}$. These "event-to-event" differences can be attributed to a number of factors, most important the altitude of the aerosol layer [Herman

et al., 1997; Torres *et al.*, 1998], but also aerosol composition, size, and column thickness. The event of July 12 corresponds to the highest TOMS AI value (close to 7, implying both large amounts of aerosol and higher than usual plume altitudes) observed at Tenerife. Figure 5 presents the corresponding AI images over Africa and eastern NAO for July 10–12. The dust event had its origin in northern Mauritania on July 10. On July 11, TOMS shows the dust cloud passing over northern Spanish Sahara, and on July 12 the image shows the dust cloud passing over the Canary Islands.

For a more quantitative comparison, Table 1 presents African dust events, classified as a function of their intensity, detected by TOMS over the 5-year period 1988–1992. The criterion for TOMS detection is the occurrence of an AI equal to or greater than 0.5 during the African dust event. A dust event is defined here as a period when the mineral dust concentration measured at the sampling site was continuously greater than $20 \mu\text{g m}^{-3}$. Over this period, 96 African dust events occurred at Tenerife; TOMS detected 80% of these. For 19 events, the TOMS AI did not clearly indicate the presence of dust. Many of these undetected

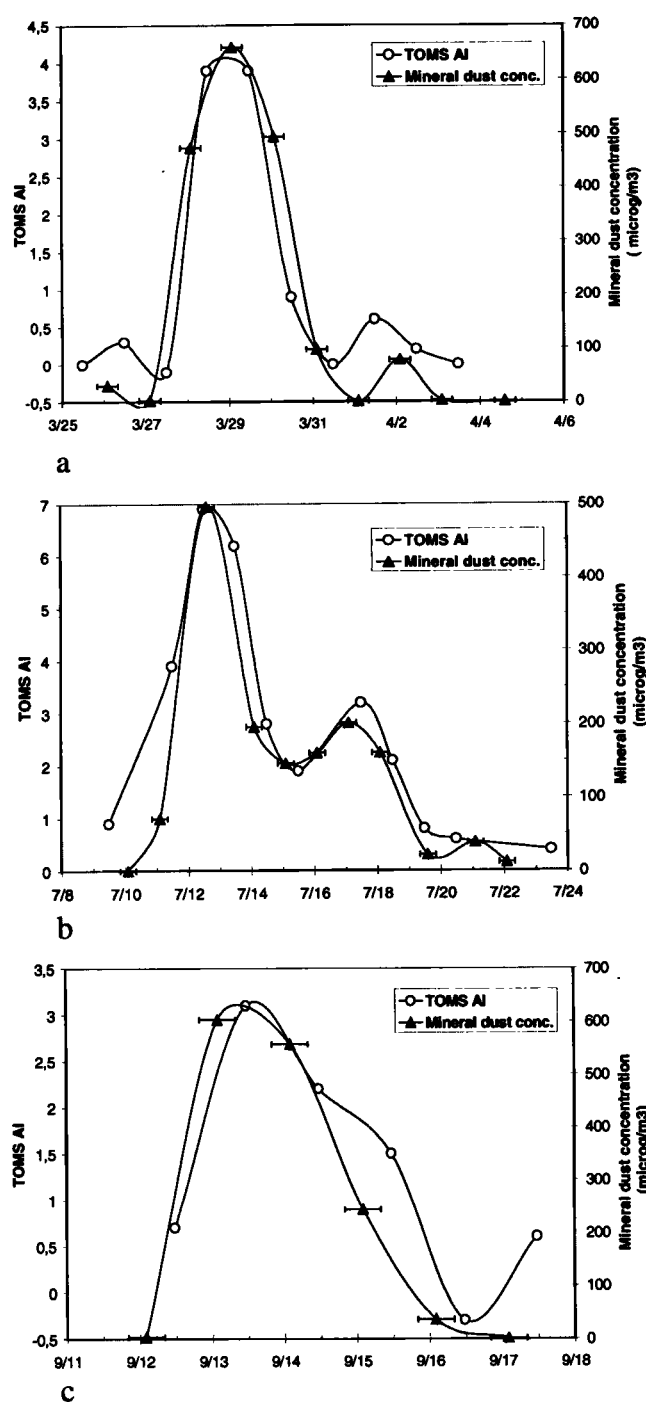


Figure 4. Time series of daily values of TOMS aerosol index and mineral dust concentration at Izana Observatory, Tenerife, during the three major dust events that occurred in 1988: (a) March 25 to April 5; (b) July 9–23; and (c) September 12–17. The length of the horizontal bar marking the dust concentration indicates the duration of the aerosol sample; at Izana, aerosol samples are only collected during the night, and thus the aerosol data do not overlap with the TOMS AI measurement.

events were marginal in intensity and/or duration. If we exclude events during which some of the TOMS data are missing and also, short (1-day) duration events, TOMS only failed to detect one event (in October 1988) in which the mineral dust concentration was quite low, around $25 \mu\text{g m}^{-3}$. If we consider

only those dust events with concentrations greater than $50 \mu\text{g m}^{-3}$ (in Table 1, major and intermediate events) and exclude 1-day events, TOMS successfully detected every one. The failure of TOMS to detect 1-day dust events might be explained by the fact that at Tenerife the aerosol samples are collected at night, whereas the TOMS measurement is made at about 1130 LT,

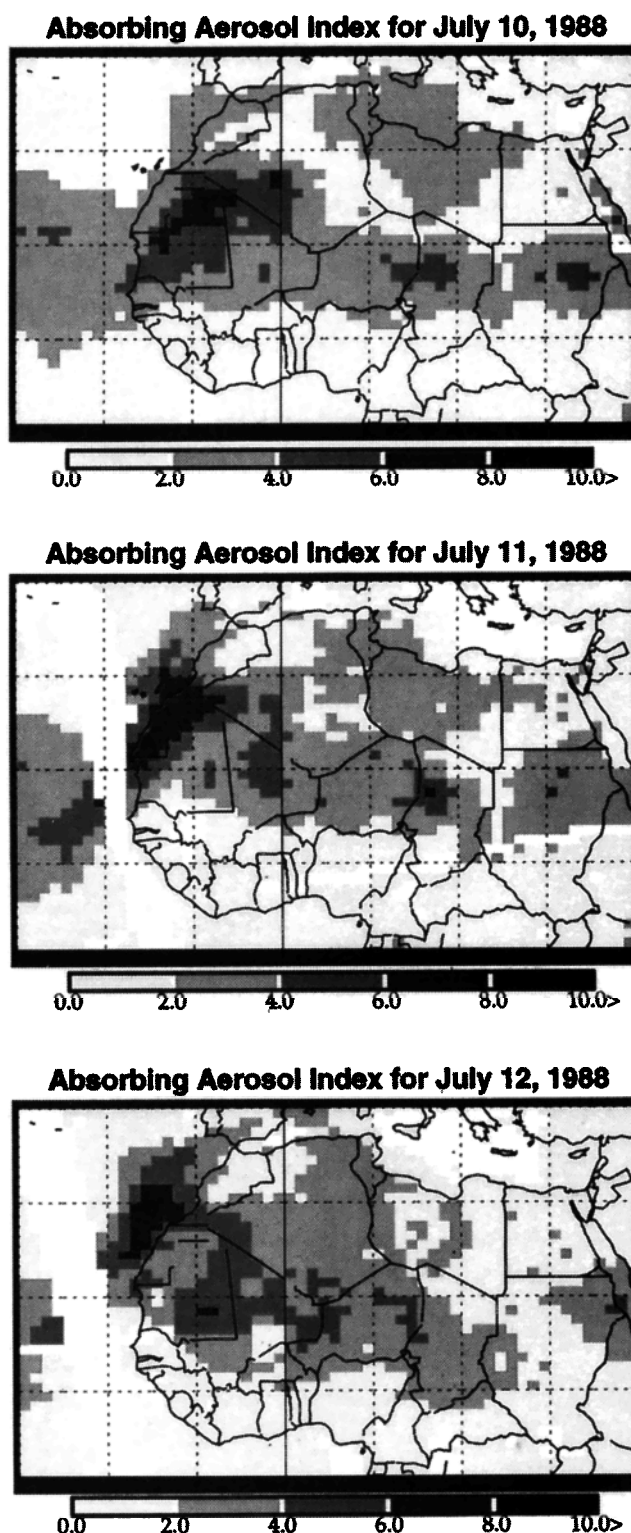


Figure 5. TOMS aerosol index distribution over Africa and the North Atlantic for July 10–12, 1988.

Table 1. Summary of the TOMS Detection of African Dust Events at Tenerife, Canary Islands, 1988-1992

Intensity of the Dust Event	Measured at Ground	Detected by TOMS	Not Detected by TOMS		
			Missing TOMS Data	One-Day Duration	Other
Major	42	40		2	
Intermediate	28	25		3	
Minor	26	12	2	11	1
Total	96	77	2	16	1
Percentage		80%	2%	17%	1%

The criterion for TOMS detection was a TOMS aerosol index value of 0.5 or greater. There are three categories of dust events: major, dust concentration greater than $100 \mu\text{g m}^{-3}$; intermediate, dust concentration $50\text{--}100 \mu\text{g m}^{-3}$; and minor, dust concentration $20\text{--}50 \mu\text{g m}^{-3}$. In order to be considered as an event, the dust concentration had to be above $20 \mu\text{g m}^{-3}$ continuously during the event.

completely outside the aerosol sampling period. Our observations at this site (which began in 1988 and continue to the present) show that the dust concentrations can change dramatically over a period of a few hours when a dust outbreak moves into the region.

3.2.3. Barbados. The aerosol record from Barbados enables us to test the performance of TOMS in detecting dust events after

transport across the NAO, that is, about a week after leaving the coast of Africa. Figure 6 presents the time series of daily dust concentration in 1984 along with the TOMS AI. First, it should be noted that most dust concentrations are lower here than those measured at Tenerife. Dust events occur mainly during the late spring, summer, and early fall; the highest values of the TOMS AI also occur during this time period. Figure 5b shows the

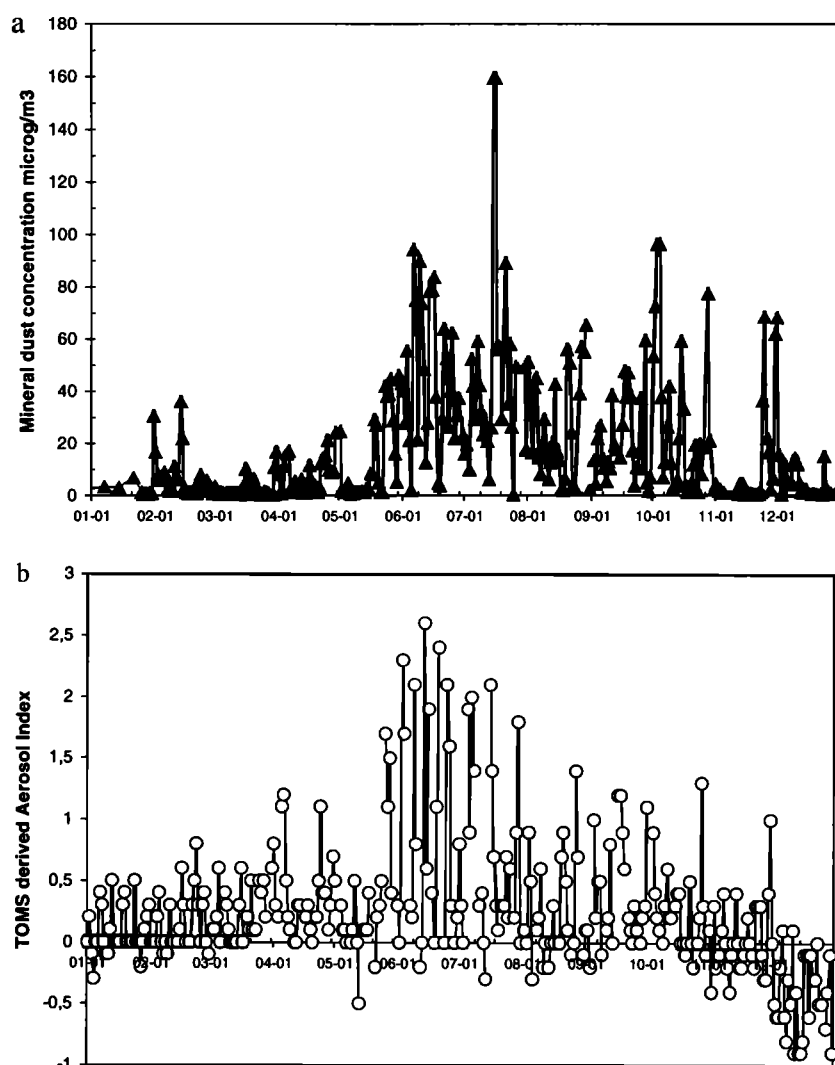


Figure 6. Time series of daily values of (a) the mineral dust concentration, and (b) the TOMS aerosol index, at Barbados during 1984.

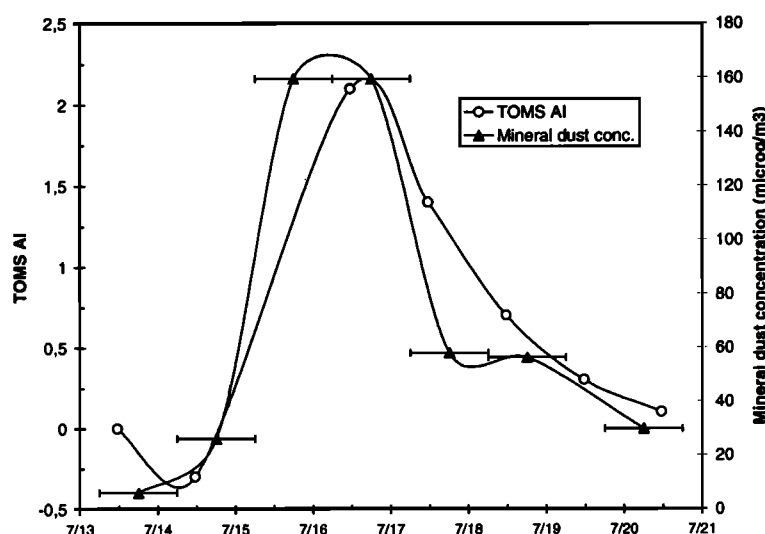


Figure 7. Time series of daily values of the TOMS aerosol index and mineral dust concentration at Barbados during a major dust event, from July 13 to 20, 1984. The length of the horizontal bar marking the dust concentration indicates the duration of the aerosol sample.

occurrence of negative values of the TOMS AI in December. Negative AI can be related to the occurrence of nonabsorbing aerosols, i.e., sulfates and/or sea-salt aerosols. However, as reported by Torres *et al.* [1998], low-altitude weakly absorbing aerosols also yield negatives AI and cannot be distinguished from nonabsorbing aerosols. During 1984, only one dust event (in July) yielded concentrations greater than $100 \mu\text{g m}^{-3}$. Figure 7 presents the daily mean mineral dust concentrations along with the AI during this event; the agreement is quite good. This event yielded maximum dust concentrations of around $160 \mu\text{g m}^{-3}$, which were associated with TOMS AI values around 2. As an illustration of a TOMS depiction of a dust transport event across the NAO, Figure 8 presents the TOMS AI images corresponding to this event from July 11 to 18. The appearance and persistence of very high values over northern Mauritania and southern Algeria on July 11–12 suggests that the sources of the dust lie in this region. The progress of the dust outbreak can be followed from the African coast (on July 11) to Barbados (on July 16). Note that the main path of the dust cloud was to the north of Barbados. The transit time of 5–6 days is typical for such dust events.

In Table 2 Barbados dust events during the period from 1979 to 1992 are classified into three categories. For very intense dust events (where dust concentrations were higher than $100 \mu\text{g m}^{-3}$), TOMS detected 15 of the 17 observed at Barbados over the 14-year period. TOMS failed to detect two events, both of which were of 1-day duration; moreover, there were missing TOMS values for one of these events.

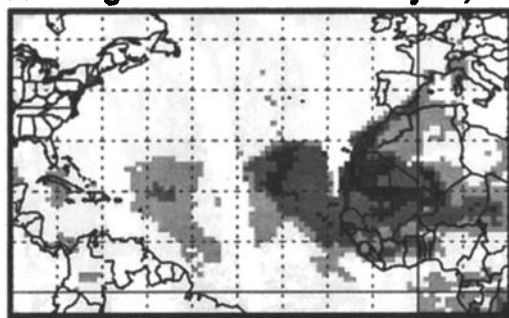
In the intermediate category ($50\text{--}100 \mu\text{g m}^{-3}$), TOMS detected 52 of the 69 events recorded at Barbados from 1979 to 1992. Of the 17 events missed by TOMS, 13 of them had some AI data missing during the event. Two other events were of 1-day duration. The two remaining undetected events occurred in November 1984 (3-day duration) and January 1987 (2-day duration); these had TOMS AI values of 0.3 and 0.4, respectively, values that placed them below the criterion level (0.5) but which were nonetheless relatively close to the threshold.

In the category of minor dust events ($20\text{--}50 \mu\text{g m}^{-3}$), there were a total of 278 events; of these, TOMS detected 171. Of the

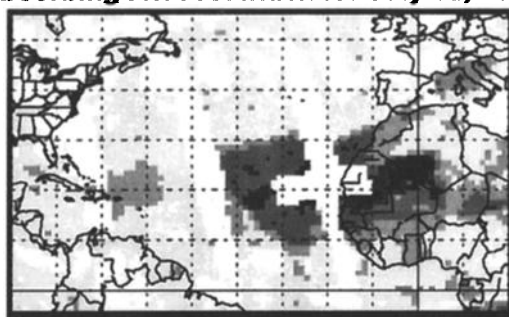
107 undetected events, 63 involved days when TOMS AI data were missing during the event, and 35 events lasted only one day. The nine remaining undetected events were of 2- or 3-day duration; most of these, eight, occurred in fall/winter, and only one occurred in summer.

In summary, this classification scheme yields excellent results in term of TOMS detection of African dust events at Barbados. Indeed, when we exclude 1-day duration events and events with missing TOMS AI data, TOMS failed to detect only 3% of all the African dust events occurring at Barbados (a total of 11 events) over the 14-year period. This performance is good even for the class of low-intensity events. The results are especially impressive when one considers that the Barbados site is located in the MBL; as previously stated, in summer, much of the dust is transported above the MBL, in the SAL [Prospero and Carlson, 1972; Talbot *et al.*, 1986]. Thus the dust concentrations measured at ground level can differ significantly from those above the MBL; in addition, TOMS measures a vertically integrated property of the aerosol that is weighted toward the high-altitude dust. These various factors could lead to very disparate results for these two types of measurements. The good agreement between the two suggests that the Barbados site provides a good monitoring of the “high altitude” African dust events occurring in the western NAO region in summer.

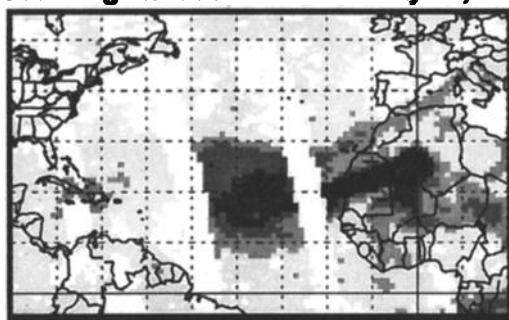
3.2.4. Miami. Figure 9 presents the daily time series of mineral dust concentrations and TOMS AI in Miami during the year 1984. African dust events at Miami are much less frequent than in Barbados, and they occur mainly in late summer. The corresponding variations of the TOMS AI appear much noisier than in Barbados; this is due in part to the fact that there are relatively few AI values above the 0.5 threshold. As a consequence, the correspondence between the dust events and the highest values of the TOMS AI is not as good as at the other sites. Only one very intense African dust event occurred during 1984, at the end of July; this was the same event that was observed at Barbados and which is discussed in the previous section. Figure 10 shows that during this event the mineral dust concentrations and TOMS AI follow one another rather closely. The maximum is characterized by a mineral dust concentration

Absorbing Aerosol Index for July 11, 1984

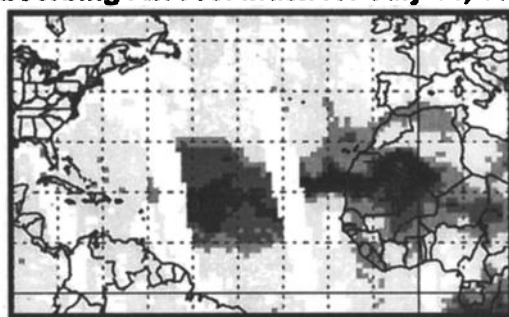
0.0 1.0 2.0 3.0 4.0 5.0>

Absorbing Aerosol Index for July 12, 1984

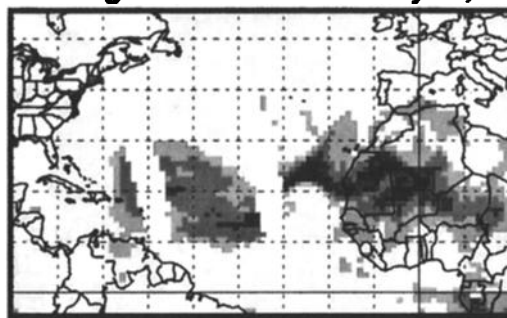
0.0 1.0 2.0 3.0 4.0 5.0>

Absorbing Aerosol Index for July 13, 1984

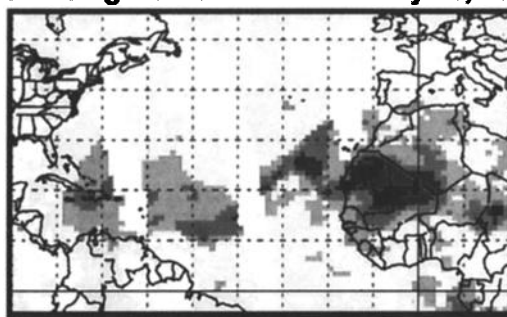
0.0 1.0 2.0 3.0 4.0 5.0>

Absorbing Aerosol Index for July 14, 1984

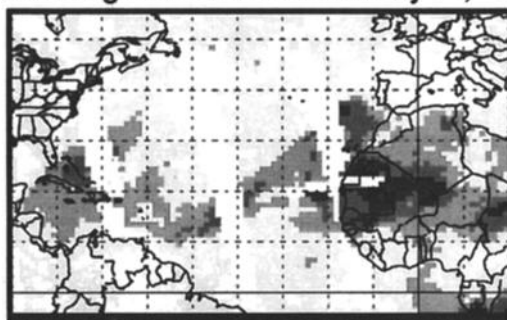
0.0 1.0 2.0 3.0 4.0 5.0>

Absorbing Aerosol Index for July 15, 1984

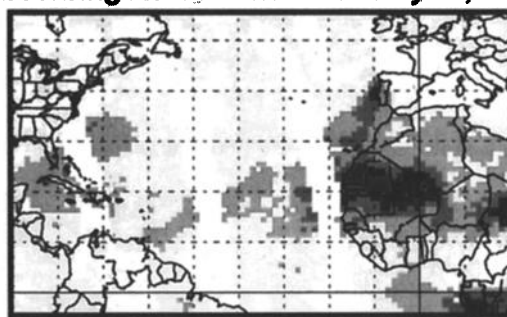
0.0 1.0 2.0 3.0 4.0 5.0>

Absorbing Aerosol Index for July 16, 1984

0.0 1.0 2.0 3.0 4.0 5.0>

Absorbing Aerosol Index for July 17, 1984

0.0 1.0 2.0 3.0 4.0 5.0>

Absorbing Aerosol Index for July 18, 1984

0.0 1.0 2.0 3.0 4.0 5.0>

Figure 8. TOMS aerosol index distribution over Africa and the North Atlantic for July 11–18, 1984.

around $120 \mu\text{g m}^{-3}$ on July 19 and an AI value around 1 on July 18. Despite some time deviations, the daily variations of the TOMS AI clearly show the influence of the African dust event on the satellite signal. Figure 8 shows the progress of the dust event moving toward Florida on July 17 and entering the Miami area on July 18.

Table 3 shows that only six highly intensive African dust events occurred at Miami over the whole period 1979–1992 and that TOMS detected only two of them. For the four remaining events, TOMS did not indicate clearly the presence of dust. Three of them were only of 1-day duration, and they did not occur in the summer, but rather in the fall, winter, and spring seasons. The

Table 2. Same as Table 1 but for Barbados African Dust Events Over the Period 1979–1992

Intensity of the Dust Event	Measured at Ground	Detected by TOMS	Not Detected by TOMS		
			Missing TOMS Data	One-Day Duration	Other
Major	17	15	1	1	
Intermediate	69	52	13	2	2
Minor	278	171	63	35	9
Total	364	238	77	38	11
Percentage		65%	21%	11%	3%

last event undetected by TOMS persisted for 3 days, and it occurred in late September 1985. A total of 18 intermediate dust events occurred in Miami over the period 1979–1992; of these, nine were detected by TOMS. Among the nine undetected events, five lasted only 1 day, three lasted 2 days, and one lasted 4 days. Of the 75 minor dust events, 32 were detected by TOMS. Of the 43 undetected events, four occurred when AI value data were missing during the event, and 25 were only of 1-day duration. In summary, 19% of the Miami dust events were not detected by TOMS, a much poorer performance than at Barbados and Tenerife. Nonetheless, the performance is acceptable when one takes into account the low intensity of most of these events and the great distance between Miami and the sources in Africa.

4. Comparison With Aerosol Optical Thickness Measured in Africa

Over Africa, we use AOT data from field experiments performed in Senegal and Niger to test the TOMS detection of mineral aerosols. Figure 11 presents the time variation of the AOT measured at 450 nm at M'Bour, Senegal, in April 1987 along with the TOMS AI from the pixel centered on this location. Because there were large variations in the aerosol content during the day (variations in the AOT up to a factor of 1.5–3) [Jankowiak and Tanré, 1992], only the measurements taken closest to the satellite acquisition time were selected for each of the 15 days during which measurements were performed. During the experiment there were frequent and intense dust outbreaks, which are a common occurrence at this time of the year [Jankowiak and Tanré, 1992]. Depending on the synoptic situation, air masses came both from the ocean and the land; consequently, the dust content of the winds varied greatly, depending on their trajectory, and the AOT ranged between 0.6 and 2.2. The corresponding values of the TOMS AI ranged

between 1 and 4.7. The TOMS AI time series closely follows the variations of AOT for both very dusty conditions (AOT greater than 1.5) and relatively clean air (AOT lower than 1). Some discrepancies appear (see May 1 and 2), but they could be at least partly explained by differences between the satellite acquisition time and that of the Sun photometer measurement (which range between a few minutes and several hours).

For a more quantitative comparison, Figure 12 shows a scatterplot of TOMS AI versus AOT at 450 nm during the three African field experiments mentioned above (M'Bour, 1986 and 1987, and HAPEX Niger, 1992). For this comparison we retained only Sun photometer measurements obtained within 2 hours of the satellite acquisition time. Since the time of the ground measurements sometimes differed considerably from the satellite acquisition time and because of cloudiness, validation data are only available for 33 days; in this data set, AOT values ranged between 0.25 and 2.2. The corresponding values of the TOMS AI ranged between 0.7 and 4.7. The agreement between the TOMS AI and the measured AOT (correlation coefficient of 0.84) is quite good, especially when one takes into account the uncertainties inherent in this comparison. First of all, because the TOMS AI is very sensitive to the height of the aerosol layer [Herman *et al.*, 1997; Torres *et al.*, 1998], some of the deviations in Figure 12 can be explained by variations in the aerosol content with altitude. In contrast, the AOT is a vertically integrated measurement of the dust content, and the measurement is not sensitive to the altitude of the aerosol layer. Moreover, the AI is also dependent on aerosol composition and size distribution, which could have been very different from one day to another during these experiments. Finally, the coarse spatial resolution of the TOMS measurements may also explain some of the discrepancies. Nonetheless, these results clearly indicate that the TOMS AI is strongly related to the vertically integrated desert dust amount, as characterized here in terms of AOT, over the African continent.

Table 3. Same as Table 1 but for Miami African Dust Events Over the Period 1979–1992

Intensity of the Dust Event	Measured at Ground	Detected by TOMS	Not Detected by TOMS		
			Missing TOMS Data	One-Day Duration	Other
Major	6	2		3	1
Intermediate	18	9		5	4
Minor	75	32	4	25	14
Total	99	43	4	33	19
Percentage		44%	4%	33%	19%

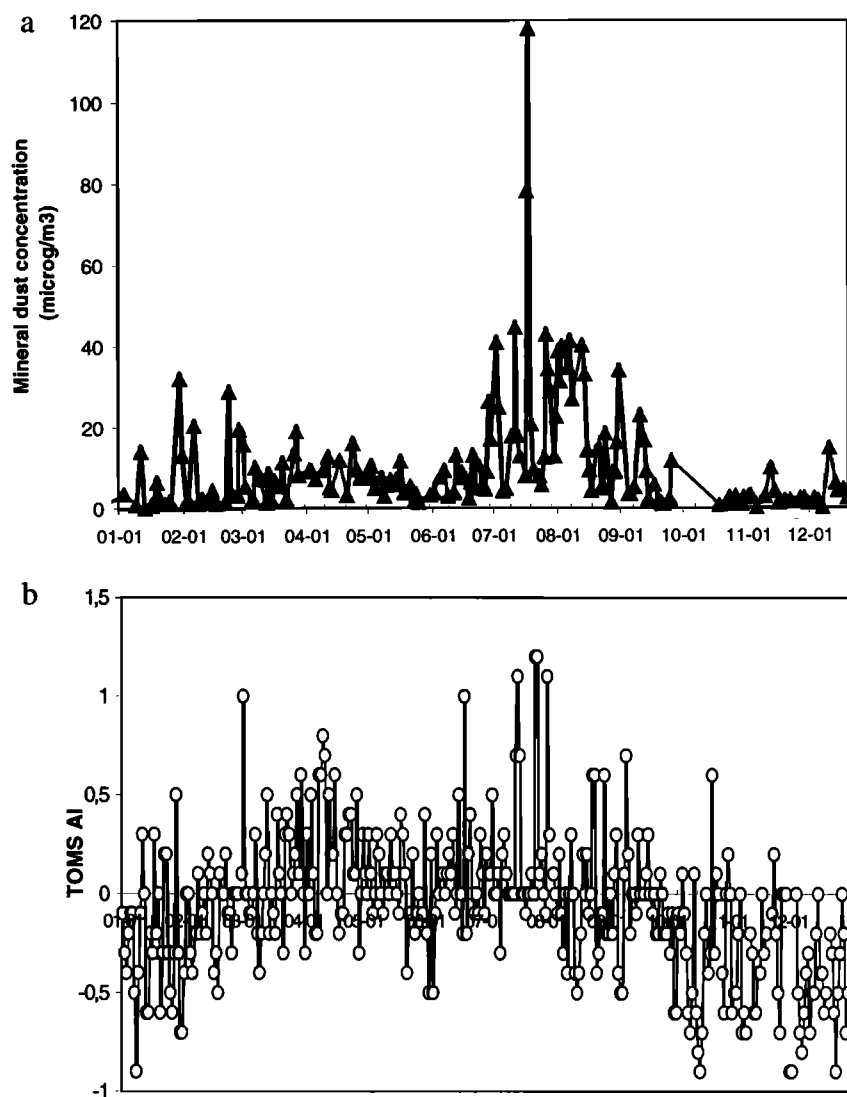


Figure 9. Time series of daily values of (a) the mineral dust concentration, and (b) the TOMS aerosol index, at Miami during 1984.

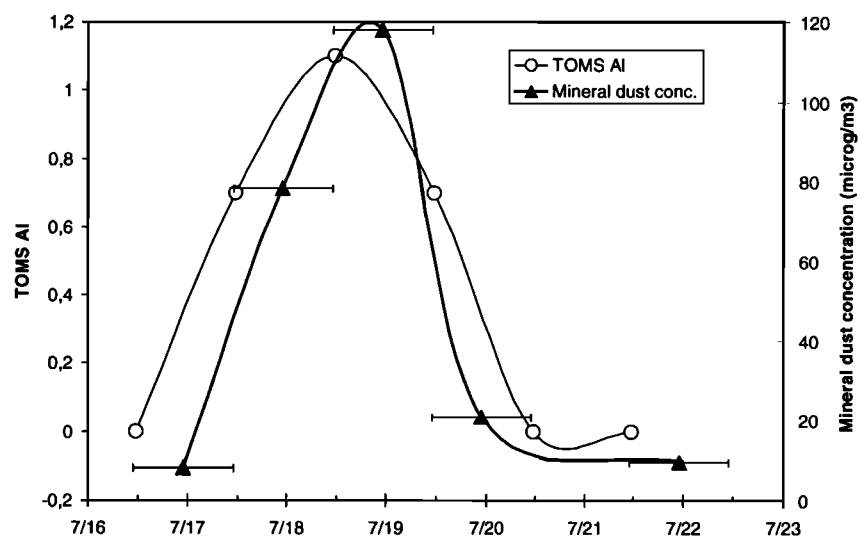


Figure 10. Time series of daily values of the TOMS aerosol index and mineral dust concentration at Miami during a major dust event, from July 16 to 22, 1984. The length of the horizontal bar marking the dust concentration indicates the duration of the aerosol sample.

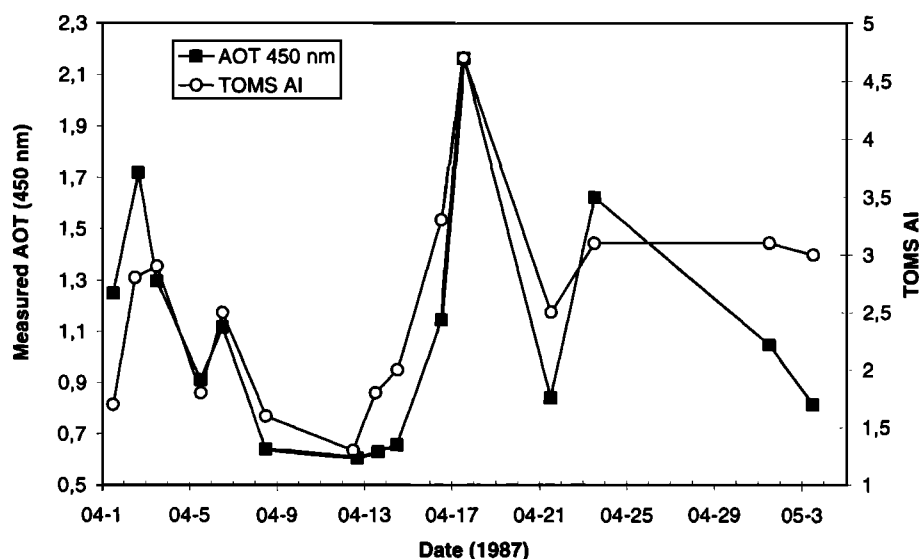


Figure 11. Time series of the TOMS aerosol index and aerosol optical thickness (AOT) measured at 450 nm in M'Bour, Senegal, from April 1 to May 3, 1987.

5. Conclusion

In this paper we use daily aerosol measurements of African mineral dust to test the ability of Nimbus 7 TOMS AI to detect absorbing aerosol over both the NAO and North Africa. The comparison was performed at Sal (Cape Verde Islands), Tenerife (Canary Islands), Barbados, and Miami. At Tenerife, from 1988 to 1992, 80% of the dust events (i.e., events where the dust concentration exceeded $20 \mu\text{g m}^{-3}$) were detected by TOMS; excluding those dust events during which some of the TOMS data are missing and also 1-day duration events, TOMS detected 99% of the events. The excellent correlations at Tenerife are due in part to the elevation of the sampling site (2360 m), which places it within the Saharan air layer, where much of the dust is transported during the summer months. Because the TOMS

response to absorbing aerosol increases with increasing altitude, the Tenerife site is ideal for the characterization of the TOMS ability to detect high-altitude dust aerosol. In contrast, during the winter months, much of the dust transport off the west coast of North Africa takes place at relatively low altitudes. The site at Sal Island lies in the path of much of the winter transport; our measurements from Sal Island suggest that despite the relatively low altitude of the dust transported in winter, TOMS was able to detect the African dust events. At Barbados and Miami, the TOMS success rate decreased, as might be expected due to the lower aerosol concentrations at these sites, which at times approach the 0.5 threshold set for the TOMS AI; over the period 1979–1992, TOMS detected 65% and 44% of the African dust events over Barbados and Miami, respectively. However, if we consider only multiday dust events with no missing values of the TOMS AI, TOMS detected 97% of the events at Barbados and 81% in Miami. Most of events that were not detected were of low intensity.

Over Africa, there was good agreement between the TOMS AI and ground-based measurements of AOT performed during campaigns in Niger and Senegal. The comparison yielded a nearly linear relationship between the TOMS AI and the AOT. Despite the limited time span of the AOT measurements, these results confirm that the TOMS AI is strongly related to the AOT. This comparison also demonstrates the ability of TOMS to provide a measure of the mineral dust content of the atmosphere over continental regions, in contrast to other satellite detection systems based on measurements in the visible range (e.g., AVHRR and Meteosat), which can only be routinely used to retrieve aerosol contents accurately over the oceans [Husar *et al.*, 1997; Moulin *et al.*, 1997a, b] and low-reflectivity land surfaces.

These results constitute an important step in the validation process of the TOMS AI product; we have shown that the TOMS AI provides a remarkable detection of the African dust events recorded over the NAO but does not quantify accurately the intensity of these events, due mainly to the sensitivity of TOMS to the altitude of the dust. The quantitative development of the TOMS AI will be done in terms of the aerosol optical depth [Torres *et al.*, 1998]. However, this will require a careful characterization of aerosol composition, size, optical properties,

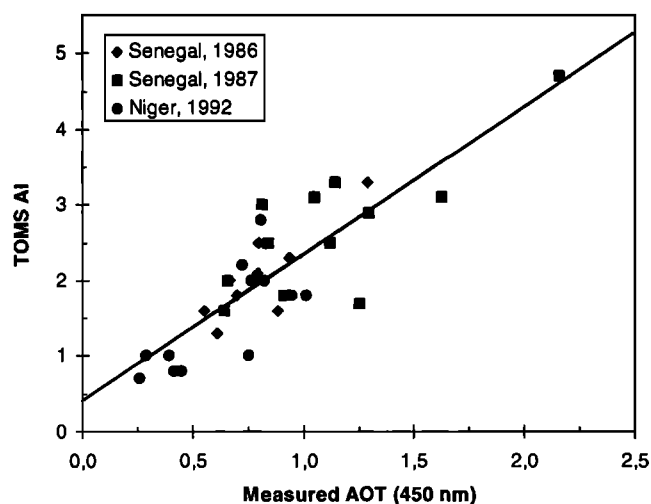


Figure 12. Scatterplot of TOMS aerosol index against aerosol optical thickness measured at 450 nm at ground level during three experiments in Africa: M'Bour in April 1986 and April 1987, and Niger (Hydrologic Atmospheric Pilot Experiment) in September 1992. The linear regression is given by $\text{AI} = 1.94(+0.22)\text{AOT} + 0.40(+0.21)$; $r = 0.84$.

and altitudes of the aerosol layers. Nonetheless, our study of mineral aerosol from a specific region (west Africa) suggests that the TOMS AI can be used to characterize desert dust distributions over both oceanic and continental regions. The 14.5-year record of Nimbus 7 TOMS affords a unique opportunity to assess the dust transport record on a global scale. The TOMS data will provide us with valuable information about the major sources of mineral dust, the factors that affect dust output from these sources (including weather, climate, and land use), and the meteorological conditions associated with dust mobilization and long-range transport. Information on these processes will be important for the development of climate models that incorporate mineral dust as a climate-forcing agent.

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