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# Understanding the 30-year Barbados desert dust record

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[1] Atmospheric mineral aerosols influence climate and biogeochemistry, and thus understanding the impact of humans on mineral aerosols is important. Our longest continuous record of in situ atmospheric desert dust measurements comes from Barbados, which shows fluctuations of a factor of 4 in surface mass concentrations between the 1960s and the 1980s [*Prospero and Nees*, 1986]. Understanding fluctuations this large should help us understand how natural and anthropogenic factors change mineral aerosol sources, transport, distributions, and deposition, although we are limited in our ability to interpret the results as there is a quantitative record only at one location. We test the hypothesis that dry topographic lows (and not disturbed sources such as cultivated areas or new desert regions) are the sources of desert dust, using a hierarchy of models as well meteorological data sets to look at decadal scale changes in the North Atlantic desert dust. We find that the inclusion of a disturbed source improves our simulations in many (but not all) comparisons. Unfortunately, we are severely limited by the accuracy of the available data sets and models in making definitive statements about the role of disturbed sources or anthropogenic activity in changing the atmospheric desert dust cycle. Processes that might change the size or intensity of desert dust sources in North Africa (such as new sources due to desertification or land use) may be difficult to distinguish from topographic low sources in models due to their similar geographical locations and impact on atmospheric aerosol distributions. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 4801 Oceanography: Biological and Chemical: Aerosols (0305); *KEYWORDS:* mineral aerosols, desert dust, North Africa, desertification

## 1. Introduction

[2] Estimates of the anthropogenic radiative forcing of climate change are uncertain for all aerosols, but especially mineral aerosols [*Intergovermental Panel on Climate Change (IPCC)*, 2001]. This is due in part to the large uncertainties in the radiative forcing due to mineralogy, size distributions, vertical distributions and albedo effects [e.g., *Sokolik and Toon*, 1996; *Liao and Seinfeld*, 1998], but it is also due to the difficulty in quantifying the human impact on atmospheric desert dust. *Prospero and Nees* [1986], *Prospero et al.* [1996] and D. Savoie (personal communication, 2001) have measured in situ Barbados desert dust concentrations from the late 1960s to the present, shown in Figure 1. This time series suggests that desert dust at Barbados has increased by 2–4 fold since the late 1960s, corresponding to an extended drought in the western Sahel of North Africa (also shown in Figure 1 calculated from *Dai et al.* [1996] gridded observations). There was a change in measurement technique at the Barbados site between 1970 and 1971, and analysis was conducted in order to minimize differences in the measured concentrations depending on the measurement techniques [*Prospero and Nees*, 1986]. Even if the values prior to 1970 are not regarded as robust, the low concentrations during 1975–1976 were similarly low (7 $\mu g/m^3$ instead of 5 $\mu g/m^3$), suggesting that large fluctuations in mineral aerosols have been observed at Barbados. Also shown in Figure 1 is the visibility data for Gao in the Sahel region of North Africa [*Mbourou et al.*, 1997], suggesting a similar increase in dusty days in the Sahel between the 1960s and 1980s. It has been speculated that the observed mineral

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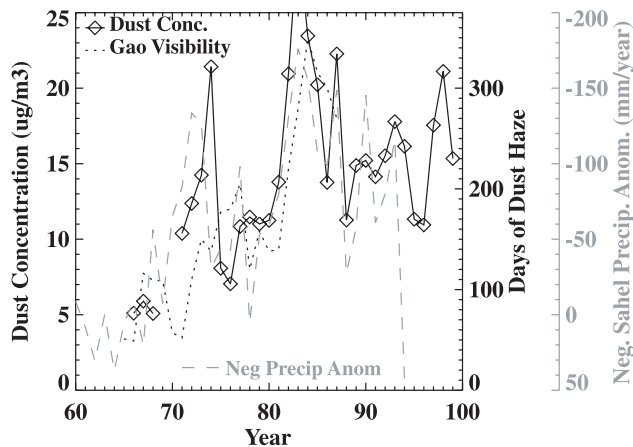
**Figure 1.** Annually averaged observed concentrations of desert dust from Barbados [*Prospero et al.*, 2002] (scale on the left hand side, solid line with diamonds), days with dust haze at Gao, Mali [*Mbourou et al.*, 1997] (scale on right hand side, dotted line—only extends through 1986) and Negative Sahel Anomalous Precipitation from *Dai et al.* [1996] (scale on the right hand side, dotted line) averaged between 10N and 22N, 15W and 15E (only extends through 1995).

aerosol increase at Barbados and in the source region is due the Sahel drought and/or human land use [*Prospero and Nees*, 1986; *Tegen and Fung.*, 1995; *Prospero et al.*, 1996; *Mbourou et al.*, 1997].

[3] The sources of atmospheric mineral aerosol or desert dust are dry, unvegetated soils in regions with strong surface winds and easily erodible soils [e.g., *Marticorena and Bergametti*, 1996]. *Tegen and Fung* [1995] argue that "disturbed soils" (cultivated soils, soils disturbed by human-induced land use changes and newly created desert regions, whether natural or anthropogenic) have caused a 50% increase in atmospheric desert dust. Studies have suggested that cultivated lands can be very active dust sources [e.g., *Gillette*, 1988; *Saxton et al.*, 2000]. On the other hand, *Prospero et al.* [2002] and *Ginoux et al.* [2001] have provided strong arguments using TOMS satellite, geomorphological data and model studies that the dominant sources of atmospheric desert dust are low-lying regions (topographic lows) such as dry lake beds. *Prospero et al.* [2002] argue that there is little evidence for land-use impacts on desert dust sources globally and in the Sahel, although they do not directly address whether changes in the Sahara-Sahel boundary could be responsible for sources.

[4] Besides the possibility that humans directly impact sources due to cultivation or pasture use, some studies suggest that the well-documented extended drought in North Africa is due to human land use changes [e.g., *Charney et al.*, 1977]. If that is the case, then there may be an "indirect" effect of human land use on atmospheric desert dust. Human land use could induce a more arid climate, creating more extensive desert dust source regions and decreasing wet deposition, thereby allowing desert dust to travel farther downwind.

[5] In this paper we seek to understand the causes of the change in desert dust in the Barbados dust record, to understand the relative role of sources and transport, as well as to apportion the importance of natural variability and anthropogenic activities in changing concentrations at Barbados. We make a first step toward doing this using the Barbados data set [*Prospero and Nees*, 1986], AVHRR [*Husar et al.*, 1997] and TOMS [*Torres et al.*, 2002] satellite data, in addition to 3-D model simulations. We are especially concerned with capturing the largest part of this signal: the difference between the late 1960s minimum and the 1983–1984 maximum in desert dust at Barbados, which shows a four-fold change. In subsequent papers we plan to look more closely at our ability to capture events and inter-annual variability during the 1980 and 1990s, which will also shed light on natural and anthropogenic impacts on atmospheric desert dust.

[6] The paper is organized as follows: first we describe the source regions and model we use in the 3-D modeling study in section 2. Also in section 2, we present results from the 3-D modeling studies, as well as comparisons with observations. Here we focus on the simulations for 1984 and 1966. In section 3, we consider other source changes that we have not included in the model, as well as the timing of source changes. Section 4 summarizes the results of this study.

## 2. 3-D Model Studies

[7] Studies such as *Guelle et al.* [2000] and *Ginoux et al.* [2001] have shown that 3-D chemical transport modeling studies based on forecast center analyses can do a good job simulating the climatology of desert dust and even specific events. In this study, we use the Dust Entrainment And Deposition (DEAD) desert dust module developed by C. S. Zender et al. (The mineral dust entrainment and deposition (DEAD) model: Description and 1990s dust climatology, submitted to *Journal of Geophysical Research*, 2002, hereinafter referred to as Zender et al., submitted manuscript, 2002) based on wind tunnel studies and in situ studies [*Iversen and White*, 1982; *Marticorena and Bergametti*, 1995; *Gillette et al.*, 1998; *Fecan et al.*, 1999]. We assume that the process that entrains soil particles into the atmosphere begins with strong winds at the surface moving over unvegetated and dry soils, causing a horizontal flux of soil particles (saltation). Once soil particles are saltating, a small fraction of the horizontal flux is translated into a vertical flux, and thus is "mobilized" or "entrained" into the atmosphere for transport by the transport model. This horizontal flux is a function of the friction wind speed and a threshold wind friction speed, which in turn is dependent on the soil properties and environment. Our dust entrainment (the vertical flux of soil particles) is proportional to the vertical flux calculated following this methodology, multiplied by our preferential source areas (defined in section 2.1). The equations describing the mobilization are included in other papers [*Iversen and White*, 1982; *Marticorena and Bergametti*, 1995; *Gillette et al.*, 1998; *Fecan et al.*, 1999]. We use four aerosol size bins, with the mass distributed in the source regions between the different size fractions as shown in Table 1. Besides having four explicitly simulated aerosol size bins, we assume a lognormal size distribution within each bin, thus allowing more information about the smallest and largest particles to be

**Table 1.** Lifetime of Desert Dust in Different Bins

| Bin (Radius, μm) | Total Lifetime, days | Wet Deposition Lifetime, days | Dry Deposition Lifetime, days | Source Fraction of Dust From Each Bin | Atmospheric Loading Fraction From Each Bin |
|---|---|---|---|---|---|
| 1 (0.05−0.5) | 11.7 | 12 | 362 | 10% | 21% |
| 2 (0.5−1.25) | 10.5 | 12 | 81 | 30% | 56% |
| 3 (1.25−2.5) | 3.5 | 12.6 | 4.8 | 30% | 18% |
| 4 (2.5 5.0) | 1.0 | 15 | 1.1 | 30% | 5% |
| Total Dust | 5.7 | 12 | 10.5 | | |

carried with only four size bins. Within each bin, the gravitational settling rates and optical properties are computed as the cross-sectional area-weighted mean of an assumed sub-bin lognormal distribution. The sub-bin distribution has a mass median diameter of 2.5 μm and geometric standard deviation of 2.0, which represents well the long range transport mode of dust [*Schultz et al.*, 1998]. Also included in the DEAD module are the loss mechanisms for mineral aerosols, and turbulent dry deposition and gravitational settling are included as described by *Seinfeld and Pandix* [1996]. Wet deposition is parameterized using a simple scavenging coefficient, following *Tegen and Fung* [1994].

[8] We use this dust module in the MATCH model, which is an offline transport model [*Rasch et al.*, 1997; *Mahowald et al.*, 1997] using the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP) reanalysis meteorology [*Kalnay et al.*, 1996; *Kistler et al.*, 2001], used at a horizontal resolution of T62 (1.8° × 1.8°), with 28 levels in the vertical and at 6 hourly intervals. The dust model was simulated using meteorology from 1966 and 1984 for most of the studies, with sensitivity tests during 1967, 1976 and 1983. We allowed a one-month spin up time during all simulations. Since the model is an offline chemical transport model, there is no modeled feedback between the aerosols and the meteorology (although the real meteorology could include the feedback implicitly [e.g., *Alpert et al.*, 1998]).

[9] The lifetime of desert dust in each size bin due to different processes in the 1984 simulations is shown in Table 1. Also shown in Table 1 is the fraction of dust in each bin assumed input in the source regions, and resulting in the model predicted dust loading. The lifetimes are roughly consistent with previous studies [e.g., *Tegen and Fung*, 1995], and are similar for the different sources used for this study.
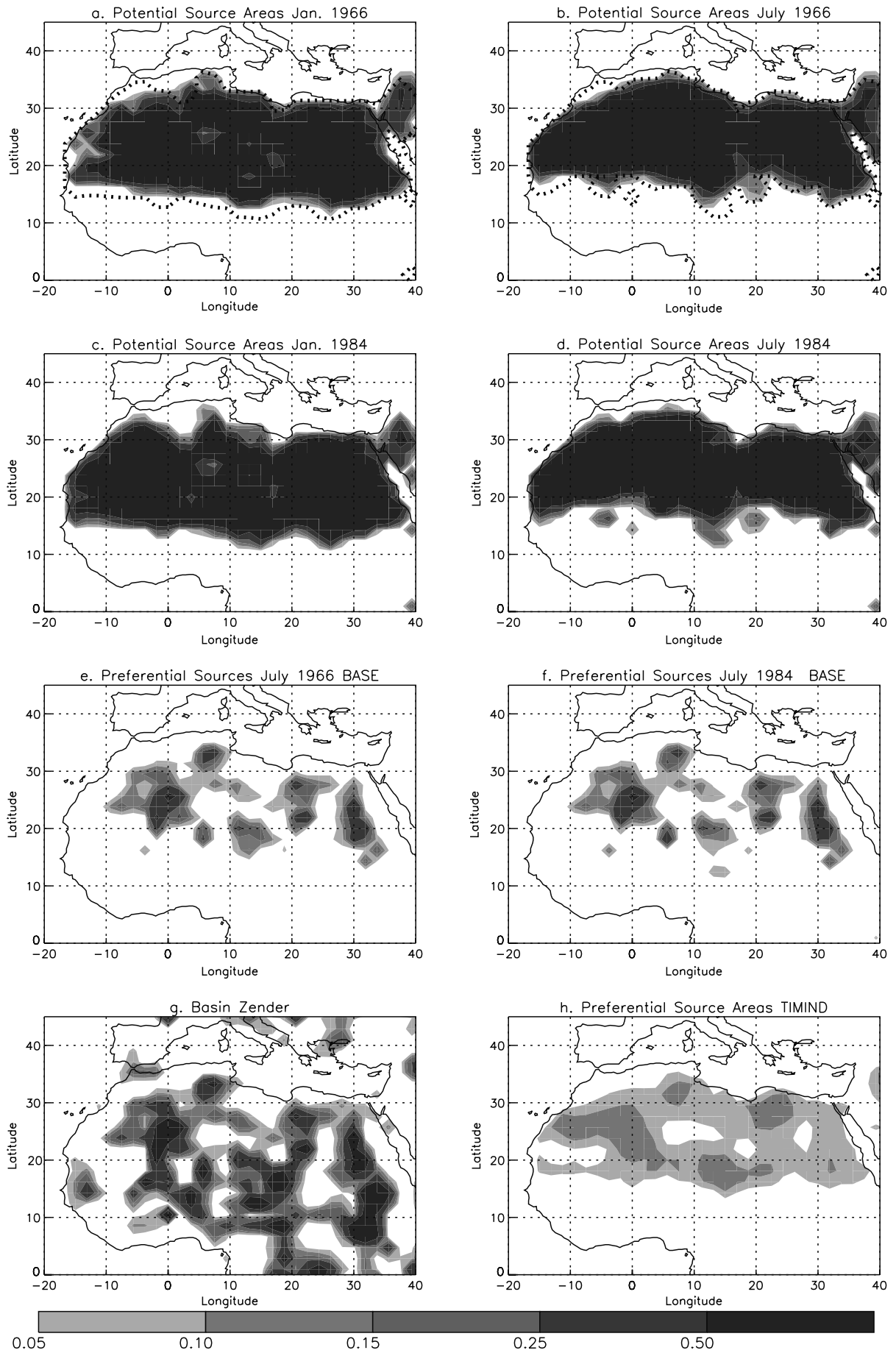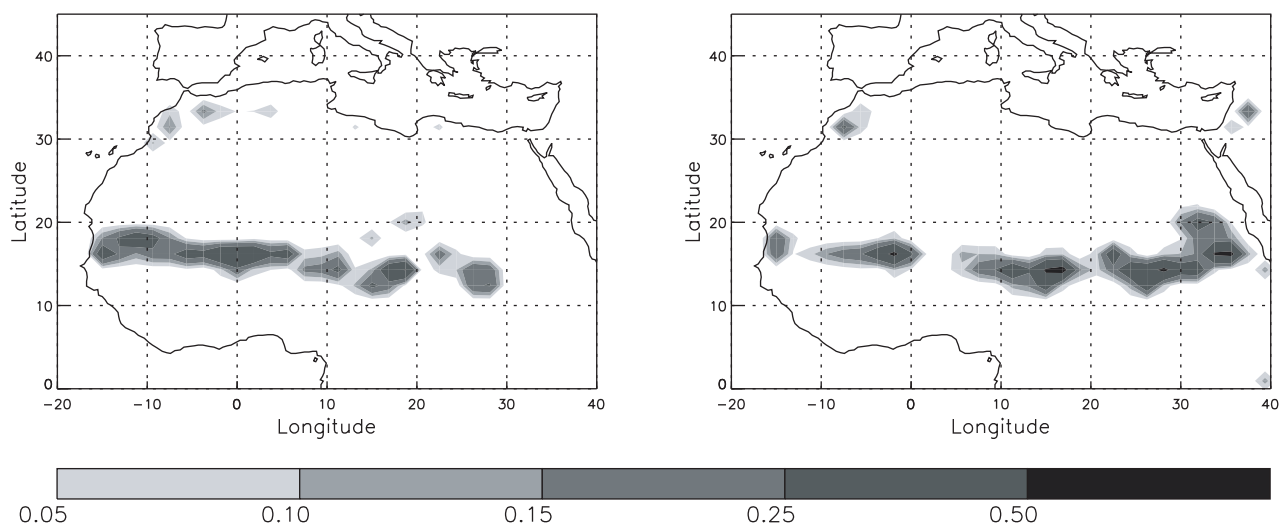
## 2.1. Source Areas

[10] The dust module described in section 2 is derived from wind tunnel and in situ studies. The original algorithms require the source soil size distribution and assume unvegetated soils. Because we do not have good information globally for the soil size distribution, we assume soils are replete with particles optimally sized to initiate saltation, and use a factor to describe what fraction of each grid box consists of easily erodible soils. We define "potential source areas" as dry, unvegetated regions, and "preferential source areas" as dry, unvegetated regions with easily erodible soils. The total amount of desert dust entrained into the atmo-

sphere is the "mobilization". Analysis of the TOMS aerosol index has suggested that low lying regions are the strongest sources [*Prospero et al.*, 2002] and presumably have soil size distributions which are optimal for mobilization of desert dust. Since these regions are periodically injected with sediment transported by water or have substantial lake deposits, they still have easily erodible soils. In contrast, it is thought that the wide expanses of the Sahara, for example, have already been denuded of their easily erodible particles after thousands of years of wind erosion [e.g., *Prospero et al.*, 2002]. Regions of "disturbed soils" (which include cultivation, other types of land use and regions where the vegetation has changed) have also been proposed as good source areas [e.g., *Tegen and Fung*, 1995], because they may contain easily erodible soils.

[11] In order to explore the role of dry topographic lows and "disturbed" soils on impacting desert dust source areas, we use two different types of sources. First, we look at the topographic low sources, following the methodology of *Ginoux et al.* [2001] and Zender et al. (submitted manuscript, 2002), but allow for changes in the vegetation before and after the beginning of the drought. We use the BIOME3 equilibrium vegetation model [*Haxeltine and Prentice*, 1996] to predict potential source areas, which are defined using the methodology of *Mahowald et al.* [1999], but with anomalous precipitation from the *Dai et al.* [1996] gridded precipitation data set (based on meteorological station observations), averaged for 5 year increments starting in 1950, and the NCEP reanalysis for changes in temperature and insolation. In addition, we define potential source areas for each month, using the soil moisture criteria for each month. (Note that soil moisture is checked both to determine whether an area is a potential source area, using BIOME3 output, and inside the dust mobilization scheme, using NCEP reanalysis soil moisture.) Since the leaf area index is an annual average in this model, we use the annual average leaf area index to indicate whether the region is unvegetated. Vegetation in arid regions appears to respond quickly to precipitation changes [e.g., *Tucker and Nicholson*, 1999] so that using 5-year averages in an equilibrium vegetation model when looking at arid regions is reasonable, while in other regions a much longer time frame would be appropriate. Figures 2a–2d show the "potential source areas" for 1965–1969 and 1980–1984, for January and July. In Figures 2a and 2b, representing January and July 1965–1969, there is a dotted line, which represents the 0.05 potential source area contour line from January and July 1980–1984, respectively, in order to make the larger potential source areas in 1980–1984 clear. The potential source areas extend farther south in January than July due to changes in the Inter-tropical Convergence Zone (contrast the location of the potential source areas and the 20°N latitude line in Figures 2a and 2b, or 2c and 2d).

[12] In order to define the dry topographic lows, we use the Zender basin factor, which calculates the lowest areas globally, based on a U.S. Geological Survey topographic map [*Ginoux et al.*, 2001] (Zender et al., submitted manuscript, 2002), shown in Figure 2g. The preferential source areas are thus regions which the BIOME3 model predicts to be unvegetated and dry and where the Zender basin factor suggests is a topographic low, shown in Figure 2e and 2f,

a. Potential Source Areas Jan. 1966

b. Potential Source Areas July 1966

c. Potential Source Areas Jan. 1984

d. Potential Source Areas July 1984

e. Preferential Sources July 1966 BASE

f. Preferential Sources July 1984   BASE

g. Basin Zender

h. Preferential Source Areas TIMIND

0.05      0.10      0.15      0.25      0.50

**Figure 3.** "New desert" sources, as defined in the text (and called the NEW case) (a), as well as cultivation in desert sources (b). Represent fraction of grid box, except (b), which is 10*fraction).

for July of 1966 and 1984, respectively. Also, shown for comparison is the Ginoux source [*Ginoux et al.*, 2001], which includes both topography and time independent vegetation, which we include for a sensitivity analysis (Figure 2h). Both the Ginoux and Zender maps define source regions from the same topographic data sets, but use slightly different resolution and functional relationships to determine source areas, with Zender having a higher fraction of the source concentrated in the topographic lows (as seen in Figures 2e and 2h). (At the time of the revision of this manuscript, an error in the computer program used to derive the Zender basin factor was found, which appears to be responsible for some of the differences between the two source areas. We did not repeat the experiments, since the changes will make the results of the model studies even more similar.) Notice that the southward and northward extent of the preferential source regions specified from the BIOME3 model are similar to those specified by *Ginoux et al.* [2001], which were based on satellite retrieved vegetation, suggesting that constraining unvegetated regions from the two different methodologies (BIOME3 or satellite data) provides similar results. In the rest of the paper, we will call the Zender basin with the time varying vegetation the BASE case, and call the time independent source areas from *Ginoux et al.* [2001] TIMIND.

[13] Second, in order to explore the role of disturbed soils, we look at both new desert and cultivated desert regions, shown in Figures 3a and 3b, respectively. New desert regions are calculated from the BIOME3 analysis, and represent regions that are defined as a potential source area in 1980–1984, but were not potential source areas during 1965–1969, which was a fairly wet time period.

New desert source areas supported plants previously, and the plants acted to hold down the soils. When the plants are removed, there should be larger amounts of easily erodible soils than in regions that have been desert for many years, similar to the "Sahara Boundary Shift" source by *Tegen and Fung* [1995] although derived differently.

[14] Also shown in Figure 3b are the areas that are considered "cultivated" in the *Matthews* [1983] data set (including pasture) in addition to being a potential source area in 1980–1984; in other words, these regions have dry, unvegetated soils being cultivated or used for pasture. The cultivated desert region largely disappears in 1965–1969, due to the wetter Sahel region (not shown). It may also be there that there was less land use in 1965–1969, as discussed in section 3.2. We are presuming that the land use would disturb the soils and allow the soil particles to be more easily mobilized [e.g., *Saxton et al.*, 2000], although other effects are possible as described in section 3.2.

[15] Both the "new desert" and the "cultivated desert" sources represent preferential sources that could be present in 1984 but not 1966. Notice that the areas are largely geographically colocated and, it would be difficult to discern between these two types of sources in the atmosphere. This has two implications. First of all, we need not simulate the impact of both sources on the atmosphere, so we include simulations of the "new desert" source only (called NEW), but we can use the impacts of the NEW source to represent the "cultivated desert source". Second, this implies that it may be difficult to determine the process responsible for sources in this region, since they could be either due to a vegetation shift or due to cultivation in a region (including pasture usage).

**Figure 2.** (opposite) Potential source areas in fraction of the grid box for 1966 in January (a) and July (b), and for 1984 in January (c) and July (d). The thick dotted line in (a) and (b) represent the extent of the 0.05 contour interval in 1984 (c and d, respectively) so that the expansion in 1984 can be seen. Preferential sources for July 1966 (e) and July 1984 (f) are also shown, which represent the potential source areas times the Zender basin factor (g), which represent the source areas for the BASE case. For comparison, the preferential source areas from Ginoux are shown (h), and are called the TIMIND sources. All represent fraction of grid box.
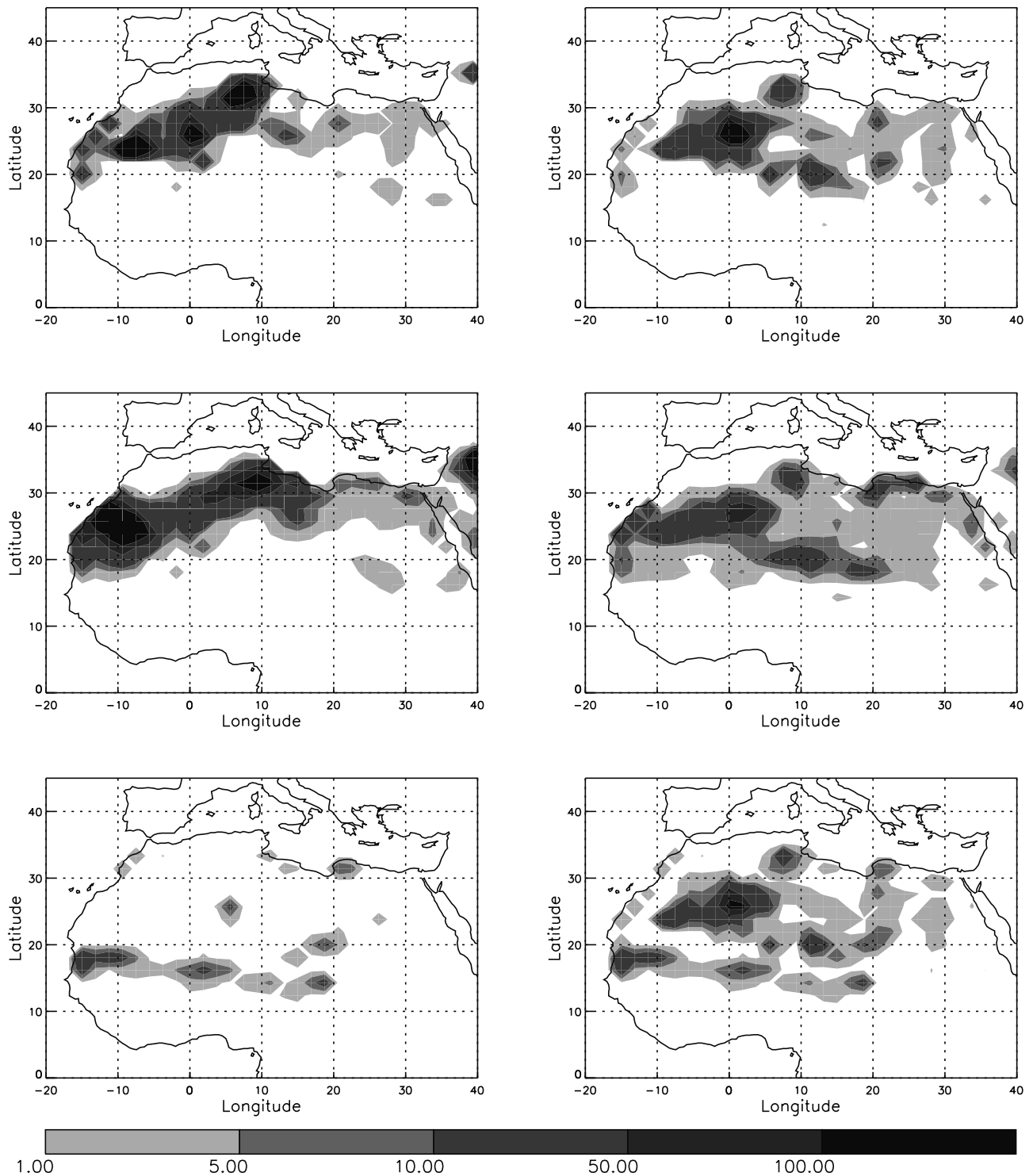
**Figure 4.** Model calculated mobilization (in g/m$^2$/month) of soil particles for July in 1966 (a) and 1984 (b) using the BASE source, for 1966 (c) and 1984 (d) using the TIMIND source and for 1984 with the NEW source in (e). Also shown is the mobilization using the BASE plus NEW in (f). The mobilizations are normalized so that 1984 annual concentrations match the Barbados observations [except in (e), which shows the portion of (f) which comes from the NEW source].

[16] The resulting mobilization (or entrainment of dust into the atmosphere) is calculated for 1966 and 1984 for the BASE case and shown in Figures 4a and 4b, respectively. All of the model runs have been normalized so that the mean 1984 concentration at Barbados is the same as the observations. For comparison, the mobilization for 1966 and 1984 for the TIMIND source is shown in Figures 4c and 4d, respectively, and the mobilization from NEW

sources is shown in Figure 4e (this is normalized as part of the BASE plus NEW source). Figure 4f shows the sum of the BASE plus NEW source for 1984 assuming that the land fraction from the new desert sources are twice as effective at mobilizing desert dust (this gives us the correct 1966/1984 ratio at Barbados, as seen in section 2.4) [e.g., *Gillette*, 1988; *Tegen and Fung*, 1995; *Saxton et al.*, 2000]. Since the processes included in the model are linear, these normalizations are done after the simulations are complete. Notice that mobilization from the new desert areas is located in regions similar to the broad topographic lows defined in the western Sahel region in the TIMIND source—thus discerning between different mechanisms causing these sources may be difficult.

[17] For this paper, we conducted two simulations using the BASE source (1966 and 1984), two simulations using the TIMIND source (1966 and 1984), and one simulation using the NEW source (1984). The NCEP reanalysis is valuable because it contains 3-D data sets going back to 1948, however studies have noted problems in the reanalysis, especially due to changes in the observations between the 1960s and 1980s [e.g., *Kistler et al.*, 2001; *Santer et al.*, 1999; *Trenberth and Guillemot*, 1998]. Note that both the BASE and TIMIND source area studies use the Zender dust module (described in section 2), which uses a different mobilization scheme than used by *Ginoux et al.* [2001], while the source area used for TIMIND comes from *Ginoux et al.* [2001]. In addition, we conducted several sensitivity analyses, which will be briefly mentioned in the text. In the next section we compare observations of aerosol optical depths with model results.

## 2.2. Aerosol Optical Depths

[18] *Tegen and Fung* [1995] argue that there is an observed seasonal shift of aerosol optical depths from the AVHRR satellite [*Husar et al.*, 1997]—in the wintertime the maximum optical depths are at approximately 10 N during the winter and 20N during the summer (seen in Figure 5). In their desert dust model, they require a "disturbed soil" source in the western Sahel region in order to capture this seasonal shift in aerosol optical depths. From this analysis and other constraints on desert dust, they argue that approximately 50% of the atmospheric desert dust is due to disturbed sources. In contrast, using our model, there is no requirement of a disturbed source in order to capture the shift in maximum—the natural topographic low sources in combination with the NCEP meteorology will cause a shift in optical depths, as seen in Figure 5, consistent with previous forecast center analyses-based model studies [*Guelle et al.*, 2000; *Ginoux et al.*, 2001; Zender et al., submitted manuscript, 2002]. Notice that the magnitude of the optical thicknesses in winter in the BASE case are less than in the AVHRR satellite data, which could be due to biomass burning or other aerosols contributing to the AVHRR aerosol optical depth, errors in the optical depth retrieval algorithm or errors in our model. A similar shift is seen when TIMIND source is used. Notice however, that inclusion of the new desert source (NEW), while not required to match the latitudinal shift, does improve the relative magnitudes of the winter and summer seasonal averages. This may or may not be appropriate, depending on the size of the biomass burning signal during the
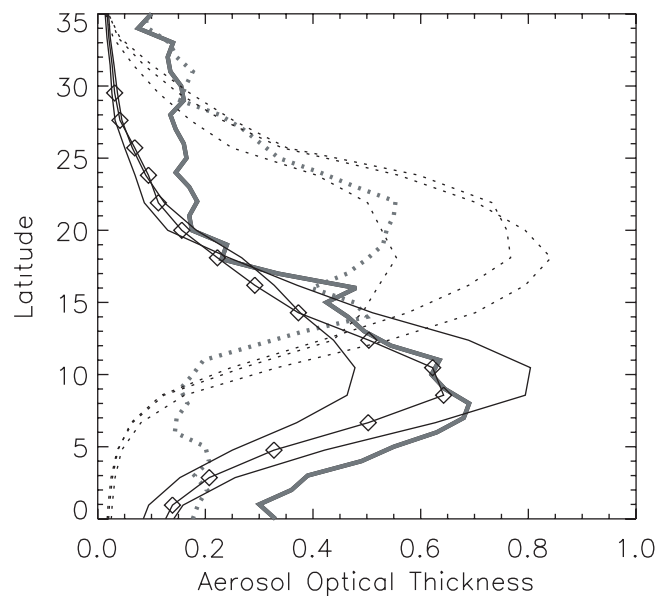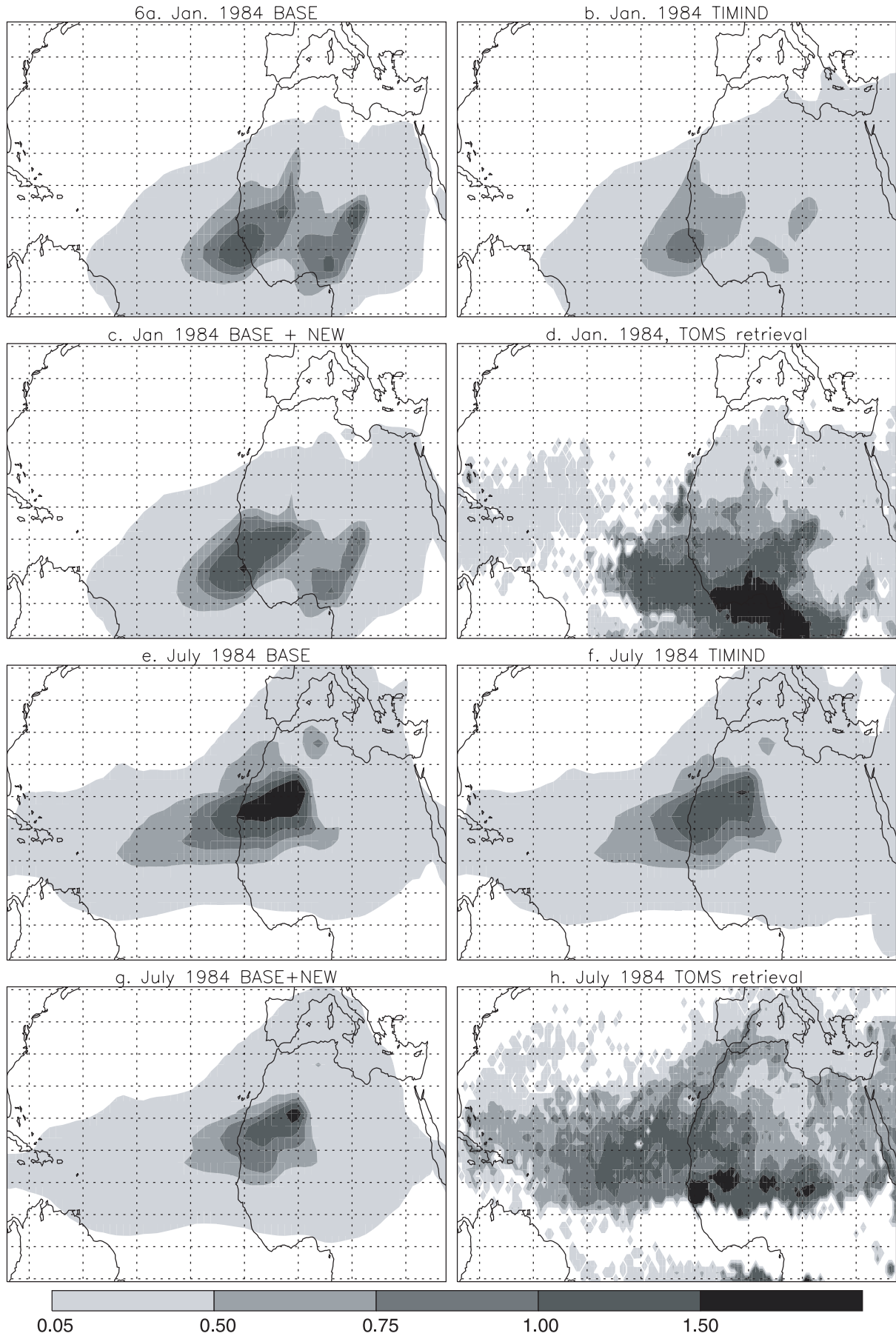


**Figure 5.** Aerosol optical depth at 20W for the AVHRR satellite data [*Husar et al.*, 1997] during 1984 for a December, January, February (grey solid line) average and a June, July, August Average (grey dotted line). Model results for 1984 are also shown in thin lines for the same time periods using the BASE (diamond), TIMIND (triangle) and BASE plus NEW (square) source areas assuming a nominal wavelength of 630 nm.

summertime, which we do not constrain in this study, and which could contribute substantially to the aerosol optical thicknesses during the dry season.

[19] Figure 6 shows the aerosol optical depths at 380 nm in July from the BASE, TIMIND, and BASE plus NEW sources, as well as those derived from the TOMS satellite [*Torres et al.*, 2002] for January and July 1984. The optical depths from the TOMS satellite are calculated using measured radiances at two different wavelengths in the *uv* range [*Torres et al.*, 1998], allowing *Torres et al.* [2002] to estimate optical depths over land. In addition, *Torres et al.* [2002] used the vertical distribution of the aerosols from *Ginoux et al.* [2001] in order to convert from radiances to aerosol optical depth. The vertical distribution in this model and *Ginoux et al.* [2001] are likely to be different, especially in the case of the BASE plus NEW source, which may lead to discrepancies between the optical depths predicted here and reported by *Torres et al.* [2002].

[20] The January optical depths are difficult to interpret due to the frequency of biomass burning south of the desert dust sources during the winter [e.g., *Savoie et al.*, 1992; *Liouisse et al.*, 1996], but we include them in order to show the seasonal cycle. The models capture the general features of maxima over North Africa, and the latitudinal switch between summer and winter, as seen in Figure 5. Notice that the optical depths vary between different model versions, but are more similar to each other in terms of their spatial pattern than optical depths available from the satellite observations. The maxima in optical depths are stronger in the BASE or BASE plus NEW simulations than in the TIMIND simulations, similar

6a. Jan. 1984 BASE

b. Jan. 1984 TIMIND

c. Jan 1984 BASE + NEW

d. Jan. 1984, TOMS retrieval

e. July 1984 BASE

f. July 1984 TIMIND

g. July 1984 BASE+NEW

h. July 1984 TOMS retrieval

0.05      0.50      0.75      1.00      1.50

to what is seen in Figure 5. The observations appear to lie between the two models in terms of magnitude. It does appear that all three of the model simulations may be underestimating the entrainment in the Lake Chad/Bodele basin area, although this area is a source area in all of the cases we examined (see Figures 2 and 3). It may be the NCEP winds are underestimating the surface winds in this region, or that these soils are more erodible then we consider them in our analysis (Figures 2 and 3).

[21] The maxima in optical depth in the TOMS retrieval seen in July are farther south than the optical depths simulated in this modeling study, and are located right over the new desert sources (NEW) or the southern most extent of the topographic lows (BASE or TIMIND). It is not clear that we can conclude that the Sahel source should be stronger in July than previously modeled, due to the possibility of biomass burning or errors in the retrieval in this area. One possible source of errors in the satellite retrieval is uncertainty and variability of the optical properties of mineral aerosols [e.g., *Sokolik and Toon*, 1996; *Claquin et al.*, 1999]. We might expect substantial cloud interference in this area during July, but over 14 days of data are included in the retrieval at these datapoints.

[22] All the model simulations have a dust plume that does not extend out as far into the North Atlantic or as far south as the TOMS data suggests in July. This may be due to an underestimate in the lifetime of the smallest particle bin. Here we use a wet deposition lifetime of 12 days, similar to most estimates of aerosol lifetimes [e.g., *Balkanski et al.*, 1993; *Kriedenweis et al.*, 1999], while in the work of *Ginoux et al.* [2001] the lifetime to wet deposition is 56 days. This results in a slightly longer total lifetime in the work of *Ginoux et al.* [2001] than in this study. A longer lifetime of the smallest particles would improve our comparison with the observations in this case, although it is unlikely to change our ability to distinguish between sources. It is possible that the smallest size bin is not as well scavenged by precipitation as previously thought.

## 2.3. Barbados Variability

[23] Measured daily averaged surface mass concentrations at Barbados are available in 1984 from *Prospero and Nees* [1986] and D. Savoie (personal communication, 2002). Comparison of model results to observations suggests that the model is doing a reasonable job predicting daily concentrations for 1984 (see Figure 7). Table 2 shows the correlation coefficient of the different model versions and observations. These correlation coefficients are generally similar than those obtained in simulations of radon using the same model [*Mahowald et al.*, 1997]. Since radon has simpler source characteristics, and many of the radon observing stations are in midlatitudes, where there is more meteorological data available, this suggests that the model is doing a good job in capturing specific desert dust events at Barbados.

[24] Overall, the different model versions are much closer to each other than they are to the observations. The inclusion of the NEW source slightly degrades the correlation between the model predictions and the observations, and the TIMIND source appears to capture the daily variability better than the BASE source, however these differences are only statistically significant if we assume concentrations are uncorrelated after only 3 days, which as we see in Figure 7, is not true [also, e.g., *Cakmur et al.*, 2001].

[25] Monthly averaged concentrations at Barbados are available in both 1966 and 1984 [*Prospero and Nees*, 1986] (D. Savoie, personal communication, 2001) and are shown in Figures 8a and 8b, respectively. Modeled concentrations from the BASE, TIMIND and BASE plus NEW sources are shown as well. Overall, the models can capture the general seasonal cycle, but tend to overpredict the concentrations in May, especially in 1966 and in the case of BASE. The model also tends to underpredict concentrations in October and November. From Figure 7, we can see that the model has over- or underpredicted one or two large events in 1984 when the monthly averages are incorrect, although in both May and October, the model appears to capture the events, but misses the magnitude and/or the timing. But as discussed in more detail next, only when the BASE plus NEW source is used, is the model capable of having low enough 1966 concentrations. (Remember that 1984 model concentrations are used to set the value of the total dust in the models, and thus on an annual average are the same as the observations.)

[26] In summary, the 3-D model and observational comparisons in 1984 suggest that the model is doing a reasonable job in capturing the seasonal cycle and dust events at Barbados, in addition to the optical depths over North Africa, although we hope to improve both in the future. The model results suggest that a topographic low source (BASE) and a topographic low source plus new desert source (BASE plus NEW) cannot be differentiated using the available satellite or in situ observations. One can do a similar analysis as conducted in this section using the TIMIND plus NEW source and obtain qualitatively similar results (not shown), suggesting that the specific parameterization for the dry topographic low sources is not important to our results.

## 2.4. Decadal Variability at Barbados

[27] Next we look in more detail at the ratio of the 1966/1984 Barbados concentrations in the observations and the model simulations. Table 3 shows the ratio of the concentrations at Barbados between 1966 and 1984 for each of the model studies.

[28] Also in Table 3 is the ratio of the magnitude of the West North African mobilization for 1966 versus 1984 (averaged in North Africa west of 24E). In addition, we calculate a "transport factor" that is the fraction of the dust mobilized in West North Africa that is transported to

**Figure 6.** (opposite) Model calculated aerosol optical depths from January 1984 from the BASE (a), TIMIND (b) BASE plus NEW (c) source areas compared with the TOMS aerosol optical (d) (courtesy of Omar Torres [*Torres et al.*, 2002]) calculated at 380 nm. Also shown are the July 1984 optical depths from the BASE (e), TIMIND (f) BASE plus NEW (g) source areas and the TOMS data (h).
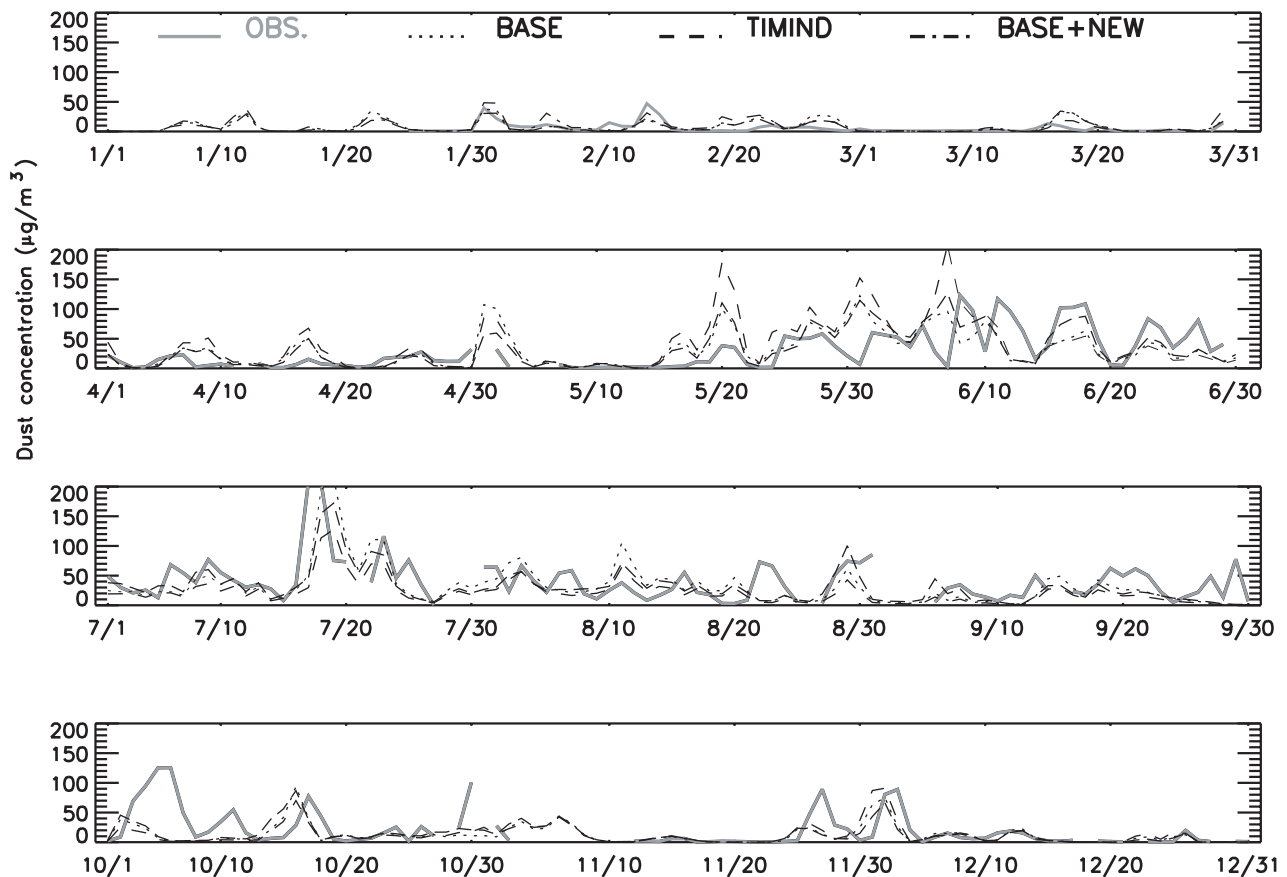
**Figure 7.** Daily averaged Barbados dust concentrations (μg/m³) in 1984 from observations (solid grey) and the model using the BASE (dotted), TIMIND (dashed) and BASE plus NEW (dash–dot) source areas.

Barbados (the concentration at Barbados for a given year, divided by the source in western North Africa for that year). If we take the ratio the transport factor between 1966 and 1984, we obtain an estimate of the change in the transport factor between 1966 and 1984, shown in Table 3.

[29] Notice that the model is unable to capture the observed change in concentrations at Barbados with only a topographic low source (BASE or TIMIND source alone). However, the ratio of the transport factors are very close to the observed ratio of concentrations at Barbados between 1966 to 1984—if the mobilization were equal during 1984 and 1966, the model would be able to capture the observed concentration changes at Barbados. In order to determine why the transport factor changed so much (whether it was a change in the mean winds or a change in the mean wash out rate), we conducted a sensitivity analysis with no wet deposition conducted for the summers (when most of the transport occurs) of 1984 and 1966. This sensitivity study suggests that the change in transport factor between 1966 and 1984 is due to two processes: changes in transport time to Barbados from North Africa (roughly half of the change in the transport factor is due to faster transport in 1984 than in 1966) and the large change in precipitation predicted by the MATCH model based on NCEP winds—desert dust is removed more quickly via wet deposition in 1966.

[30] In addition to the change in the transport factor, the model also predicts that the mobilization is actually larger in 1966 than 1984 (see Table 3) using the BASE and TIMIND source areas. The area of unvegetated topographic lows is smaller in 1966 by ~10%, so it is interesting that the entrainment of dust is larger. This appears to be due to the strength of the winds—the NCEP reanalysis suggest that wind speeds are larger in the source regions in 1966 than in 1984. Since the mobilization of desert dust to the atmosphere is thought to be dependent on the wind speed cubed, our dust entrainment is very sensitive to changes in wind speeds. The NCEP reanalysis suggests that the wind speed cubed is about 1.6 times as large in 1966 than in 1984 over one of the large source areas in North Africa (in central Algeria). In the next section we will attempt to verify the winds in the NCEP reanalysis.

**Table 2.** Comparison of Daily Averaged Observations and Model Predictions at Barbados During 1984

| Description | Correlation Coefficient |
|---|---|
| BASE versus Obs | 0.44 |
| TIMIND versus Obs | 0.48 |
| BASE + NEW versus Obs | 0.33 |
| BASE versus TIMIND | 0.95 |
| TIMIND versus BASE + NEW | 0.87 |
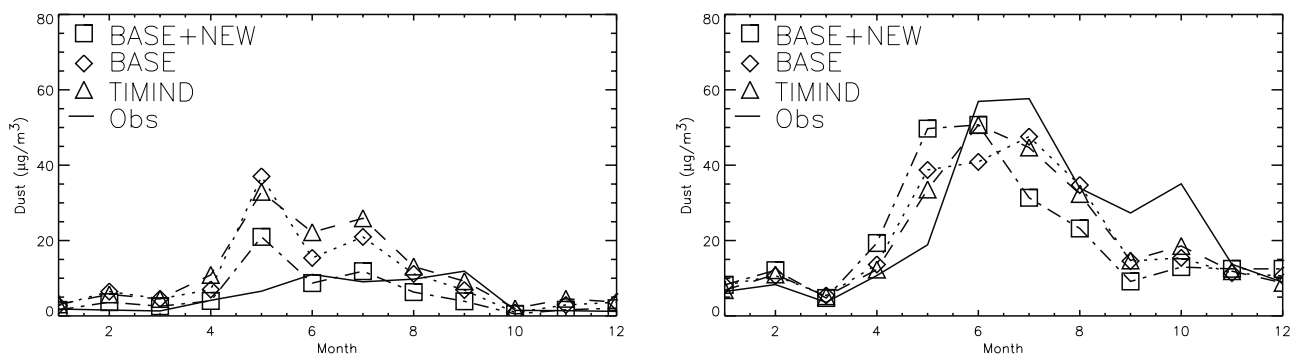
**Figure 8.** Monthly averaged Barbados dust concentrations ($\mu$g/m$^3$) in 1966 (a) and 1984 (b) from observations (solid line) and the model using the BASE (diamond, dotted line), TIMIND (triangle, dashed line) and BASE plus NEW (square, dashed–dotted line) source areas.

[31] In order to determine whether the problems with the simulation have to do with specific years, we also conducted a sensitivity analysis where we simulated 1985 and 1967 (using an earlier version of the model), but found that that simulations in other years do not improve the model's ability to capture the Barbados 1980s/1960s signal—in fact the 1967 study had even higher concentrations than 1966, which appear to be associated with very low precipitation in the Sahel (the drought seems to start in 1967 in the NCEP reanalysis instead of during 1968–1969 as seen in the *Dai et al.* [1996] data set). We also explored different wet deposition schemes, such as the Giorgi-Chaimedes scheme [*Giorgi and Chaimedes*, 1986], but the results were similar to what is shown in Table 3.

[32] Finally we consider a sensitivity study looking at changes between 1976 and 1984 in Table 4. As shown in Figure 1, 1976 is a low dust year at Barbados, but the North African visibility data shows medium high numbers of dusty days, suggesting that 1976 is not an easy year to interpret with the few data available. However, the results at Barbados are similar to the 1984/1966 comparisons—the model is unable to capture the large change at Barbados without the inclusion of the NEW source during 1984 (Table 4). If we include the NEW source in 1976 at half the magnitude as in 1984, the 1984/1976 ratio in concentrations at Barbados is 0.43, which is too high, but much closer to the observations (0.30–0.33) than if no NEW source is allowed in 1984 (0.61). The changes in mobilization and transport factors are smaller than seen in 1966, but show the same direction of changes as in 1966. Overall, this sensitivity study suggests that the model results in 1976/1984 are no more consistent with a dry topographic low source than the model results in 1984/1966, and more consistent with a NEW source being included in 1984 (and perhaps even in 1976, but as a smaller source area than in 1984). The model is not capable of capturing the 0.23 to 0.30 factor fluctuations in concentrations observed at Barbados without changes in source areas.

[33] The 3-D model results comparing 1966 to 1984 can be summarized as follows: a) there is a large change in the fraction of dust transported to Barbados between 1984 and 1966, with less transported in 1966 due to changes in transport rates and precipitation, b) there is a strong sensitivity to surface winds in the source region, with 1.6 times stronger wind speeds cubed in 1966 than in 1984 and c) the model is unable to capture the Barbados 1966/1984 signal with the topographic low source only (either BASE or TIMIND), but does capture these changes if the NEW source is included. Because of the large sensitivity suggested in the model to the winds in the source area and the precipitation, we will next evaluate our results by comparing the NCEP reanalysis to meteorological station data.

## 2.5. Observational Estimates of Precipitation and Surface Winds Between the 1960s and 1980s

[34] Our goal in this section is to compare NCEP reanalysis with meteorological station data for surface wind and precipitation fields because of the large sensitivity of our model results to these fields as shown in section 2.4. We calculate a summer time average of the wind speed cubed for 10 stations in the west of North Africa near a large source (central Algeria). Due to the sparseness of the stations and the difficulty in retrieving winds from the station data, a comprehensive comparison is beyond the scope of this study.

**Table 3.** Ratio of Concentrations at Barbados (1984/1966) in Observations and 3-D Model

| Description | Ratio of Barbados Concentrations (1966/1984) | Ratio of West North African Mobilization (1966/1984) | Ratio of Transport Factor (1966/1984) |
|---|---|---|---|
| Observations | 0.23–0.29 | | |
| BASE | 0.47 | 1.6 | 0.30 |
| TIMIND | 0.50 | 2.1 | 0.23 |
| BASE + NEW sources | 0.27 | 1.04 | 0.29 |

**Table 4.** Sensitivity Study: Ratio of Concentrations at Barbados (1984/1976) in Observations and 3-D Model

| Description | Ratio of Barbados Concentrations (1976/1984) | Ratio of West North African Mobilization (1976/1984) | Ratio of Transport Factor (1976/1984) |
|---|---|---|---|
| Observations | 0.30–0.33 | | |
| BASE | 0.61 | 1.5 | 0.40 |
| TIMIND | 0.62 | 1.5 | 0.38 |
| BASE + NEW sources | 0.35 | 0.93 | 0.38 |
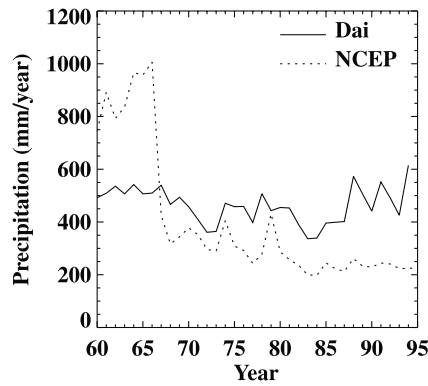
**Figure 9.** Annually averaged western Sahel precipitation, averaged between 10 to 22N and 15W to 15E, from the *Dai et al.* [1996] gridded observations (solid) and the NCEP reanalysis (dotted line) in mm/year.

We consider 1966–1967 and 1984–1985, and we obtain the statistically significant result (using a T-test) that the wind speeds cubed are larger in 1984–1985 than in 1966–1967 by a factor of 1.6, directly contrary to what the NCEP reanalysis suggests for the same time periods and region (as mentioned in section 2.4). However, comparing winds or precipitation from the NCEP reanalysis to the station winds is difficult, because of the differences in resolution and representativeness between an individual station (or collection of stations) and a $1.8° \times 1.8°$ forecast center wind analysis. With that caveat, this comparison does suggest that our 3-D model predictions for a larger source in 1966 than 1984 may be biased due to changes in the forecast center assimilation. Unfortunately, we do not have available winds from other forecast centers extending back to the 1960s. This problem may be due to the changes in the meteorological data included in the assimilation between 1984 and 1966 and thus may not be improved in other forecast center reanalysis [*Santer et al.*, 1999; *Trenberth and Guillemot*, 1998].

[35] We can compare the western Sahel region averaged precipitation from the Dai gridded data set (shown in Figure 1) based on station observations [*Dai et al.*, 1996] with the climatological observational precipitation from *Shea* [1986] and the NCEP precipitation. A comparison of the *Dai et al.* [1996] gridded data set and the NCEP reanalysis precipitation is shown in Figure 9, averaged in the western Sahel from 10N to 22N and 20W to 15E. Observational data sets suggest that the precipitation in 1966–1967 is 43% higher than in 1984–1985, while the NCEP reanalysis suggests that there is 320% greater precipitation in 1966–1967 than 1984–1985. This suggests that the precipitation changes in western North Africa in the NCEP reanalysis and thus our transport model simulations are not reliable, which is consistent with other analyses of forecast center precipitation [e.g., *Trenberth and Guillemot*, 1998]. In this case the NCEP reanalysis seems to overestimate the observed drought signal by a large margin. This implies that the ratio of the transport factors shown in Table 3 is likely significantly underestimated. On the other hand, the source area change between the 1966 to 1984 may be smaller than predicted in the model due to the exaggerated precipitation signal, although this appears to be a small effect, since the

mobilization in 1966 is much larger than 1984. This very large change in precipitation in the NCEP reanalysis extends over much of North Africa, not just the Sahel, and appears much more geographically widespread than in the *Dai et al.* [1996] data set (not shown). Thus, qualitatively, our conclusions are not sensitive to the region we chose to average over in Figure 9.

[36] The model results indicate that there was a change in the transport factor from North Africa to Barbados between 1984 and 1966, even when wet deposition was not included. There is no effective way to evaluate the transport time against observations. But since the precipitation and wind data suggest differences between station data and NCEP reanalysis over North Africa, our model results may be biased due to the forecast center data set. Overall, the main reasons for the signal shown in Table 2 do not appear to be robust, casting doubts on our 3-D modeling results comparing the Barbados record in 1966 and 1984.

## 3. Other Source Changes

[37] Because of the importance of source areas in determining the concentrations downwind, we return to this subject in this section and discuss in more detail changes in ephemeral lakes and time trends in land use and new desert sources.

### 3.1. Changes in Seasonal Lake Sizes

[38] Our model neglects to explicitly consider any changes in seasonal lake area, although the modeling approach does include model predictions of soil moisture from both BIOME3 and NCEP; these model predictions of soil moisture must be considered very uncertain. It is well documented that the size of Lake Chad had been reduced by an order of magnitude between the 1980s and the 1960s, exposing 20,000 $km^2$ of topographic low in 1984 [e.g., *Birkett*, 2000]. The *Prospero et al.* [2002] study suggests that the Lake Chad and Bodele basin are the largest sources in North Africa, implying that changes in Lake Chad's size might be responsible for some of the Barbados signal. Of course, much of the low lying region near Lake Chad is never inundated, but one could hypothesize that recently dried lake beds (e.g., Owens Lake [*Gillette et al.*, 1997]) might have more easily erodible soils than older exposed lake beds, although differences in salt content and vegetation can make this simple picture inaccurate. We conducted a sensitivity study in our model where we considered the impact of the Lake Chad source alone on concentrations at Barbados. This study suggests that the desert dust mobilization from Lake Chad basin is not large enough or effectively carried to Barbados, so even an order of magnitude change in the size of the topographic low area in Lake Chad would not have a significant effect on concentrations at Barbados. More convincingly, the TOMS AI analysis conducted by *Prospero et al.* [2002] suggest that most of the aerosols in this region come from the Bodele basin, not the area near Lake Chad. While it may be that the Bodele basin dried out and became a more effective source since the 1960s, we cannot find data which would support this hypothesis and we did not simulate this in the BIOME3 model using *Dai et al.* [1996] precipitation.

[39] There are many other ephemeral lakes in North Africa. In our model or the TOMS data, the region in the southern central part of Algeria is very active as a source and there are several areas that are considered "seasonally flooded" on maps [e.g., *Times Comprehensive Atlas of the World Millennium Edition*, 1999], which would presumably reduce their emissions during the wet season. We cannot find literature evidence that these lakes were inundated during the wet or dry season during the 1960s, so it is difficult to use this explanation for the changes in the Barbados concentrations. In addition, human water and land use may be changing the size of these lakes, an effect that we have not included in our modeling simulation. Overall the role of fluctuations in ephemeral lakes in causing fluctuations in atmospheric desert dust is not well known, and considering the possible importance of ephemeral lakes as sources, should be further explored.

### 3.2. Changes in Land Use and Desert Size

[40] It is difficult to estimate the regional changes in land use and vegetation before the satellite era. One study from the western Sahel area suggested that land use has increased at approximately 4.5%/year from 1960 to 1983, but only at about 1%/year since 1983 [*Stephenne and Lambin*, 2001]. This study is based on Burkino Faso, in the southern and western Sahel area (and thus wetter), and may not be indicative of the entire Sahel region, especially the more arid part, which we are interested in. *Stephenne and Lambin* [2001] explains the slower increase in land use after 1983 as a saturation of available resources, and an intensification of land use on existing land areas. Figure 10 shows a cartoon version of the land use from this study. We also show the predictions from the BIOME3 model for new source areas as a function of time in Figure 10, as well as the total size of the source in North Africa if both topographic lows and desertification sources were active (averaged in North Africa west of 24E). The new source areas are defined as in section 2.1 and represent areas that are unvegetated and dry during the current period, which were once vegetated. Again there appears to be an expansion in dry regions between the 1960s and 1980s, but since then a slight contraction, roughly consistent with satellite based observations [e.g., *Tucker and Nicholson*, 1999]. Both of these very rough estimates of changes in the Sahel region suggest large changes between 1960s and 1980s, and smaller changes since then (especially for land use), when the satellite record becomes easier to access. Notice the very different scales of the fraction of land use and the fraction of new desert source. If a very small fraction of the land use regions in Burkino Faso were active as desert dust sources, it could have a profound impact on the area of desert dust sources. We present these results as the best available information we could find on this issue, and hope to encourage other studies to present more refined analysis.

[41] One problem with proposing a land-use source of desert dust is that the type and intensity of the land use will substantially change how effectively soils can be mobilized. For example, if the land is intensely cultivated with irrigation and includes wind blocks, then the land use may decrease the erodibility of the soils. On the other hand, if the land is only intermittently used and the land use degrades the vegetation cover, then the land use could
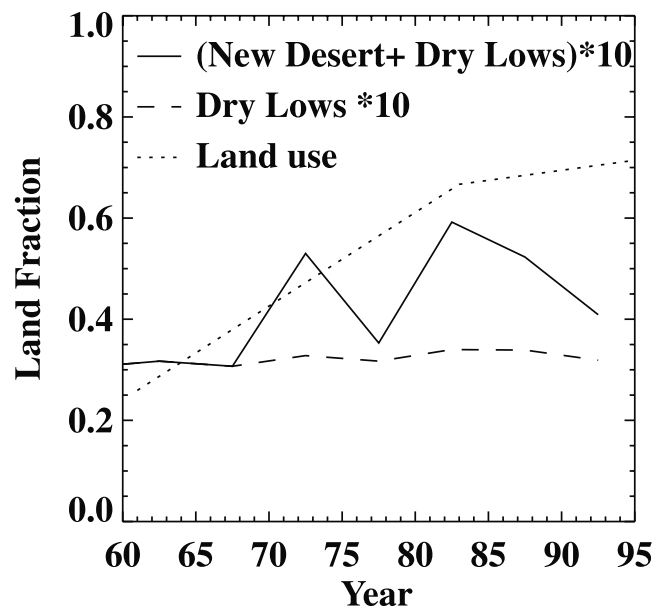


**Figure 10.** The fraction of land that is new desert plus the dry topographic low source (total times ten) during each 5 year period from the BIOME3 simulations (solid line), and the size of the dry topographic lows with time (BASE; dashed–dotted line). Also shown is the fraction of land used by humans in the western Sahel (dotted line) taken from *Stephenne and Lambin* [2001] for the country of Burkina Faso as a function of time.

increase the mobilization of soil particles. Thus, including an accurate land-use source in a global model may be years away, even if they are thought to be of vital importance.

[42] Changes in the precipitation between the 1960s and 1980s in the Sahel could have changed not only the vegetative cover, which we try to include in Figure 10, but also the soil texture. There may be changes in the crusting of the surfaces as the time since the last precipitation changes, or changes in the soil particle distribution as the sources evolve with time. We have not included this change in our model.

## 4. Discussion

[43] In order to make future predictions, we need to understand how humans and climate impact desert dust concentrations and deposition. The Barbados dust record, which represents our longest in situ record, and has a fourfold change in desert dust within it, may be the best way to test our understanding of the causes of fluctuations in atmospheric desert dust. In this paper we attempt for the first time to understand the relative roles of sources and transport fluctuations in creating this large signal. We also try to deconvolve the role of humans and climate change in this signal. However, because we only have available to us quantitative data at one site (Barbados) along with qualitative data in North Africa region (visibility data from *Mbourou et al.* [1997]), there are limits to our ability to make definitive conclusions. There are model errors in sources and transport, in addition to problems with the representativeness of one observing station for a model grid

box (1.8° by 1.8°). There was also a change in observing methods at Barbados, adding more uncertainty to our data record, although attempts were made to minimize the impact of the differences in measurement technique [*Prospero and Nees*, 1986]. However, because this record represents our longest record of in situ dust observations, and contains a four-fold change in concentrations, it is a valuable record to use to understand what drives fluctuations in desert dust concentrations.

[44] Our 3-D model suggests that the dry topographic low (e.g., dry lake beds) source is not sufficient to explain the observed variability, and thus a change in source area (due to the creation of new deserts or human land use change) is required to match the observations. This new desert source could be due to the increased soil erodibility of newly created desert regions or land use. In our modeling study, the new desert source contributes approximately 42%, 23%, 40%, 40% to the source area, source strength, maximum optical depth at 20W, and concentration at Barbados, respectively. But our comparison of the forecast center analyses with observed data sets suggests that the NCEP reanalysis may have such large uncertainties in important variables (precipitation and surface winds) that the NCEP reanalysis may be unable to correctly simulate the change in desert dust between 1966 and 1984. There is indeed some evidence that the winds may be stronger in 1984 than 1966 (contrary to the NCEP reanalysis), and that this might be responsible for the change in desert dust observed at Barbados. Unfortunately it is beyond the scope of this study to look more closely at the North African surface winds. We also conducted sensitivity studies looking at 1967 and 1976 (both low dust years at Barbados) and using different wet deposition parameterizations, and these studies supported the conclusions from the simulations for 1966 and 1984. Model and data comparisons suggest that the model does a good job of capturing the monthly averaged concentrations at Barbados in 1966 and 1984, and appears to be able to capture many specific events at Barbados during 1984. In addition, the model is able to capture the latitudinal shift in optical depths off the coast of North Africa that occurs between winter and summer in 1984. We encourage other groups to consider the 1966/1984 concentration ratio at Barbados and whether their models can capture this large change.

[45] In order to understand the Barbados signal, we need to understand the sources of desert dust in the current climate. *Prospero et al.* [2002] makes a contribution in their study that uses satellite and geomorphological data to suggest that topographic lows currently dominate the desert dust sources. However, how active these sources were in the past and how they respond to human or natural climate variability remains a question. Even if we use satellites to remotely sense the desert dust over North Africa, it is very difficult to distinguish between a topographic low source and a topographic low source plus new desert source because their optical depths are so similar (see Figure 6). If the new sources lie in the western part of the Sahel, then they lie under the path of advected dust from upwind sources, and it is difficult to separate local dust from transported dust in satellite retrieved optical depths. If we look farther away from the sources at Barbados, our modeled daily averaged concentrations are much closer to

each other (even using different sources), than to the observations (see Figure 7). Concentrations at Barbados are likely to be more sensitive to the variations in meteorology in the transport than in the source distribution in North Africa.

[46] We present very preliminary evidence that some processes which could change the source areas (such as new desert sources or changes in land use) may have occurred before 1983, and thus not be apparent unless we are observing or simulating dust prior to 1980. However, this represents a problem for both satellite based studies and modeling studies using forecast center winds, since much of the satellite data does not extend farther back than 1979. The inclusion of satellite data in 1979 changed many characteristics about the forecast center winds, and comparisons using reanalyses data sets prior to and after 1979 may not be robust [*Kistler et al.*, 2001; *Santer et al.*, 1999]. *Prospero et al.* [2002] argued by looking at maps of roads and the TOMS aerosol index that many regions of active dust sources in the Sahel region of North Africa did not appear inhabited by humans. Of course, it is possible that their maps are out of date, or do not contain marginal roads; in addition, other satellite retrievals, such as from METEO-SAT give a slightly different picture of the mineral aerosol sources [e.g., *Brooks*, 1999]. However, this type of approach, but perhaps done on a finer scale with multiple remote sensing techniques, is the type of approach which can determine human land use impacts on desert dust sources. Unfortunately, this approach will not eliminate the possibility that vegetation shifts are an important mechanism of creating new sources of desert dust.

[47] Studies looking at large scale changes in vegetation in North Africa have relied on satellite data, which only extends back to 1979 [e.g., *Tucker and Nicholson*, 1999]. Since 1980, when satellite data became widely available, evidence suggests that the unvegetated regions follow the precipitation [e.g., *Tucker and Nicholson*, 1999], and thus when precipitation returns to a "desert" region, it quickly becomes revegetated.

[48] It is difficult to estimate large-scale changes in the vegetation before 1979, but most studies suggest that the Sahel drought caused vegetation to retreat along the Southern border of the Sahel [e.g., *Lamprey*, 1975]. However, a recent study based on classified satellite data suggested no changes in the vegetation between 1950 and 1980 in one area of the Sudan [*Schlesinger and Gramenopoulous*, 1996], casting doubts on previous estimates of desert expansion, and thus on many of the premises of our study. Future work should illuminate the extent to which the desert areas in North Africa have changed over the past 40 years.

[49] *Moullin et al.* [1997] have shown that the desert dust at Barbados and seen in satellites is correlated with the North Atlantic Oscillation (NAO). Since the NCEP reanalysis clearly shows the NAO patterns and is used to study the NAO [e.g., *Deser*, 2000; *Baldwin and Dunkerton*, 2001], our model studies using the NCEP reanalysis should be able to capture the source and transport changes associated with the NAO. Thus, the results of this study would suggest that changes in the NAO alone, using only a dry topographic low source, are not enough to explain the 1966 to 1984 changes, and that some other change in the sources is required, either land use or natural vegetation shifts. However, the results in

this paper, as well as previous analyses [*Trenberth and Guillemot*, 1998; *Santer et al.*, 1999; *Trenberth et al.*, 2001] suggest that there are problems with the NCEP reanalysis, especially in the poorly sampled tropics.

[50] The important question of what processes are responsible for changes in atmospheric desert dust needs to be answered before we can make predictions of human impacts on the radiation budget or biogeochemistry due to mineral aerosols. If we include the impact of carbon dioxide on arid plants, we predict that the sources will contract in the future due to higher carbon dioxide [*Harrison et al.*, 2000], while the IPCC estimate suggested slightly larger desert dust source areas due to climate change [*IPCC*, 2001]. Including the possibility of the land use or new desert source areas increases the complexity of predicting atmospheric desert dust in the future. Unfortunately it is difficult from the available evidence to be sure that human land use or new desert sources are not currently active. The dominant desert dust sources may indeed be in the low lying regions, as argued by *Prospero et al.* [2002], but unfortunately in North Africa, regions that have undergone changes in vegetation and land use tend to lie in low lying regions. Our model results suggest that a new desert source or a land use source may be responsible for the large changes observed at Barbados, but the uncertainty in the model and meteorological data sets used as input to the model do not allow us to be conclusive.

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