Numerical simulation of a continental-scale Saharan dust event

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[1] Using an integrated dust-storm modeling system, we simulate the severe Saharan dust episode between 1 and 10 March 2004. The simulations are compared with surface synoptic data and satellite images and are found to agree well with the observations. The synoptic systems that generated the dust storms and the evolution of the dust patterns are analyzed. It is revealed that a cyclogenesis over central Sahara, accompanied by an anticyclone over the Atlantic and a monsoon trough in the tropics, was responsible for the widespread continental-scale dust storms in North Africa. Dust first appeared in west Sahara, then in east Sahara and much of the dust emitted from east Sahara was transported to the monsoon trough, resulting in high concentrations of suspended dust over the Sahel (column dust load up to 10 g m$^{-2}$). The main dust source regions were (1) Mauritania, (2) Chad and Niger, and (3) Libya, Egypt, and Sudan. The region between 10°N and 17°N was one of net dust deposition. We estimate that 715.8 megatons (Mt) of dust was emitted from North Africa during the episode, 608.2 Mt of which was deposited to the continent, and the net dust emission was 107.6 Mt. Of the 107.6 Mt, with respect to the model domain, 7.3 Mt was deposited to the ocean, 79.8 Mt was transported across the domain boundaries, and 20.5 Mt was suspended in the atmosphere.


1. Introduction

[2] The Sahara, together with the Sahel, is the largest dust source on Earth. Model simulations suggest that the dust emission from this region contributes to about 65% of the global total. However, the existing estimates of the Saharan dust emission vary over a wide range. For example, the estimate by Jaenicke [1979] is 260 megatons (Mt) yr$^{-1}$, that of Marticorena et al. [1997] is between 586 and 665 Mt yr$^{-1}$, and that of Callot et al. [2000] is 760 Mt yr$^{-1}$. Laurent et al. [2008] reported that the Saharan dust emission for the years between 1996 and 2001 ranges from 585 to 759 Mt yr$^{-1}$. The estimates of Zender et al. [2003], Ginoux et al. [2004], and Tanaka and Chiba [2006] using global models are 980 Mt yr$^{-1}$ (size range $\leq 10$ μm), 1430 Mt yr$^{-1}$ (size range 0.1–6 μm), and 1150 Mt yr$^{-1}$ (size range 0.2–20 μm), respectively. The substantially different estimates in previous studies can be attributed to a number of reasons: (1) the dust emission schemes used in the modeling studies are poorly calibrated and have large uncertainties; (2) various atmospheric systems over a range of scales can generate dust emission over the northern African continent and the accurate predictions of the atmospheric predictions are difficult; (3) over the vast areas of the Sahara and the Sahel, the geomorphology and land surface conditions are complex, but the parameters required for specifying these conditions for dust modeling are low in reliability; and (4) the term “dust emission” was not rigorously defined in previous studies, making the comparison of the results difficult. For example, the estimates of Saharan dust emission made by Zender et al. [2003], Ginoux et al. [2004], and Tanaka and Chiba [2006] referred to different particle size ranges. The differences between “dust emission,” “net dust emission,” and “exported dust” considered in the different studies also contributed to confusion.

[3] Our basic understanding of the atmospheric systems that generate Saharan dust can be summarized as follows.

[4] 1. Dust activities in North Africa are closely related to the seasonal migration of the surface monsoon trough, sometimes called the west African heat low [Knippertz, 2008], between the annual extreme locations of about 7°N in January and 22°N in August [Lavaysse et al., 2009]. North of the monsoon trough blow the Harmattan from the subtropical high-pressure belt [Barry and Chorley, 2003]. In the Harmattan-affected regions, widespread dust haze occurs in light wind conditions. Here a convective boundary layer, up to 5 km deep, exists during the hot season of the year [Parker et al., 2005; Flamant et al., 2007].

[5] 2. South of the trough is a shallow, moist, southwesternly airflow. This monsoon flow, especially in the summer months, is overridden by a midlevel easterly jet. Easterly waves develop along this jet accompanied by surface cyclones in the monsoon trough area [e.g., Thornicroft et al., 1995; Fink and Reiner, 2003]. These mostly dry disturbances can generate strong surface winds and entrain...
large amounts of dust into the atmosphere [Westphal et al., 1988]. Dry convection also effectively mixes momentum from the midlevel easterly jet down to the surface where dust can be mobilized [Prospero and Carlson, 1981].

3. While northeasterly winds prevail in northern Sahara, the region is also affected by northwesterly flows and frontal systems. Strong winds associated with cold air outbreaks and cyclogenesis south of the Atlas Mountains can produce severe and widespread dust storms in North Africa [Knippertz et al., 2009].

4. Other small-scale dust events may be associated with gust fronts, density currents, dry thunderstorms, or squall lines [Knippertz et al., 2007]. The breakdown of the nocturnal low-level jet also generates localized dust activities [Schepanski et al., 2009].

Many questions related to Saharan dust are yet to be answered. Particularly important is the radiative forcing of the Saharan dust on global and regional atmospheric systems. Tompkins et al. [2005] showed that a correction in the aerosol optical depth in the European Centre for MMedium-Range Weather Forecasts forecast model can remove the large bias related to the weakening and poleward migration of the African easterly jet in the 10 day forecast. Using the U.K. Met Office Unified Model, Haywood et al. [2005] found a 50 W m\(^{-2}\) difference between the satellite and model top-of-atmosphere outgoing long-wave radiation over cloud-free areas in the west Saharan heat low region. The most plausible explanation for this discrepancy is the neglect of mineral dust in the model. Dust feedback processes are also of considerable interest. Heinold et al. [2008] studied the feedback between dust and the boundary layer using a regional dust model and found that the feedback contributes to the formation and breakdown of the low-level jet in the Bodélé Depression. Pérez et al. [2006] incorporated radiation schemes in a regional atmospheric model and simulated the effect of dust on atmospheric radiative fluxes and temperature profiles and the feedback on dust emission.

The prerequisite for answering the aforementioned questions is that we can reliably quantify dust concentration, pattern, size, and fluxes. Although satellite and ground-based remote sensing can provide semi-quantitative dust estimates, integrated dust models represent so far the most effective approach to answering dust-related questions. A number of detailed case studies using dust models on Asian dust storms were successfully carried out [e.g., Nickovic et al., 2001; Liu et al., 2001; Uno et al., 2005]. Satellite observations have shown spectacular images of Saharan dust storms (e.g., http://oiswww.eumetsat.org) and have prompted a number of recent model studies on such storms [Pérez et al., 2006; Heinold et al., 2007; Menut et al., 2009; Todd et al., 2008; Bou Karam et al., 2009; Schepanski et al., 2009; Reinfrid et al., 2009; Cavazos et al., 2009]. Using a regional climate model, Zakey et al. [2006] simulated two Saharan dust episodes (one in northeastern Africa and one in western Africa). Their model appeared to have captured the main features of the dust patterns, but the latter authors did not present the details of dust fluxes (emission, deposition, and transport).

We have developed an integrated system, known as the Computational Environmental Modelling System (CEMSYS), which couples an atmospheric model, a land surface scheme, dust schemes for emission, transport, and deposition, and a geographic information system (GIS) database, for the modeling of dust storms. CEMSYS was successfully applied to the simulation of dust events in Asia and Australia [Shao et al., 2003, 2007]. In this study, we apply CEMSYS to simulate the 1–10 March 2004 Saharan dust storms. These storms have attracted much attention from the dust-research community because of their intensity, wide coverage, and endurance [e.g., Knippertz and Fink, 2006; Li et al., 2007]. They were, for example, significantly larger than those studied by Zakey et al. [2006]. The characteristics of dust transport, as revealed later in this study, are worth particular attention, because the dust activities over the vast areas of the Sahara and the Sahel are closely related, rather than independent. Our objectives of this study are (1) to identify the regions of dust emission and deposition, (2) to estimate the strengths of the dust sources and sinks, (3) to simulate dust distribution and transport, and (4) to understand the synoptic systems that generate such dust storms. Owing to the lack of observations across the Sahara, a rigorous quantitative verification of the model simulations is not possible, but the simulated dust patterns are compared with surface synoptic data and satellite images. In general, dust models have large uncertainties and these uncertainties are difficult to quantify. Nevertheless, we provide a dust budget for the March 2004 dust episode based on a small ensemble of model simulations.

2. March 2004 Saharan Dust Episode

During 1 and 10 March 2004, severe and widespread dust storms occurred in North Africa. We first describe the synoptic background for this dust episode, focusing on the interactions between the high-pressure system located over the subtropical Atlantic Ocean, a low-pressure system over the central northern Sahara, and the monsoon trough located to the south of the Sahel.

The most outstanding feature during the early stage of the episode was the intensification of a high-pressure system over the subtropical Atlantic Ocean, accompanied by a cyclogenesis over the central north Sahara. Figure 1 depicts the evolution of the surface weather patterns during the episode. On 1 March 2004, the high-pressure system of cold air was situated over the subtropical Atlantic, with its center located at about 20°W, 30°N. The monsoon trough was located at around 7°N and the northern African continent was dominated by weak northeasterly winds. A zone of strong surface baroclinicity stretching from west to east across the Sahara, as reflected in the strong north-south temperature gradient, existed at around 25°N. A disturbance in the temperature field was identified over south Algeria and Libya. On 2 March, an upper-level trough moving into northwest Africa induced a strong cyclogenesis at the surface baroclinic zone [Knippertz and Fink, 2006] and, together with the northeastward movement and intensification of the anticyclone, resulted in a substantially strengthened northerly flow over west Sahara and the formation of a surface cold front. Dust appeared behind the cold front over Algeria.
winds over western Sahara and northwesterly winds over eastern Sahara. On this day, large areas of the Sahara were dominated by strong near-surface winds reaching 20 m s$^{-1}$ and dust became widespread. On subsequent days, the anticyclone, together with the cold air, moved gradually into western Sahara and the cyclone moved northeastward to the Middle East. Winds were generally weaker (below 6 m s$^{-1}$) over western Sahara, but remained strong (above 10 m s$^{-1}$) over eastern Sahara until 10 March. The dynamics of the anticyclone and cyclogenesis was described by Knippertz and Fink [2006] and is not repeated here.

[14] Overall, there was very little rainfall during the entire episode. Figure 2 shows the observed and model simulated daily rainfall for the first 4 days of March 2004. Associated with the development of the cyclone and the frontal system, rainfall occurred on these 4 days, but was confined to the very northern part of the Sahara. In a small area of the desert regions of northeastern Algeria and northwestern Libya, however, the 24 h accumulated rainfall between 3 and 4 March 2004 exceeded several tenths of millimeters. Knippertz and Fink [2006] suggested that the evaporative cooling of the raindrops in the dry Saharan boundary layers contributed to the enhancement of the surface cold front. From 5 to 10 March 2004, no significant rainfall was observed or predicted. Figure 2 also shows that the model, to be detailed later, very well simulated the rainfall pattern.

Figure 1. Simplified surface weather pattern for the period 1–10 March 2004 based on NCEP/NCAR reanalysis. Representative surface temperature contours (lines, 294–302 K, with 2 K intervals), wind vectors (arrows) with magnitude exceeding 6 m s$^{-1}$, and areas (shaded) with wind speed exceeding 10, 15, and 20 m s$^{-1}$ are shown.
It can be concluded from the above discussions that the prevailing windy and dry weather patterns provided excellent conditions for dust-storm development over the Sahara.

3. Numerical Simulation

3.1. Model Description

The dust model used in this study is CEMSYS, which was described in several previous publications [e.g., *Shao et al.*, 2007]. CEMSYS consists of an atmospheric model and schemes for land-surface processes, dust emission, transport and deposition, as well as a GIS database. The atmospheric model used in CEMSYS is a limited-area model [Leslie *et al.*, 1985], which includes the treatments for atmospheric dynamic and physical processes such as advection, convection, turbulent diffusion, radiation, clouds, and the atmospheric boundary layer. The land-surface scheme used in CEMSYS is the Atmosphere and Land Surface Interaction Scheme (ALSIS) developed by *Irannejad and Shao* [1998]. ALSIS simulates soil moisture and temperature in the unsaturated zone and land-surface energy, mass, and momentum fluxes.

Soil is divided into *I* particle size bins. In previous studies, a unified set of rules was not applied to the division of dust into different size bins [Uno *et al.*, 2006]. *Westphal et al.* [1988] used four dust bins: $d \leq 2$, $2 < d \leq 6$, $6 < d \leq 60$, and $d > 60 \ \mu m$. *Tegen and Fung* [1995] also used four, but somewhat different, dust bins: $d \leq 2$, $2 < d \leq 20$, $20 < d \leq 50$, and $d > 50 \ \mu m$. It is useful to introduce a uniform division of dust bins in future studies to facilitate comparisons. Suppose we use settling velocity $w_t$ as a criterion and assume that $w_t$ varies by a factor of 4 within each dust bin (i.e., $w_{i+1}/w_i = 4$). As $w_t \sim d^{1/2}$ for dust particles, we have $d_{i+1}/d_i = 2$. A division of dust bins used in this study is, thus, as follows: $d \leq 1$, $1 < d \leq 2$, $2 < d \leq 4$, $4 < d \leq 8$, $8 < d \leq 16$, $16 < d \leq 32 \ \mu m$, etc.

The dust emission scheme of *Shao* [2001, 2004] is used to estimate wind erosion threshold friction velocity, sand drift intensity, and the rates of dust emission for different particle-size groups. The scheme takes into consideration three dust emission mechanisms, namely, aerodynamic

![Figure 2](image-url). Observed and model-simulated daily cumulative rainfall (in mm) for 1–9 March 2004. Significant rainfall was observed and predicted only on 3 and 4 March 2004 in the very northern parts of the Sahara. On the other days of the dust episode, no significant rainfall was observed or predicted.
entrainment, salination bombardment (also known as sand blasting), and aggregates disintegration (also known as self-abrasion), and predicts that
\[
\bar{F}(d_i, d_d) = c_j \eta_0 [(1 - \gamma) + \gamma \sigma_p (1 + \sigma_m) \frac{gQ}{u^*}],
\]
where \(\bar{F}(d_i, d_d)\) is the dust emission rate for the \(i\)th dust bin generated by the salination of particles of size \(d_i\), \(c_j\) is a dimensionless coefficient, \(\eta_0\) is the dust mass fraction of the \(i\)th dust bin (from fully dispersed particle-size analysis), and \(\gamma\) is a weighting function that satisfies
\[
\gamma = \begin{cases} 
1 & u^* \rightarrow u^*y, \\
0 & u^* \rightarrow \infty.
\end{cases}
\]

\(Q\) is the salination flux of sand grains of size \(d_i\), and for a given \(d_i\), \(Q\) can be calculated using the Owen [1964] model; \(g\) is acceleration due to gravity; and \(\sigma_p - p_m(d)/p_f(d)\), where \(p_m(d)\) and \(p_f(d)\) are the minimally and fully dispersed particle size distributions, respectively. The bombardment efficiency \(\sigma_m\) is estimated by
\[
\sigma_m = 12\gamma^2 \frac{\rho_p}{p} \left( 1 + 14u^* \frac{\rho_p}{p} \right),
\]
where \(\rho_p\) is the soil bulk density and \(p\) is the soil plastic pressure; \(\rho_p\) is about 1000 kg m\(^{-3}\) but can be approximated as \(\rho_p = \rho_p (1 - \nu_s)\), where \(\rho_p\) is the particle density and \(\nu_s\) is the soil porosity. The rate of dust emission for the \(i\)th dust bin is determined by
\[
\bar{F}(d_i) = \int_{d_1}^{d_2} \bar{F}(d_i, d_d) \delta d,
\]
where \(d_1\) and \(d_2\) are the lower and upper limits of salination particle size. The total dust emission rate is
\[
F = \sum_{i=1}^{l} \bar{F}(d_i).
\]

Shao [2004] compared the predicted and measured \(F\) for several soil texture and surface conditions and found that \(c_j\) falls between \(1 \times 10^{-5}\) and \(5 \times 10^{-5}\) and \(p\) between 1000 and 50,000 Pa.

Although the dust emission scheme just described is quite simple, it does have the capacity to represent the essential factors that affect dust emission. Dust emission is highly dependent on the parent soil mineralogy (e.g., the diatomite fragments in the Bodélé Depression may be easily broken on the hard surface, leading to dust emission [Chappell et al., 2008]), but it is not possible for quartz sand grains to produce any dust. In the dust scheme, this observation is represented by the use of \(p_f(d)\) and \(\gamma\). The former is the particle-size distribution of the soil fully disturbed by mechanical forces, while the latter represents the “easiness” of whether the soil can be mechanically disturbed. The form of \(\gamma\) suggested by Lu and Shao [2001], which satisfied equation (2), is
\[
\gamma = \exp \left[ -\kappa \left( u^* - u^*y \right) \right],
\]
The parameter \(\kappa\) describes how rapidly \(\gamma\) approaches zero or how easily soil becomes “fully disturbed.” A large \(\kappa\) represents a soil with aggregates that are easily broken, such as the fragments (special case of aggregates) observed in the Bodélé Depression, whereas a small \(\kappa\) represents a soil with aggregates that are hard to break. However, at this stage of the study, it is not possible to estimate what precisely \(\gamma\) should be for the vast area of North Africa. In this study, we have uniformly set \(\kappa\) to 1.

[19] The threshold friction velocity \(u^*_t\) for sand grains (or aggregates) of size \(d_i\) on a natural soil surface is expressed as
\[
\begin{align*}
\text{(6)}
\end{align*}
\]
where \(u^*_x(d_i)\) is the threshold friction velocity for sand grains of size \(d_i\) in the idealized situation when the surface is bare and soil is dry, free of salt, free of crust, etc. In this study, \(u^*_x(d_i)\) is calculated using the expression given by Shao and Lu [2000]. The factors \(\lambda\), \(f_{sc}\), \(f_{cc}\), and \(f_{cr}\) are correction functions for surface roughness elements, soil moisture, salt concentration, and crust, respectively. The correction function \(\lambda\) follows from the work of Raupach [1992] and Raupach et al. [1993], and \(f_{sc}\) follows from the work of Fécan et al. [1999]. Equation (6) shows \(u^*_x\) is influenced by a soil salt concentration correction function, \(f_{sc}\), and a soil crust correction function, \(f_{cr}\), which we have set to 1 for the entire northern African continent in this study. This unrealistic simplification is made for two reasons. First, the precise forms of \(f_{sc}\) and \(f_{cr}\) are not yet well known, although Nickling and Eccleston [1981; Nickling, 1984] presented some preliminary results on \(f_{sc}\) and Ishizuka et al. [2008] did the same for \(f_{cr}\). Second, there is very little information about the soil salt-content and soil-crust pattern over the northern African continent for dust modeling purposes. Soil salt content and surface crust are important factors which suppress dust emission and it is thus desirable in future studies to establish a soil salt content and soil crust database and develop a temporal crust evolution model. In this sense, our dust model tends to overestimate the rate of dust emission.

[20] Dust transport through advection, (subgrid) convection, and diffusion has been considered. The evolution of dust concentration obeys the mass conservation equation, which is numerically solved simultaneously with the atmospheric model equations. The particle eddy diffusivities in the conservation equation are calculated following the work of Csanady [1963]. The treatment of subgrid convective dust transport is as described by Jung et al. [2005]. The dry deposition velocity is parameterized following the work of Raupach et al. [2001], and the wet deposition from below-cloud scavenging is represented using the scavenging coefficient approach (Scheme I described by Jung and Shao [2006]). Dust wet deposition caused by cloud nucleation is not considered.

3.2. Area of Simulation

[21] The model was run for the area of 70°W, 0°N to 80°E, 50°N with a spatial resolution of 50 km. The area of data analysis was 40°W, 0.5°N to 54°E, 43°N. The latter area is referred to as the model domain in this study, which
covered a land surface area of $28 \times 10^6 \text{ km}^2$ and an ocean surface area of $17 \times 10^6 \text{ km}^2$.

The $\sigma$-coordinate system was used and the atmosphere was divided into 25 vertical layers with smaller increments near the surface. The National Centers for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCAR) reanalysis data were used for specifying the initial and boundary conditions for the atmospheric model of CEMSYS. The boundary conditions were updated every 6 h. CEMSYS5 was run for the 10 day period of 1–10 March 2004 by making sequential 24 h runs; that is, at the beginning of each 24 h run, the atmospheric variables (temperature, wind, humidity, etc.) were initialized using the NCEP-NCAR reanalysis, whereas the dust variables were initialized using the predictions of the previous day. The atmospheric, land-surface, and dust fields were updated every 2 min, but the model outputs were 3 h averages.

### 3.3. Potential Dust Sources

[D’Almeida, 1986] identified four major dust source areas based on the data analysis of the African turbidity network (Figure 3). Source 1 extends from western Sahara to northern Mauritania; source 2 is located in Algeria and Niger in the triangle formed by the Hoggar, Adrar des Iforhas, and Air mountains, northeast of Gao (18°N, 1°E, Mali); source 3 is situated north to northeast of Bilma (18.7°N, 13°E, Niger) off the west side of the Tibesti Massif; and source 4 is located in the northern part of the Sudan and the southern part of Egypt. The largest dust sources are sources 1, 2, and 3, each producing a dust export of more than 200 Mt yr$^{-1}$ [D’Almeida, 1986]. Dust emission from source 4 is relatively weak. There are other secondary sources, for instance, the area to the south of the Mediterranean Sea, including Libya, Egypt, Sinai, and the Negev [Goudie, 1983]. Evidence collected in recent expeditions shows that the Bodélé Depression is a significant dust source. Dust appears to be produced from the region even under light wind conditions, as flow accelerates over large dunes to entrain diatomite fragments which abrade against each other, producing dust [Chappell et al., 2008; Tegen et al., 2006; Todd et al., 2007]. In terms of significant regional- and continental-scale dust events, the Bodélé source is turned on and off by synoptic systems as reported in several other studies [e.g., Washington and Todd, 2005].

The above-described locations of dust sources are generally consistent with those identified by Prospero et al. [2002] on the basis of the Total Ozone Mapping Spectrometer (TOMS) aerosol index (Figure 3). In the latter study, two primary sources are identified in North Africa. The first one is the Bodélé Depression between Tibesti and Lake Chad. The second one is in western Sahara, including portions of Mauritania, Mali, and southern Algeria. However, regions of high aerosol index are not necessarily dust sources, because the aerosol indices best describe transported dust.
Indeed, as Figure 3 shows, the high-aerosol-index regions are located somewhat downwind of the dust sources identified by D’Almeida [1986].

[25] In this study, dust emission is computed by using the dust emission scheme, but it is useful to divide the surface into nonerodible lands and potential dust source regions and to compute dust emission only for the latter category. We define the potential dust source regions on the basis of (1) remotely sensed leaf area index (LAI), (2) topography, and (3) surface type. Using the ArcGIS software, we prepared a set of potential dust sources using the criteria of LAI < LAIc, H < Hc, and S = Sc, where LAIc is a critical LAI (e.g., 0.3), Hc is a critical height of topography (e.g., 500 m above sea level), and Sc is a type of surface that is erodible (water surfaces, salt lakes, and stony surfaces are not erodible). The distributions of potential dust source regions are shown in Figure 4, which include large areas of western Sahara, Mauritania, and Mali in the west, parts of Algeria and Libya in the north, Egypt and Sudan in the east, and the Bodélé Depression in Chad.

[26] For the potential dust source regions, threshold friction velocity, uw*, sand drift intensity, and dust emission rates for the six dust bins (0–1, 1–2, 2–4, 4–8, 8–16, and 16–32 μm) are calculated. The soil types are derived from the Webb–Rosenzweig global soil-profile data set for the first meter of soil [Webb et al., 2000]. The data have a spatial resolution of 1° and are available from the Oak Ridge National Laboratory Distributed Active Archive Center. The soil data profile gives the percentage of sand, silt, and clay. Using these percentages, the Webb–Rosenzweig soils are regrouped into the U.S. Department of Agriculture (USDA) soil types (Appendix A). The particle-size distributions pm(d) and p(f(d)) are assigned to each of the latter soil types (see Appendix B).

[27] The calculation of uw* requires as input the roughness frontal area index λ and surface soil moisture wc. In this study, λ is estimated from LAI by assuming

\[ \lambda = a_L \text{LAI}, \]

where \( a_L \) is an empirical factor, ranging from 0.25 (plant height 4 times width) to 1 (plant height 1 times width). The LAI data are obtained from the Climate and Vegetation Research Group, Department of Geography, Boston University. The data are monthly composite with 4 km spatial resolution, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) TERRA and Aqua products (available from ftp://primavera.bu.edu/pub/datasets). In desert areas, the main roughness elements are not necessarily vegetation, but rocks, pebbles, and gravels. In theory, the frontal-area index of these latter roughness elements can be estimated on the basis of geometric assumptions. Pebbles are mainly ellipsoids with a flatness of around 2/3. In this case, the frontal area is approximately one half of the surface they cover. Gravels can normally be assumed to be spheres whose frontal-area index is almost equivalent to their fraction of surface cover. However, the distributions and the geometric features of rocks, pebbles, and gravels over the Sahara are not known to us and, hence, the sheltering effects of these roughness elements are neglected in the model. The surface soil moisture, wc, is estimated from the ALSIS model simulation for the first model soil layer (50 mm), w1, by assuming

\[ w_c = a_w w_1, \]

where \( a_w \) is a coefficient with a positive value smaller than 1. The introduction of \( a_w \) is necessary, because soil moisture in the top soil layer varies rapidly with depth and \( w_c \) can be substantially lower than \( w_1 \).

3.4. Ensemble of Numerical Experiments

[28] CEMSYS consists of the model components for atmospheric, land-surface, and dust processes and requires a number of input parameters. Consequently, the model simulations are expected to have considerable uncertainties. Uno et al. [2006] examined the performances and sensitivities of eight dust models, and Darmenova et al. [2009] studied in detail the performances of two dust emission...
schemes in a regional dust model, including the scheme used in this study. Despite the recent effort, the uncertainties embedded in numerical dust predictions are difficult to quantify because of the critical lack of observational data for model calibration. Because the model has a number of parameters, it is computationally difficult to generate a large ensemble of numerical experiments to enable a full-scale statistical quantification of model uncertainties. Experience shows that dust predictions are most sensitive to roughness frontal area index and surface soil moisture (because they affect threshold friction velocity) and to dust deposition velocity. The parameters $c_y$ and $p$ used in the dust emission scheme also affect dust emission. A large $c_y$ increases dust emission while a large $p$ reduces dust emission. To understand the approximate range of model predictions, we have generated a small ensemble of model simulations by varying $LAI_c$, $H_c$, $a_y$, and $a_w$ within an appropriate range. Six model runs (as listed in Table 1) are selected from the simulation ensemble and, unless otherwise stated, the results presented later in the paper are based on the ensemble mean. In the potential dust source region (Figure 4), all 12 USDA soil textures are represented, but most soils are of sandy or loamy nature. Sand (soil 1), loam sand (soil 2), sandy loam (soil 3), and loam (soil 4) cover 8%, 25%, 17%, and 38%, respectively, and the rest of the soils cover 12% of the area. Sand and loam sand do not emit dust (this is realized in the model through the specification of particle-size distribution). We have therefore perturbed the $c_y$ and $p$ values for soils 3 and 4. In experiment 8, we have increased the deposition velocity by a factor of 2. The model reaction to the parameters are discussed later in Figures 9 and 13.

4. Results

4.1. Comparison with Observations

[29] We validated the model simulation as far as observational data would permit. The data available for the comparison are the following: (1) European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Met-8 and MODIS images and Earth Probe TOMS aerosol indices for 1-10 March 2004 and (2) 3-hourly synoptic data from the surface weather stations in North Africa. These data sets are useful for verifying the simulated dust pattern and temporal evolution, but they do not provide quantitative verifications to the model simulations. [30] The distributions of the surface weather stations in North Africa and the dust records for March 2004 are shown in Figure 5. The stations in the northern and southern parts of North Africa are relatively dense, but quite sparse in the interior Sahara. Dust weather is recorded by human observers on the basis of visibility and can be grouped into the categories of “dust in suspension,” “blowing dust,” “dust storm,” and “severe dust storm” using the coding regulations of significant weather defined by the World Meteorological Organization [1995]. The dust weather reports suggest that in March 2004, the entire Sahara–Sahel region to the north of about 10°N was affected by dust activities. Dust storms and severe dust storms were observed in Algeria, Mauritania, Libya, Egypt, Sudan, etc. (Figure 5). To the south of the Mediterranean (Algeria, Libya, and Egypt), widespread “dust in suspension” and “blowing dust” were observed. Also noticeable, a dust zone was clearly visible at around 12°N. We should tentatively call this zone the Sahel dust zone. The existence of such a zone can also be identified from other case studies, for example, the 8 March 2006 dust episode [Schepanski et al., 2009].

[31] To illustrate the evolution of the dust activities during the period 1–10 March 2004, the daily dust weather records are shown in Figures 5a–5j. Despite the sparse distribution of the weather stations, it is seen that on 1 March 2004 the northern African continent was almost free of dust. Dust activities increased on 2 March 2004, and dust storms and severe dust storms occurred on 3, 4, and 5 March. On 8, 9, and 10 March, dust activities in the interior Saharan were weaker, but the Sahel dust zone persisted. Most of the dust events observed during the late stage of the dust episode were dust in suspension or blowing dust.

[32] The model-simulated dust pattern and evolution are compared with the dust weather records in Figure 6 in terms of air column dust load. The model correctly simulated the development of the dust storms on 3, 4, 5, and 6 March 2004 and the simulated evolution of the dust pattern was consistent with observations. The model simulation revealed that on 3 March 2004 dust storms developed in northwestern Sahara in conjunction with the cyclogenesis and the formation of the cold front. Much of the dust emitted from western Sahara was trapped in the cold air mass, forming a marked dust frontal structure (Figure 6b). The dust front then advanced toward the Atlantic, maintaining its shape for several days to follow (Figures 6c–6e). The Sahel dust zone came into existence as a result of the dust transported from

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**Table 1. Model Parameters $LAI_c$, $H_c$, $a_y$, and $a_w$ are Varied to Produce an Ensemble of Model Simulations**

<table>
<thead>
<tr>
<th>Name</th>
<th>$LAI_c$</th>
<th>$H_c$</th>
<th>$a_y$</th>
<th>$a_w$</th>
<th>Comments</th>
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<tr>
<td>Exp 1</td>
<td>0.1</td>
<td>500</td>
<td>0.25</td>
<td>0.33</td>
<td>For soil 3, $c_y = 4 \times 10^{-5}$, $p = 20,000$ N m$^{-2}$</td>
</tr>
<tr>
<td>Exp 3</td>
<td>0.3</td>
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<td>As Exp 1</td>
</tr>
<tr>
<td>Exp 5</td>
<td>0.5</td>
<td>500</td>
<td>0.25</td>
<td>0.33</td>
<td>As Exp 1</td>
</tr>
<tr>
<td>Exp 6</td>
<td>0.3</td>
<td>700</td>
<td>0.5</td>
<td>0.5</td>
<td>For soil 3, $c_y = 3 \times 10^{-5}$, $p = 20000$ N m$^{-2}$</td>
</tr>
<tr>
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<td>0.5</td>
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<tr>
<td>Exp 8</td>
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<td>0.5</td>
<td>0.5</td>
<td>As Exp 7, but diffusive dry deposition velocity increased by factor of 2</td>
</tr>
<tr>
<td>Exp 2</td>
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<td>0.33</td>
<td>As Exp 1; not included in ensemble</td>
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<tr>
<td>Exp 4</td>
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<td>500</td>
<td>0.25</td>
<td>0.33</td>
<td>As Exp 1; not included in ensemble</td>
</tr>
</tbody>
</table>

*Model runs used for the statistical analysis of the model results are listed.*
the Sahara. The dust pattern on 5 March 2004 can be well characterized by the presence of a dust front over the Atlantic, the west-east-running Sahel dust zone, and the active dust storms over Egypt.

[33] The predicted dust frontal structure can be compared with the EUMETSAT and MODIS (on board NASA's Aqua) images, as shown in Figure 7. At 1200 UTC, 4 March 2004 (Figure 7a), dense dust clouds over North Africa at around 15°N and a dust front over the Atlantic off the coast of West Africa can be clearly seen. A comparison of Figures 6c and 7a confirms that the model well simulated these key features of the dust event. At 1200 UTC, 5 March 2004 (Figure 7b), a somewhat more diffused dust pattern over the northern African continent and an elongated dust front over the Atlantic were clearly visible. Again, Figure 6d compares well with Figure 7b. The EUMETSAT images for other times of the event are not included here, but can be found at http://oiswww.eumetsat.org/webops/iotm/iotm/20040306_dust/20040306_dust.html. Figure 7c shows the MODIS image in a series of consecutive overpasses of Aqua. Dust transported from the Sahara was widespread across the Sahel and savanna regions of central Africa and a dust front reached thousands of kilometers over the Atlantic. Dust appeared thickest in the Bodélé Depression, indicating new dust emission from the region. Over south Egypt and large areas of Sudan, dust storms were also active. A comparison of Figures 6e and 7c confirms that the model reflected these important features. The MODIS images show that dust remained evident on 7 and 8 March over the entire Sahel (not shown). On 7 March, strong dust emission was visible in the Bodélé Depression and a thick plume of dust transported from the depression covered the northern parts of Nigeria and Cameroon, extending to the Gulf of Guinea and the tropical Atlantic. A thick dust plume also appeared in Sudan along the Sudan-Ethiopia border as well as in the Central African Republic. On 8 March, dust emission from the African continent was much weaker, but dust in suspension remained widespread over the Sahel, the Gulf of Guinea, and the tropical Atlantic. These features observed from the MODIS satellite images were well reproduced by the model.

[34] The predicted high dust concentration for the late stage of the dust episode originated from the eastern Sahara can be further verified by comparing the simulated dust pattern with the Earth Probe TOMS aerosol index. Figure 8 shows the TOMS aerosol index for 8 and 10 March 2004. On 6 March 2004, the aerosol index over the Sahel became substantially higher than in previous days (not shown). On 8 March 2004, the aerosol index over large areas between the equator and 20°N exceeded 4.5 because of the transport of dust from the Bodélé Depression, the southern part of Egypt and Sudan. The aerosol index
remained high on 10 March 2004 over the Sahel, an observation that is fully consistent with the model simulation (Figure 6f).

[35] There are several identifiable mismatches between the model results and the observations. The model appeared to have underpredicted the dust emission from central to southern Algeria on 3 March, and subsequently underpredicted dust concentration in southwest Mauritania on 4 and 5 March. These underpredictions of dust emission and dust concentration were likely to be caused by the underestimates of the near-surface wind speed in central to southern Algeria and the problem could not be rectified using the present version of the atmospheric dynamic model in CEMSYS.

[36] The quantitative behavior of the model is quite sensitive to model parameters. In Figure 9, we compare the column dust load of experiments 1, 3, 6, and 7 for 1500 UTC, 4 March 2004. While the general dust patterns are similar for all four experiments, quantitative differences are obvious with experiment 3 producing the highest dust load and the most extensive dust distribution and experiment 7 the lowest and most confined. As shown later in Figure 13, the model domain dust load predicted in experiments 3 and 7 differs by a factor of 2. The model parameters used in experiments 1 and 3 were the same, except that LAI, was enlarged from 0.1 to 0.3 (Table 1) and consequently the area of potential dust source was enlarged, extending from the Sahara to the Sahel (Figure 4). The consequence was the increased dust load over the southern part of Mali and Burkina Faso. In light of Figure 6, the simulated dust pattern of experiment 3 is in better agreement with the observations. The main difference between experiments 3 and 6 was an increase of roughness sheltering ($a_l$ increased from 0.25 to 0.5) and an increase in soil moisture ($a_s$ increased from 0.33 to 0.5). These changes resulted in increased wind erosion threshold and reduced dust emission and dust load. In experiment 7, dust emission was further reduced with respect to experiment 6 due to a decrease in $c_y$ for soil 3, despite an increase of dust emission from soil 4. These described differences among the experiments are further illustrated in Figure 13.

4.2. Dust Episode: Sources and Sinks

[37] An analysis of the synoptic systems and the patterns of dust transport of this episode reveals that the dust activities over the vast areas of the Sahara and the Sahel were closely related and they resulted from the interactions between the subtropical and tropical synoptic system. To understand the dust process, we must examine the atmo-
spheric circulation over a large area that encloses North Africa, the northeast Atlantic, and the Middle East, focusing on the cyclogenesis over central Africa, the anticyclone over the Atlantic, and the monsoon trough in tropical Africa.

[38] In light of Figures 1 and 6, we can divide the dust episode into different stages to better understand the evolution of dust patterns and the responsible synoptic systems.

1. Stage 1 (pre-1 March 2004): This is the building-up stage with weak wind blowing over the Sahara. The most important observation is the presence of a strong baroclinic zone stretching from west to east across the Sahara at around 25°N (Figure 1). By 1 March 2004, an anticyclone was situated over the subtropical Atlantic, with its center at about 20°W, 30°N. An upper-level disturbance penetrated into northwest Africa [Knippertz and Fink, 2006, Figure 7a] and was instrumental in triggering the surface cyclogenesis over the northern Algerian Sahara.

2. Stage 2 (2–4 March): On 2 March, the cyclogenesis took place over central Africa, which, together with the northeastward movement and intensification of the anticyclone over the Atlantic, resulted in a substantially strengthened northerly flow over western Sahara and the formation of a cold frontal system. As a consequence, dust was mainly lifted from western Sahara (Mauritania Tiris Zemmour region near the villages of Zouerate and Bir Moghréb and northern Mali) and was transported southwestward. On 4 March, large parts of the Sahara were dominated by strong winds exceeding 20 m s⁻¹, and dust was widely spread. The strong northeasterly flow transported a large quantity of dust to the Atlantic. An elevated dust front, stretching several thousand kilometers, was clearly visible over the Atlantic on 3 and 4 March and remained visible for several days (Figures 6b, 6c, and 7).

3. Stage 3 (5–6 March): By then, the matured and eastward moving cyclone was located over Libya, accompanied by the high-pressure system off the coast of Spain over the Atlantic. Associated with these two systems were strong northerly winds over northern Sahara, northeasterly winds over western Sahara, and northwesterly winds over eastern Sahara. Dust emission in western Sahara was weaker, but strong in the Libyan Desert, the Bodélé Depression in Chad, and Niger. Dust lifted from these regions was transported southward to the northern side of the monsoon trough, leading to the formation of the Sahel dust zone. Dust was also lifted from northern Sudan 32°E, 18°N and transported toward the Red Sea.

4. Stage 4 (7–8 March): The anticyclone, together with the cold air, was moving into western Sahara and the cyclone was moving out of Africa, northeastward to the

Figure 7. EUMETSAT Met-8 images for (a) 1200 UTC, 4 March 2004, and (b) 1200 UTC, 5 March 2004. The redish color indicates the presence of dust. (c) The dust storms on 6 March 2004 imaged by MODIS in a series of consecutive overpasses of NASA’s Aqua satellite (Image courtesy Jacques Desclèoires, MODIS Rapid Response Team, NASA-Goddard Space Flight Center).

Figure 8. (a) Earth Probe TOMS version 8 aerosol index for (a) 8 March 2004 and (b) 10 March 2004. For both days, the high aerosol index over the Sahel was caused by the dust transported from the Bodélé Depression in the southern part of Egypt and Sudan.
Middle East. Wind speed reduced over western Sahara but remained strong over eastern Sahara. As a consequence, dust emission ceased in western Sahara but remained strong in eastern Sahara. Dust was blown off from Egypt, Sudan, and Chad and again was transported toward the monsoon trough, feeding dust to the Sahel dust zone.

Stage 5 (post-8 March): Large quantities of dust particles remained in suspension to the north of the monsoon trough. They were gradually diffused by the easterly wind toward the tropical Atlantic or deposited to the ground. It is most likely that the dust that remained in suspension in the Sahel dust zone will be transported further to the west of the tropical Atlantic in the easterly flow (Figure 6f).

The dust sources and sinks also evolved considerably during the dust episode. In the model, dust emission and dust deposition were computed separately. However, it is in general the case that regions of strong dust emission were also regions of strong dust deposition. Figure 10 shows two examples of dust emission and deposition simulated for 1500 UTC, 3 March, and 0000 UTC, 4 March 2004. In the former case, the main dust sources were located in the northern and western parts of the Sahara with the strongest dust emission (ca. 500 µg m\(^{-2}\) s\(^{-1}\)) occurring in northern Libya, northern Egypt, Western Sahara, and Mauritania. The patterns of dust emission and deposition were very similar, except that deposition was also noticeable in areas of high dust concentration (e.g., off the coast of Western Sahara). Similar observations can be made from Figures 10c and 10d.

We define net dust emission, \(F_N\), as the difference between dust emission, \(F\), and dust deposition, \(F_D\); that is,

\[
F_N = F - F_D. \tag{9}
\]

In Figure 11, the daily averages of \(F_N\) for 3–6 and 10 March 2004 as well as the episode averages of \(F_N\) over the period 1–10 March 2004 are plotted. Dust emission began on 2 March on the northern fringes of the Sahara (Figure 11a) but was strongest on 3–5 March 2004. On 3 March (Figure 11b), a region of strong net dust emission existed in northwest Sahara stretching from Mauritania, Algeria to the south of the Atlas Mountains, and from the northern part of Libya to the northeast of Egypt. The strongest dust emission occurred in the vicinity of Tindouf at the Morocco–Mauritania–Algeria border, with daily averaged \(F_D\) reaching 0.3 mg m\(^{-2}\) s\(^{-1}\). Strong dust emission also occurred at the Algeria–Tunisia–Libya border and at the Libya–Egypt border. Fairly strong dust deposition, reaching 0.05 mg m\(^{-2}\) s\(^{-1}\), occurred over the northern Atlantic of the coast off Morocco near the Canary Islands. On 4 March 2004 (Figure 11c), the main dust emission region was...
located much farther to the south, at around 20°N, with a dust emission zone stretching from southern Mauritania, via Mali, to Niger. Significant dust deposition occurred to the south of the dust source region and over the Atlantic off the coast of Western Sahara. Dust emission in Western Sahara was much weaker on 5 March 2004, and the main dust sources were now located in Niger, Chad, Libya, and Egypt (Figure 11d). On 6 March, the areas of dust emission were much reduced and the main dust sources were now confined to Chad (Mordi depression area), Egypt (western desert area), and Sudan (Baiyuda and Nubian desert area). Strong net deposition occurred in the adjacent areas downstream (namely to the southwest) of the main dust sources.

The 10 day averages of $F_D$ are shown in Figure 11f. Most of the dust emission occurred to the north of about 16°N. This is clearly related to the fact that there was much better vegetation cover to the south of 16°N. The main dust source regions are found to be Mauritania, Chad, Libya, and Egypt. This distribution of main dust source regions is in general consistent with the climatic dust source regions shown in Figure 2, but for this particular episode the model predicted that eastern Sahara was the largest dust source in contrast to the findings of D’Almeida [1986] and Prospero et al. [2002]. This is caused by the strong winds over eastern Sahara, which lasted several days.

4.3. Dust Budget

To facilitate description, we introduce quantities integrated over the model domain; for example,

$$AF = \int_S F ds$$  \hspace{2cm} (10)$$

is the model domain integrated dust emission with dimensions $M m^{-1}$, where $S$ is the model domain area. Similarly, the total dust load $AM$ with dimensions $M$ is defined as

$$AM = \int_S M ds$$  \hspace{2cm} (11)$$

with $M$ being the air column dust load. The budget for the model domain can be expressed as

$$\frac{\partial AM}{\partial t} = AF - AF_D - AF_W - AF_V = AF_N - AF_V,$$  \hspace{2cm} (12)$$

where $AF_D$, $AF_W$, and $AF_V$ are the dry deposition, wet deposition, and rate of dust transported out of the domain, respectively, and $AF_N$ is the net dust emission. An integration of equation (12) over time $t$ gives

$$AM(t) = AM(0) + \int_0^t AF_N dt - \int_0^t AV dt,$$  \hspace{2cm} (13)$$

In our study, we have assumed $AM(0)$ to be zero. We therefore have

$$AM(t) = CAF_N - CAF_V,$$  \hspace{2cm} (14)$$

where $CAF_V$ is the cumulative net dust emission and $CAF_V$ is the cumulative amount of dust transported out of the simulation domain.

Figure 12 shows the ensemble-averaged time series of $AF$, $AF_D$, $AF_W$, $AF_V$, and $AM$ and $CAF_N$. The ensemble consists of six simulations, including experiments 1, 3, 5, 6, 7, and 8. As can be seen from Figure 12d, $AF$ has clear diurnal variations with stronger dust emission occurring during the
day. The largest AF values occurred on 3–5 March 2004 with a maximum reaching 9 Mt hr\(^{-1}\). Strong dust emission was always accompanied by strong dust deposition, AF\(_D\), so that much of the dust emitted from the surface was immediately deposited back to the surface. In general, AF\(_N\) is much smaller in magnitude than both AF and AF\(_D\) (Figure 12c). Over the period 1–10 March 2004, the most positive AF\(_N\) was less than 2 Mt h\(^{-1}\) and the most negative AF\(_N\) was about 0.2 Mt h\(^{-1}\), which occurred in the nighttime. Rainfall occurred during the first few days of the episode but was confined to the very northern parts of North Africa (Figure 2). As a consequence, wet deposition for this particular event was small in comparison with dry deposition (Figure 12b). The most significant wet deposition occurred on 3 March 2004 with its maximum reaching 0.18 Mt h\(^{-1}\). In comparison to dry deposition, wet deposition was almost negligible.

[50] We integrated AF\(_N\) over the 10 day time period, and the so calculated CAF\(_N\) is 100.3 Mt (note that AF\(_N\) integrated over land surface gives 107.6 Mt) and the dust remaining suspended in the atmosphere at the end of the 10 day simulation was 20.5 Mt. This implies that during the episode, a net of 79.8 Mt dust was transported through the boundaries of the model domain (namely, CAF\(_V\)). For 1981 and 1982, D’Almeida [1986] estimated the annual dust emission from the Sahara and Sahel region to be 673.8 Mt and the monthly dust emission for March to be 109.6 Mt. For 1991 and 1992, Marticorena et al. [1997] estimated the annual dust emission to be 625.7 and the monthly dust emission for March to be 132.0 Mt. Laurent et al. [2008] reported that the dust emission from the Sahara during the years between 1996 and 2001 ranges from 585 to 759 Mt yr\(^{-1}\). It is appropriate to examine the definition of “dust emission.” Marticorena...
et al. [1997] and Laurent et al. [2008] appeared to use the term “dust emission” to refer to the rate of dust being lifted from the surface, namely AF, but D’Almeida [1986] uses the term to refer to “net dust emission,” namely AF$_N$, although the “dust emissions” reported in these three studies are of the same order of magnitude. Our estimates of “net dust emission” are consistent with the results of D’Almeida [1986] in order of magnitude. Our results are consistent with those of Marticorena et al. and Laurent et al. only if the expression “dust emission” in their studies can be interpreted as “net dust emission”; otherwise, our “dust emission” would be several times their “dust emission.”

[51] It is not possible for us to quantify the accuracy of the above-presented model predictions. Figure 13 shows the ensemble of AF$_N$ and AM from the six simulations. The size of the ensemble is clearly much too small to allow us to make an accurate statement on the errors of the model estimates. Nevertheless, it can be readily seen that the ensemble discrepancies and the ensemble averages are of the same order of magnitude. For example, at the end of the 10 day simulation, the ensemble mean of AM is 20.5 Mt, but it varies between 8.3 and 31.9 Mt with a standard deviation of 7.3 Mt.

[52] The ensemble-averaged time series of dust deposition AF$_{Do}$ to the surrounding oceans and the cumulative dust deposition CAF$_{Do}$ are shown in Figure 14. In comparison with dust emission, AF, and dust deposition over the continent, AF$_{Dl}$ (not shown), AF$_{Do}$ is much smaller in magnitude. As expected, dust deposition to the ocean increased from the beginning of the model simulation to a maximum of 0.06 Mt h$^{-1}$ on 3 March 2004, and then gradually decreased to about 0.035 Mt h$^{-1}$ at the end of the model simulation. Over the 10 day time period, the total dry deposition to ocean amounted to 6.7 Mt. The total wet deposition to the ocean amounted to 0.6 Mt. Thus, the total deposition (namely, dry plus wet) amounts to 7.3 Mt. The above-described dust budget for the simulation domain can now be summarized in Figure 15.

5. Concluding Remarks

[53] Using an integrated dust-storm modeling system, we carried out a numerical simulation of the severe Saharan dust storms that occurred during the time period 1–10 March 2004. The simulated dust patterns were compared with surface weather records and satellite images and the model simulations are found in good agreement with the observations, apart from a possible underprediction of dust emission from the southern part of Algeria and a possible over-prediction of dust emission from East Africa for the late
stage of the dust episode. In this study, we again demonstrated that the CEMSYS model has the capacity to qualitatively well simulate continental-scale dust storms, as also shown by Shao et al. [2003, 2007].

[54] The synoptic system that generated this Saharan dust event and the evolution of the dust patterns are now well understood. In comparison to many other dust storms in North Africa, the March 2004 dust events swept through all of North Africa. Dust first appeared in the western part of North Africa, then in the eastern part of Africa, and, very importantly, much of the dust emitted from the latter part was transported toward the monsoon trough, resulting in quite high dust concentrations in the tropical region. This understanding of the dust transport pattern seems to be new and has considerable implications for studying the impact of dust on atmospheric radiative forcing and possible feedbacks.

[55] Our analysis shows that the synoptic systems that generated the March 2004 dust storm are related to the circulation patterns over a very large area enclosing North Africa, the northeast Atlantic, and the Middle East. The main systems involved include a cyclone and the associated fronts over central Africa, an anticyclone over the Atlantic, and the monsoon trough. At the beginning of the dust episode, a high-pressure system was located over the subtropical Atlantic, and a zone of strong baroclinic instability stretching from west to east across the Sahara existed at around 25°N. The presence of the strong baroclinic instability resulted in the cyclogenesis, which, together with the northeastward movement and intensification of the anticyclone, produced a strong northerly flow over western Sahara and the formation of a frontal system. The matured cyclone over Libya accompanied by the high-pressure system over the Atlantic generated strong northerly winds over northern Sahara, northeasterly winds over western Sahara, and northwesterly winds over eastern Sahara, with strong winds exceeding 20 m s⁻¹. On the subsequent days, the anticyclone gradually moved into western Sahara and the cyclone northeastward to the Middle East. Winds were generally weaker over western Sahara but remained strong over eastern Sahara until 10 March.

[56] Our numerical results show that most of the dust emission occurred to the north of about 16°N–17°N, and the main dust source regions are (1) Mauritania, (2) Chad and Niger, and (3) Libya, Egypt, and Sudan. This distribution of main dust sources is in general agreement with the climatic dust sources shown in Figure 2. The region between 10°N and 17°N is a region of net dust deposition. Dust was also deposited to the northern African continent.

[57] In this study, we highlighted the difference between dust emission and net dust emission. Our simulation shows that 715.8 Mt of dust was emitted into the atmosphere, but 85% of the dust (i.e., 608.2 Mt) was deposited back to the continent. The net dust emission from North Africa during the 10 day period was 107.6 Mt, of which 7.2 Mt was deposited to the ocean within the model domain, 20.5 Mt remained suspended in the atmosphere of the model domain, and 79.8 Mt was transported across the boundaries of the model domain.

[58] Overall, there was little rainfall during the entire episode between 1 and 10 March 2004. As a consequence, wet deposition (4.7 Mt) was almost negligible when compared to dry deposition (610.8 Mt) over the model domain. Thus, wet deposition during this episode was less than 1% of the dry deposition.

[59] The dust budget was derived based on the ensemble of six model simulations. However, we are still not in a position to fully quantify the accuracy and the error margin of the dust budget estimates presented in this study because the size of the ensemble is too small and indeed the increase of the ensemble size would probably not lead to better accuracy because there remains a critical lack of quantitative observations for model validations. Based on the six numerical simulations, it is clear that the discrepancies among the model simulations are quite large. The quantitative discrepancies between the model simulations and the ensemble average are of the same order of magnitude.

[60] Of considerable interest in this dust episode is the extremely wide spread of dust coverage, with high dust concentration over the Atlantic and the Sahel region, lasting for a number of days. The consequences of the dust presence on radiation transfer and atmospheric circulation are expected to be significant but are not considered in the present study. Knippertz and Fink [2006] speculated that the reduced incoming solar radiation along the Guinea Coast may have delayed the reestablishment of the West African heat low over the continent and caused an anomalously dry March 2006 along the Guinea Coast. We intend to conduct a

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Table A1. Subsample of Soil Data Used in This Study

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follow-up study to investigate the dust radiative effect and its impact on atmospheric circulation and synoptic patterns.

Appendix A: Conversion of Global Data Set of Soil Particle Size Properties to USDA Soil Classes

The soil data used in this study are based on the Global Data Set of Soil Particle Size Properties [Webb et al., 2000], available online (www.daac.ornl.gov) from the Oak Ridge National Laboratory Distributed Active Archive Center. The data set includes, among many others, the records for the Zobler soil type (106), continent code (10), profile number (15), contact depth of profile, and percentages of sand, silt, and clay. To each record in the first soil horizon, a USDA soil texture class is assigned by comparing the percentage data of sand, silt, and clay using the USDA soil texture triangle. There is no unequivocal match between the Zobler soil type and USDA soil texture classes. A subsample of the soil data is shown in Table A1.

Appendix B: Soil Particle Size Parameters and Dust Model Parameters

Table B1 lists the soil particle size parameters and dust model parameters used in this study.

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References


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