Transatlantic Saharan dust transport: Model simulation and results

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[1] Long-range transport of desert dust from the Sahara across the northern Atlantic has been recorded many times by satellite imagery and ground-based measurements. However, this evidence cannot fully describe all the phases of the atmospheric dust lifecycle. To partly compensate for the lack of such knowledge, an atmospheric model with incorporated dust uptake-transport-deposition module has been used in this study. The goal was to assess qualitatively and quantitatively the ability of the model to predict the dust cycle in the atmosphere for a long period. For this purpose, the complicated dust episode of June–July 1993 (almost one month) was simulated with the SKIRON weather forecasting system. This dust intrusion was associated with long-range transport of Saharan dust across the Atlantic Ocean and simultaneous regional transport towards the Mediterranean Sea. Comparison of the forecasts with the available observations (in a qualitative and quantitatively way) indicated that the model was able to simulate the long-range dust transport patterns and in particular to estimate the spatiotemporal distribution of the dust concentration on a satisfactory way.

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1. Introduction

[2] The atmospheric desert dust cycle is a complex geophysical process, strongly influenced by combined effects of desert soil erosion and atmospheric conditions. Due to significant impacts on climate and the environment, the topics regarding desert dust are the matter of active research and attention. It has been shown that dust material injected into the atmosphere and transported away from its sources may significantly modify the marine biochemistry after deposition to ocean waters [e.g., *Martin and Fitzwater*, 1988]. Mineral dust is also an important climate-forcing factor, causing a decrease in the net radiation forcing of about 1 Wm^{-2} [*Li et al.*, 1996]. Usually having pH greater than 7.0, dust plays a role in the neutralization of the acid rain [e.g., *Hedin and Likens*, 1996]. In the work of *Alpert et al.* [1998], the dust-forced heating of the lower troposphere was estimated to be ~0.2 K. They also pointed out that dust aerosols are an important source of inaccuracies in numerical weather prediction and especially in General Circulation Models (GCMs) used for climate research. It is also worth mentioning that some intense dust storms catastrophically affect the regions in the neighborhood of deserts, causing loss of human life and economic damage while fine-particle concentrations (i.e., <2.5 μm) have been associated with increased mortality in several cities of the United States [*Schwartz et al.*, 1999]. As was found in *Rodriguez et al.* [2001] and *Papadopoulos et al.* [2003], the contribution of Saharan dust to air quality degradation in southern European cities is significant. This has as a result the deviation from the air quality standards imposed by the EU.

[3] *Barkan et al.* [2004] estimated the monthly and annual averages of aerosol index values from TOMS instrument for the period of 1979–1992 in order to assess the climatology of dust sources in North Africa and the Arabian Peninsula. The highest aerosol index values were found in the summer months of June and July, while the area around Lake Chad has demonstrated the highest value and, contrary to the other sources, is active throughout the year. In two of the most dustier and deserted sources, in Chad and Mali at western Africa, the peak was in May. A large seasonal variability of the dust mobilization that depends on the source characteristics as well as the global atmospheric circulation was detected in both satellite observations and ground-based measurements [*Ozsoy et al.*, 2001]. During winter and spring, the Mediterranean region is affected by two upper air jet streams: the polar front jet stream, normally located over Europe, and the subtropical jet stream which is typically located over northern Africa. The combined effects of these westerly jets in late winter and spring support the propagation of extratropical cyclones towards the east and southeast, resulting in dust plume intrusion in the Mediterranean. Most of the Saharan dust events that transport significant amounts of dust towards the Mediterranean Sea and Europe occur during the low index circulation period of the year (cold and transient seasons

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as described by *Papadopoulos et al.* [2003] and *Rodriguez et al.* [2001]). During summer the amount of transported aerosols is almost twice as large as in winter [*Husar et al.*, 1997] with the highest amount of dust transport within the tropical easterly jet from Africa toward the tropical Atlantic, reaching the Caribbean Sea and North America [*Perry et al.*, 1997].

[4] Driven by the trade wind circulation, Saharan dust is often moved across the Atlantic Ocean [*Karyampudi*, 1979; *Karyampudi et al.*, 1999]. During such events, dust has been observed in Barbados [*Li et al.*, 1996] and in the eastern and southeastern parts of the United States [*Savoie and Prospero*, 1977]. There is evidence that North African dust has been deposited, over shorter geologic timescales, in sufficient quantities to become the parent material of some soils in Bermuda [*Herwitz et al.*, 1996] and mountainous islands in the Caribbean [*Muhs et al.*, 1990].

[5] *Perry et al.* [1997] performed an analysis of the frequency, spatial distribution and concentration of the dust transported from remote sources towards the eastern United States. Their study is based on an extensive record of dust concentrations from an observational network in United States, during the period from March 1988 to May 1995. The data collected by the Interagency Monitoring of Protected Visual Environments (IMPROVE) network suggests that, in many cases, the dust had its origin in North African deserts. Using the trajectory analysis and a conceptual atmospheric circulation model, *Perry et al.* [1997] postulated that the easterly winds of the summer Inter-Tropical Convergence Zone (ITCZ) in the tropics might provide a mechanism for successful long-range transport across the Atlantic. Once occurred in the vicinity of the American continent, the dust can be further driven towards the southern and eastern United States as it enters into the zone of the semi-permanent "Bermuda" high. According to *Perry et al.* [1997], most of the dust particles transported over large distances are of diameter less than 2.5 μm ($PM_{2.5}$). These particles are considered as light and therefore should remain in the atmosphere for a long time. Such approach is in agreement with *Tegen and Fung* [1994] who estimated that the lifetime of clay particles with a size of 0.7 μm is about two weeks. *Perry et al.* [1997] showed a detailed structure of observed dust load in areas located thousands of kilometers far away from Sahara for the dust event that occurred from June to July 1993. However, information on dust storm generation and associated atmospheric conditions during this long-range transport episode has remained unknown.

[6] In this paper, the specific dust episode of the summer of 1993 was analyzed with the aid of the integrated modeling system SKIRON/Eta that includes a module for simulating atmospheric desert dust cycle. The main advantage of this modeling system is that dust module is directly coupled with the atmospheric model, resulting in the computation of the dust cycle at every time step of the atmospheric model. Comparison of the model outputs with the available observations indicates that the model is capable to reproduce the dust sources, the evolution of the aerosol size distribution, the dust transport and the 3-D mass concentration on a satisfactory way. In section 2, a short description of the modeling system is provided. The design and the results of the numerical experiment are presented in sections 3 and 4, respectively. Section 5 summarizes the overall conclusions.

2. Model Description

[7] The modeling system used in this study is the SKIRON forecasting system [*Kallos et al.*, 1997]. The major parts of the system are the SKIRON/Eta limited area atmospheric model and the dust cycle module.

[8] The SKIRON/Eta model is a modified version of the Eta/NCEP model. The modifications and improvements incorporated are these suggested by the SKIRON and POSEIDON projects, especially in the parameterizations of the atmospheric radiation and surface processes [*Kallos et al.*, 1997; *Papadopoulos et al.*, 2002]. The Eta model includes state-of-the-art components of the atmospheric dynamics and physics [*Mesinger et al.*, 1988; *Janjic*, 1994].

[9] The dust module is developed and tested at the University of Athens (Atmospheric Modeling and Weather Forecasting Group), in the framework of the MEDUSE project [*Nickovic et al.*, 1997]. The integrated system has been further developed in the framework of ADIOS Project and the current model version incorporates state-of-the-art parameterizations of all the major phases of the atmospheric dust lifecycle such as production, diffusion, advection, and removal, including as well the effects of the particle size distribution on aerosol dispersion and deposition. Older versions of the system were used to perform studies of historical dust-storm events [*Kubilay et al.*, 2000; *Ozsoy et al.*, 2001; *Tsidulko et al.*, 2002]. In the currently used version of the model, four size bins were considered with centered diameters of 1.5, 12, 36, and 76 μm. This division is in accordance of classification proposed by *Tegen and Fung* [1994]. A detailed description of the dust cycle module is given in the work of *Nickovic et al.* [2001]; hence it is not repeated here.

[10] The dust cycle module is dynamically coupled with the atmospheric model, therefore at each time step the prognostic atmospheric and hydrological conditions are used to calculate the effective rates of the injected dust concentration based on the viscous/turbulent mixing, shear-free convection diffusion, and soil moisture. This offers a major advantage in numerical simulations for a more realistic description of the dust cycle in the atmosphere, contrary to the use of wind fields and turbulence for a certain period of time (∼3–6 hours).

[11] The SKIRON/Eta system with the dust component has been in operational use at the University of Athens since 1998 providing 72-hour weather and dust transport forecasts for the Mediterranean region. These forecasts are available from the Internet site http://forecast.uoa.gr. The daily operation of the system provides a unique opportunity for its evaluation and potential further developments. The latest modifications concerning the definition of the dust sources and the dust production mechanism enhance the forecast skill of the system to predict with a satisfactory accuracy the dust cycle in the atmosphere. In this study, we present evidence that the modeling system is also reliable for application for longer periods (e.g., 30-day simulations)

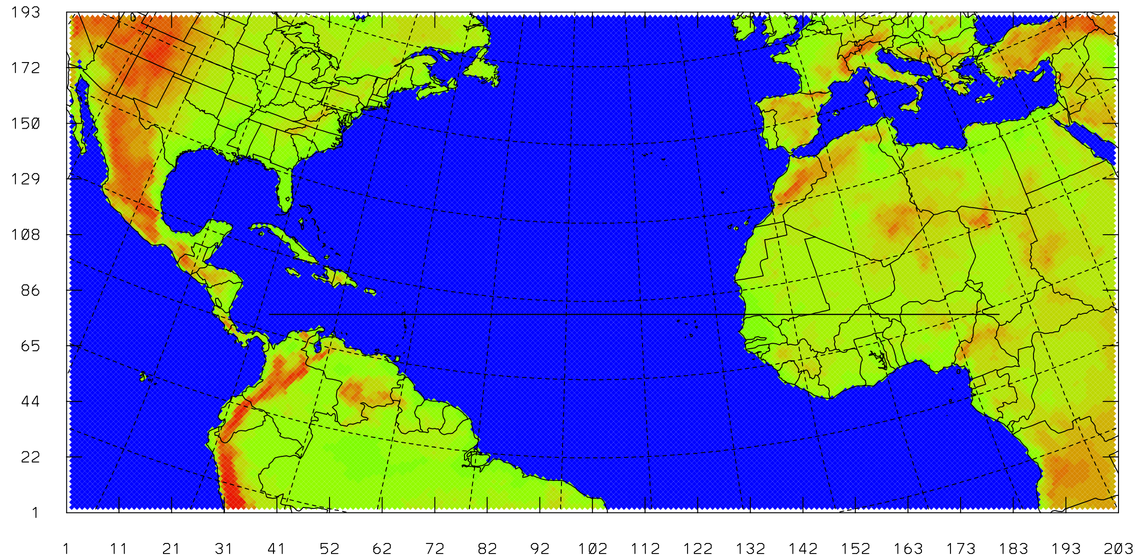

Figure 1. Model domain. The thick line indicates the position of the cross section used later.

covering an area much larger than typically used in regional applications.

3. Experimental Design

[12] For the specific experiment, the SKIRON/Eta system was integrated over a domain covering the northern half of Africa, the Mediterranean Sea, Europe, the Atlantic Ocean and Central and North America (Figure 1). In the vertical, 32 levels were used stretching from the ground to the model top (15,800 m). In the horizontal, a grid increment of 1/3 of degree was applied. The simulation was performed for the period from 10 June to 10 July 1993, about two weeks before the increased dust concentrations were recorded over the United States. Considering that approximately one week is a typical period of time for dust to cross the Atlantic Ocean [*Carlson and Prospero*, 1972], the model had enough time to establish equilibrium in the dust processes and to transfer it across the Atlantic.

[13] Special care was taken to define as accurately as possible the dust productive areas since soil properties (soil structure, soil wetness, vegetation cover) dictate the dust quantity that may be available when the turbulent state of the surface atmosphere triggers its injection into the atmosphere. According to the description of *Nickovic et al.* [2001], the effects of soil structure and particle size distribution are taken into account. Indeed, parameters such as the model grid fraction covered by desert, the fractions of clay, small silt, large silt, and sand, and the ratio between the mass available for uplift and the total mass of the respective size bin are combined to calculate the dust productivity coefficient. Then, this coefficient is used in the calculations of the surface dust concentrations that will define if and how much dust mass will finally participate in the atmospheric transport. For this purpose, the high-resolution data sets of vegetation and soil texture types that are used in the atmospheric driving model are also used for the specification of the dust sources and for the calculation of dust-related processes depended on the soil conditions. For the geographical distribution of the land cover and the dust sources two different vegetation type data sets were used, the Simple Biosphere Model (SIB) and the Olson Global Ecosystem (OGE) data sets, containing 16 and 96 vegetation types, respectively. Both are available through the U.S. Geological Survey (USGS) in global coverage with 30 $\times$ 30 arc sec resolution. For the soil texture distribution the UNEP/FAO data set was applied after its conversion from soil type to soil textural ZOBLER classes [*Papadopoulos et al.*, 1997]. The coverage of this data set is global and the resolution is 2 $\times$ 2 min. For the initial and the boundary meteorological conditions the European Center for Medium range Weather Forecasts (ECMWF) analysis data were used, with a 0.5 degree horizontal grid increment and for 11 standard pressure levels. The lateral boundaries of the model domain were updated at each time step from the ECMWF data that are available every 6 hours.

4. Results and Discussion

[14] During the period of the simulation (10 June to 10 July 1993), the atmospheric circulation over the area of interest was characterized by a strong anticyclone covering the North Atlantic (the Azores anticyclone) and by low pressure systems covering most of western Africa in the region of the ITCZ (between 10°W–10°E and 10°N–30°N)(Figure 2a). These depressions resulted from monsoonic activity and the extreme heating of the desert land. The relevant position of the anticyclonic and pressure low systems had established a strong pressure gradient over the NW part of Africa. Meanwhile, as a center of low-pressure located in the central and west Atlantic began to move eastward, the anticyclone exhibited a retrogression with its center located NE of the Caribbean Islands after 18 June (Figure 2b). This caused a strengthening of the pressure gradient over the NW African region. In addition, the Atlantic anticyclone extended eastward over the Mediterranean region. This large-scale weather pattern resulted in the establishment of a relatively strong flow from NNE to ENE directions over the Saharan region where the soil composition was favorable for dust uptake.

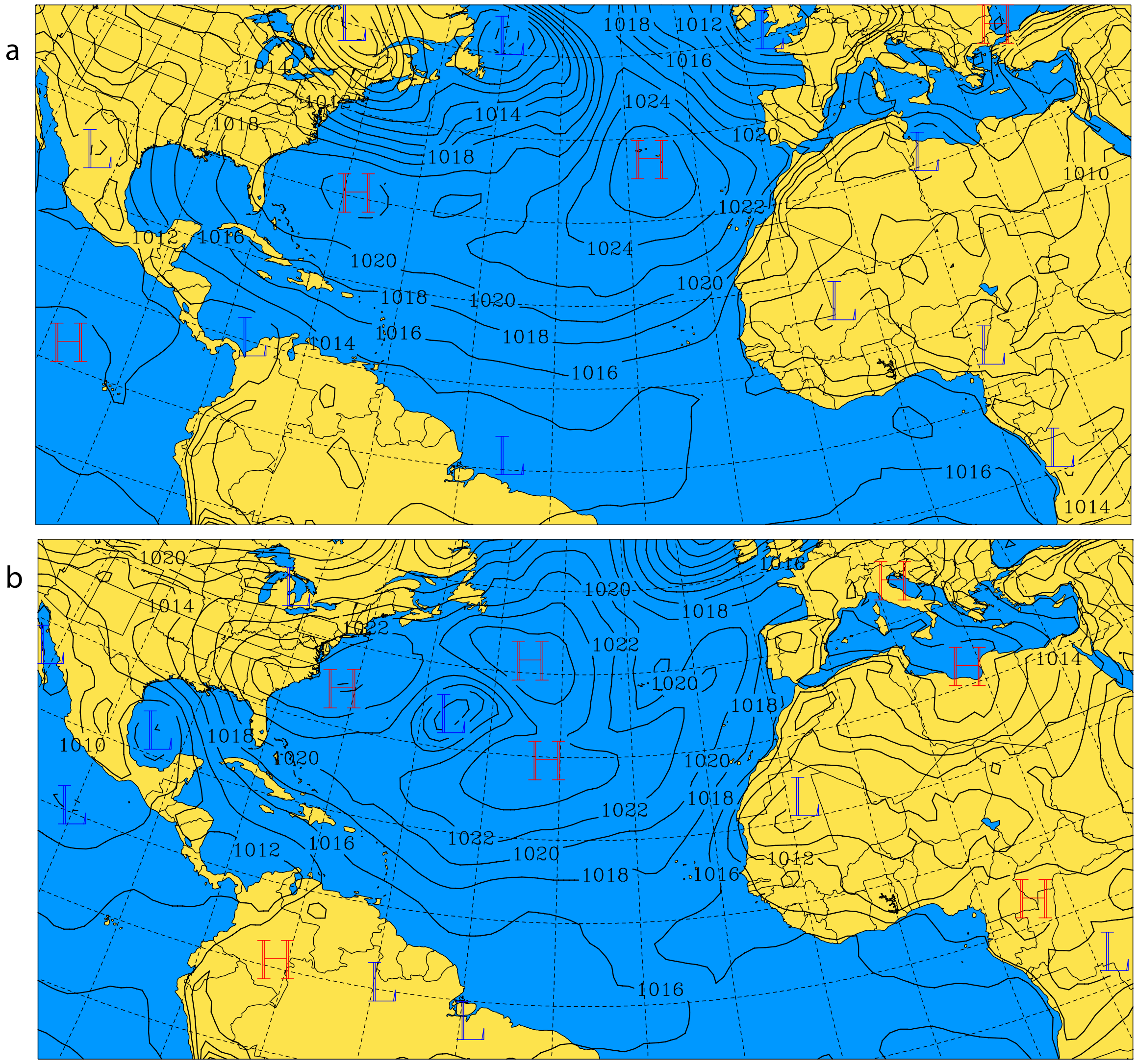

Figure 2. Mean sea level pressure maps at 1200 UTC on (a) 10 June and (b) 18 June 1993.

[15] The atmospheric circulation over the Sahara during the period from 10 to 20 June provided quite favorable conditions for dust production. This was confirmed by the simulated surface fluxes of dust concentration, which indicated increasing dust activity during the considered period. Until 17 June, several relatively moderate dust uptake events were simulated over the NW Africa. As a result, a dust plume was generated and driven by the subtropic easterlies towards the Atlantic. On 18 June, a new but more intense dust uptake was produced in the area close to the center of the low-pressure system. The model-estimated daily peak of the total surface dust flux (quantifying all four particle sizes) exceeded 9 mgr m^{-2} s^{-1} (Figure 3a). The position of the dust storm to a large extent coincided with the maximum of the friction velocity (not shown), indicating that the dust was mobilized by the transfer of momentum from the free atmosphere towards the ground. Additionally, the uptake process was supported by the mechanism of shear-free thermal convection initiated by high temperatures in the lower atmosphere (Figure 3b). From 19 June onwards, production of dust decreased as the local center of the low gradually diminished. In general, the high-productive areas are spotted in locations SSE of Atlas Mountains and within the triangle between the alluvial plain of Bilma in Niger, the Tibesti massif of Chad and the Ahaggar massif of Algeria.

[16] Since the dust production was associated with easterly winds, the dust plume was transferred toward the Atlantic. The major transatlantic transport was associated with the intense dust load over Central Mediterranean on 23 and 24 June. The secondary dust event was generated during roughly the same period (18 and 19 June). During these days the general flow pattern had two major branches: one towards Atlantic (with its maximum intensity over the highly-productive areas at SSE of Atlas Mountains) and the other one towards the Mediterranean Basin (Figure 3b). This flow pattern had as a result the splitting of the dust plume. Verifying the simulated secondary Mediterranean episode for 23 June 1993, we noted a good qualitative and quantitative agreement between model-estimated (Figure 4a) and observed vertically integrated dust load (Figure 4b). The observed dust load was estimated from the METEOSAT visible analyzed image of aerosol optical

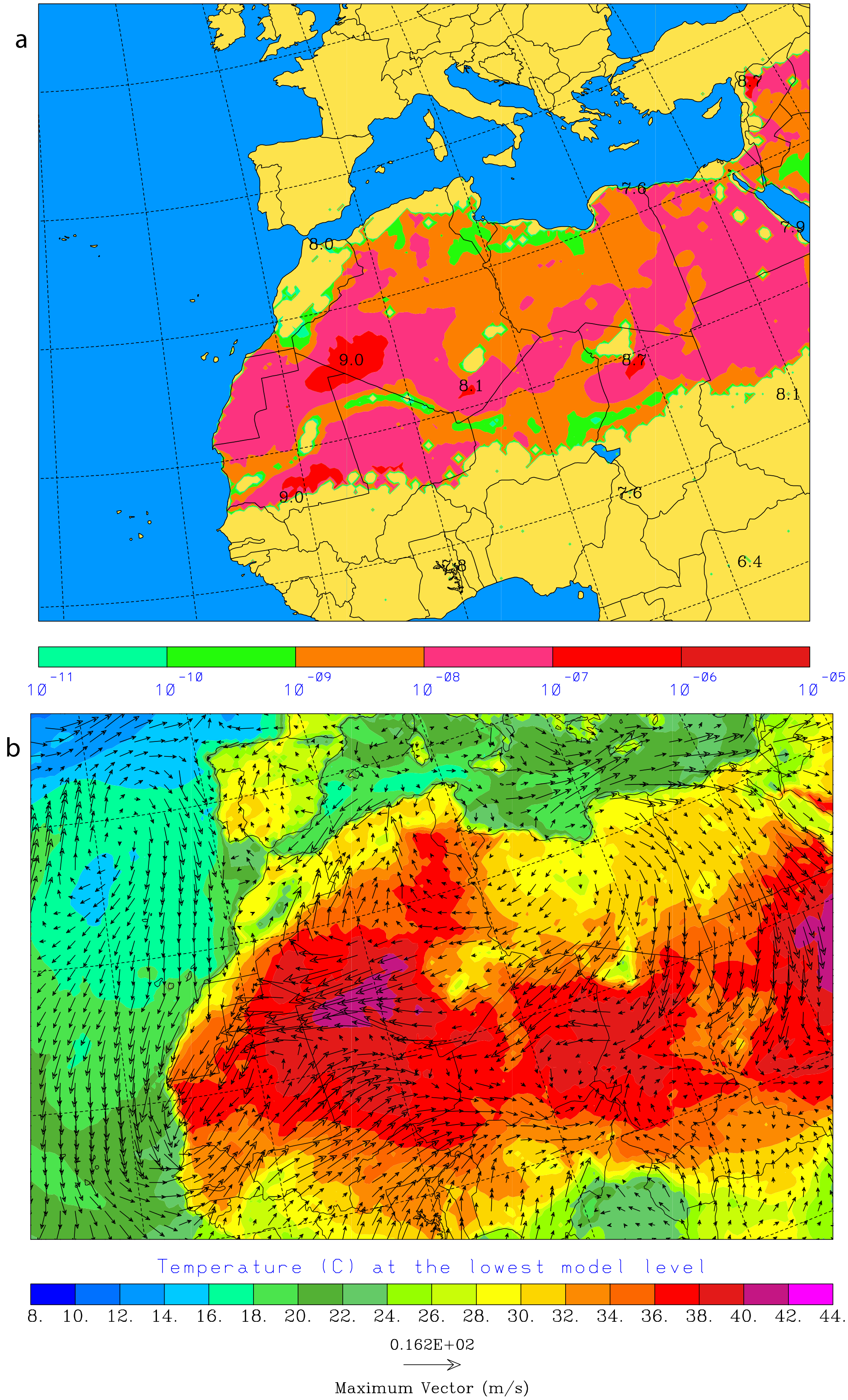

Figure 3. Model generated (a) surface dust fluxes (kg $m^{-2}s^{-1}$) and (b) temperature and wind fields at the first atmospheric level above surface (ETA level) over the Saharan desert at 1200 UTC on 18 June 1993.

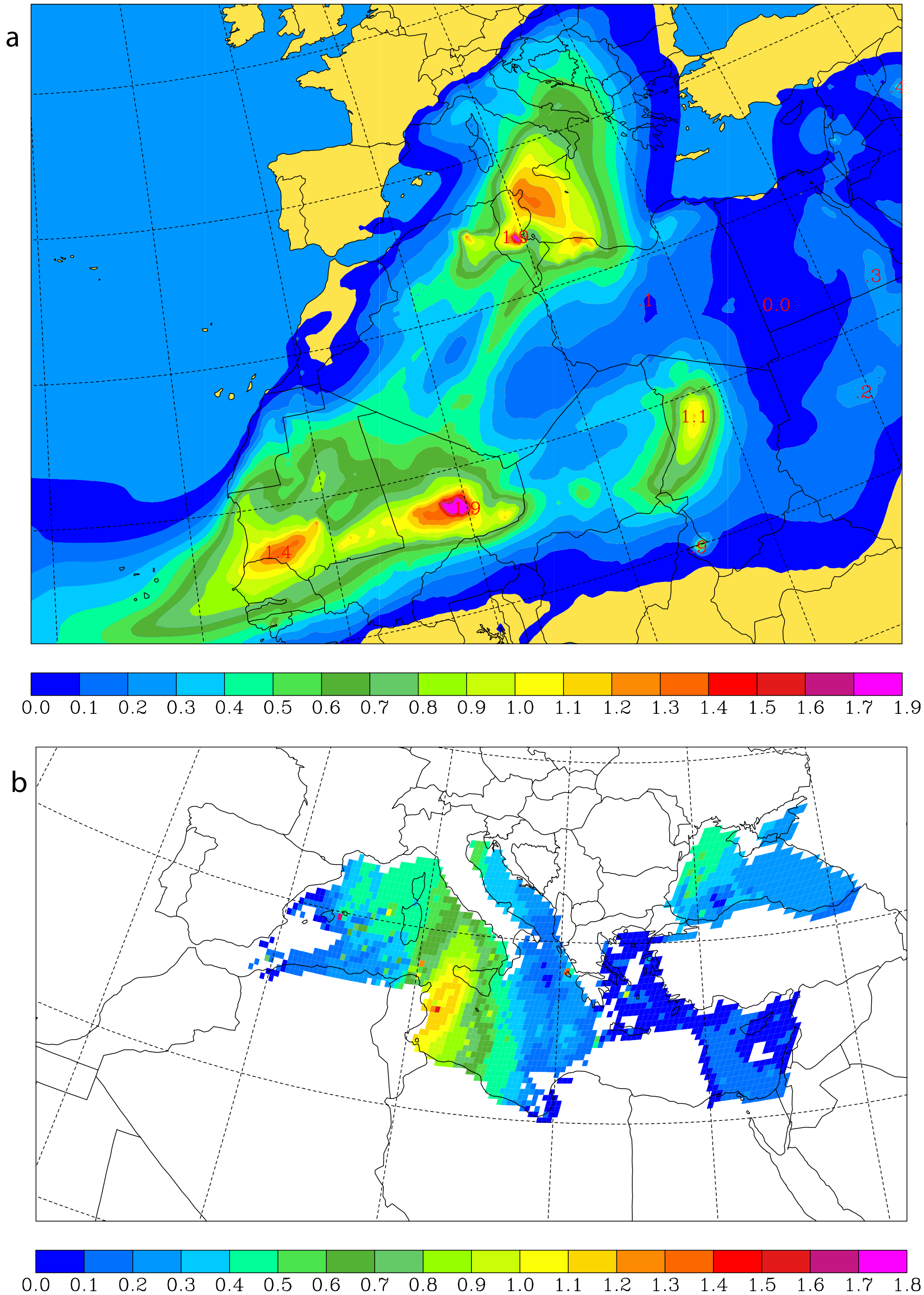

Figure 4. Vertically integrated dust load (in g m^{-2}), daily averaged over the Mediterranean Sea valid for 23 June 1993 as estimated by (a) model simulation, and (b) METEOSAT image (courtesy of Laboratoire des Sciences du Climat et de l'Environnement).

thickness following the method suggested by *Moulin et al.* [1997].

[17] After reaching the Atlantic region, the dust plume was transported further westward by a stable anticyclonic flow within slowly descending low-level stable air. The particle size analysis indicates that the dust plume, as it was moving westward, mainly consisted of particles with a diameter centered to 1.5 μm and in much smaller quantities with a diameter centered to 12 μm (Figures 5a and 5b). Model analysis also indicates that particles of diameter larger than 12 μm were not able to reach Atlantic (not shown). The first signals of the dust episode in the United States were recorded by the IMPROVE network on 23 June 1993 in the Florida region. On this day, the daily dust concentration of $PM_{2.5}$ at the Virgin Inlands National Park, in the Caribbean, exceeded 13 μg m^{-3}. Figure 5c indicates that the corresponding model-estimated daily dust concentrations match well with the available observations.

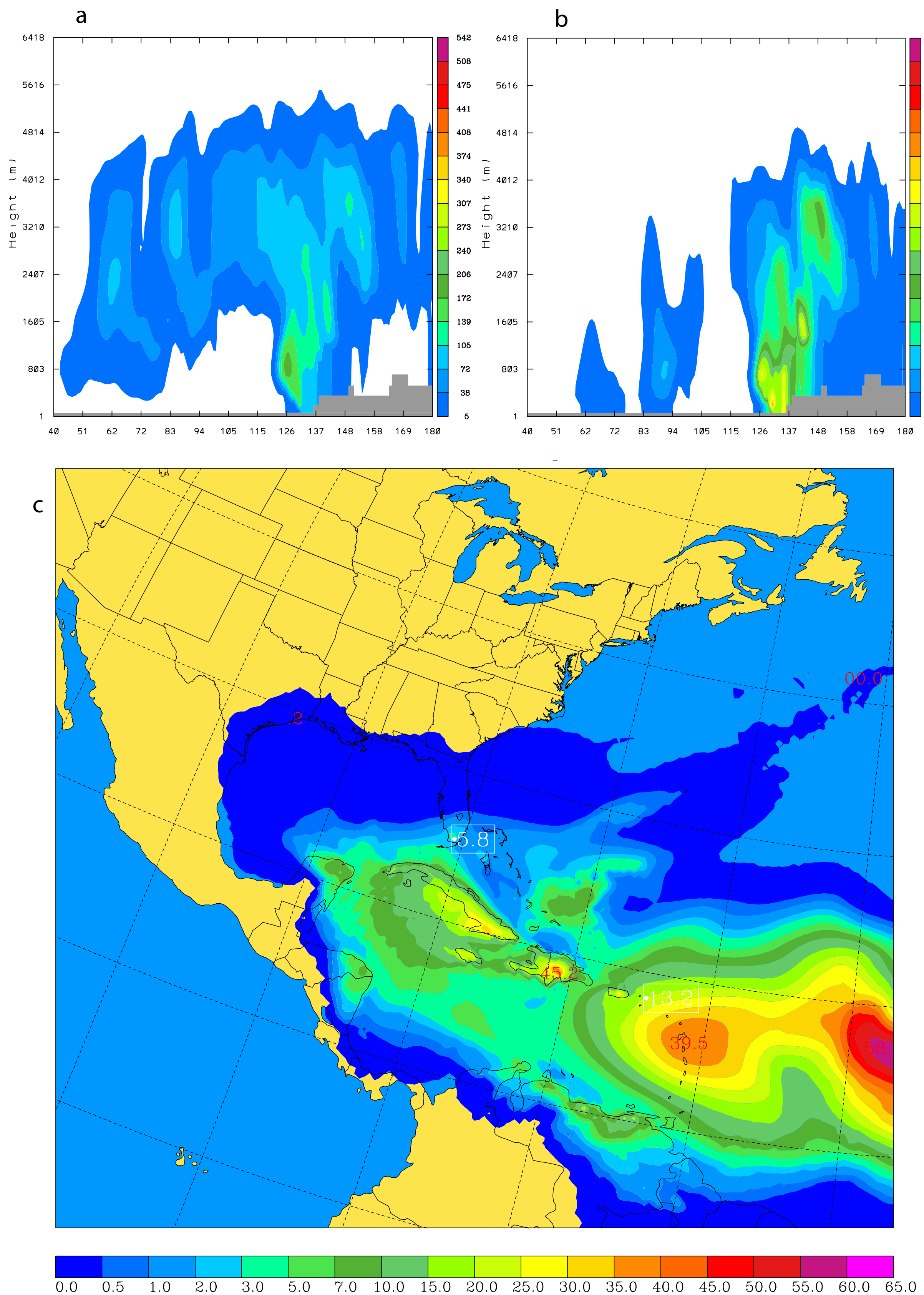

Figure 5. Model vertical distribution of concentration (in $\mu g\ m^{-3}$) of dust particles with centered diameter of (a) 1.5 μm and (b) 12 μm at 12 UTC on 23 June 1993 mapped at the cross-section denoted by the black line in Figure 1, and (c) daily averaged surface dust concentration (in $\mu g\ m^{-3}$) model-estimated (colored fields) and measured at IMPROVE observation stations (white values in borders) for 23 June 1993.

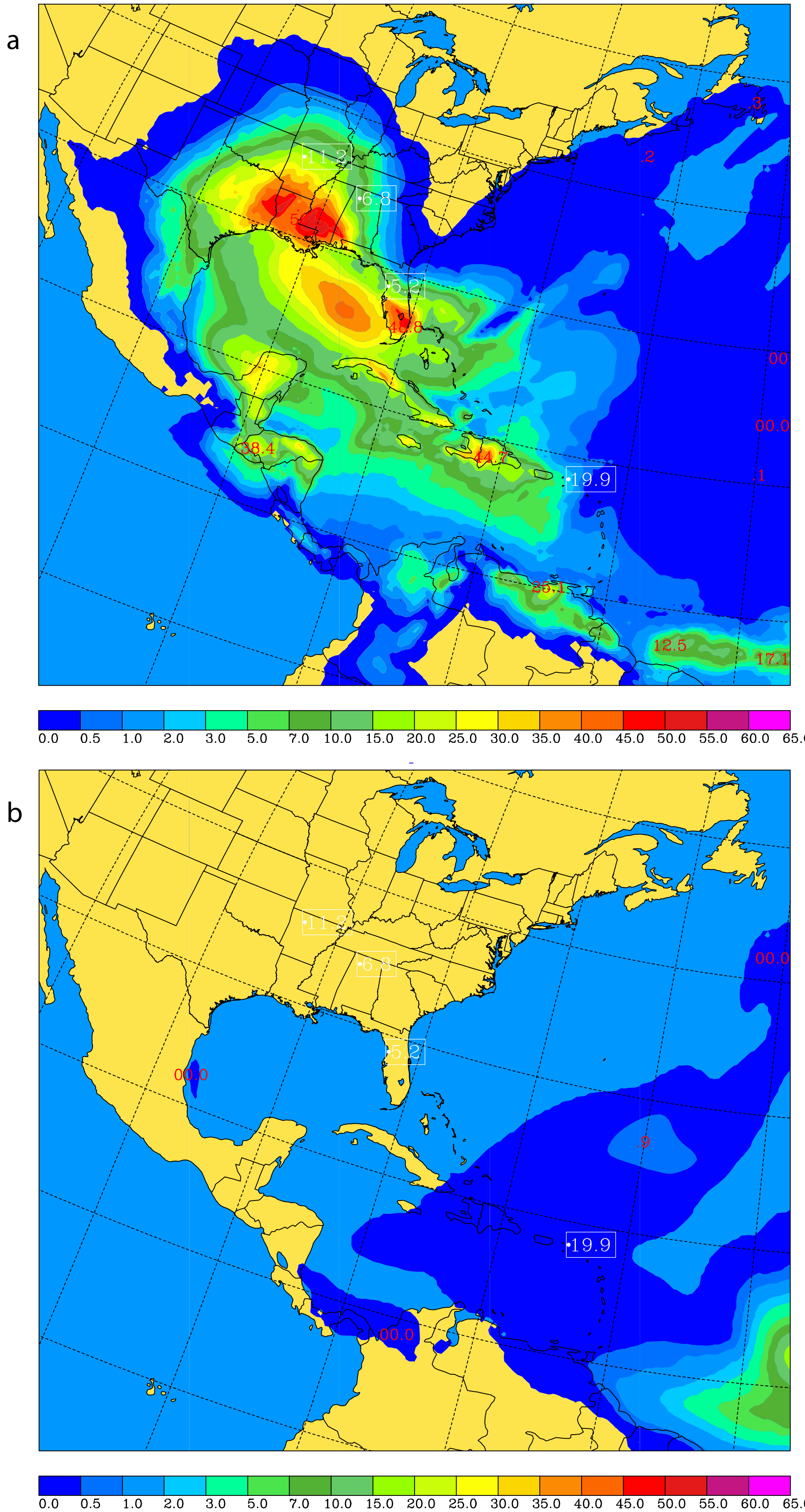

Figure 6. Daily averaged surface dust concentration (in $\mu g\ m^{-3}$) model-estimated (colored fields) and measured at IMPROVE observation stations (white values in borders) for 30 June 1993 of dust particles with centered diameter of (a) 1.5 μm and (b) 12 μm.

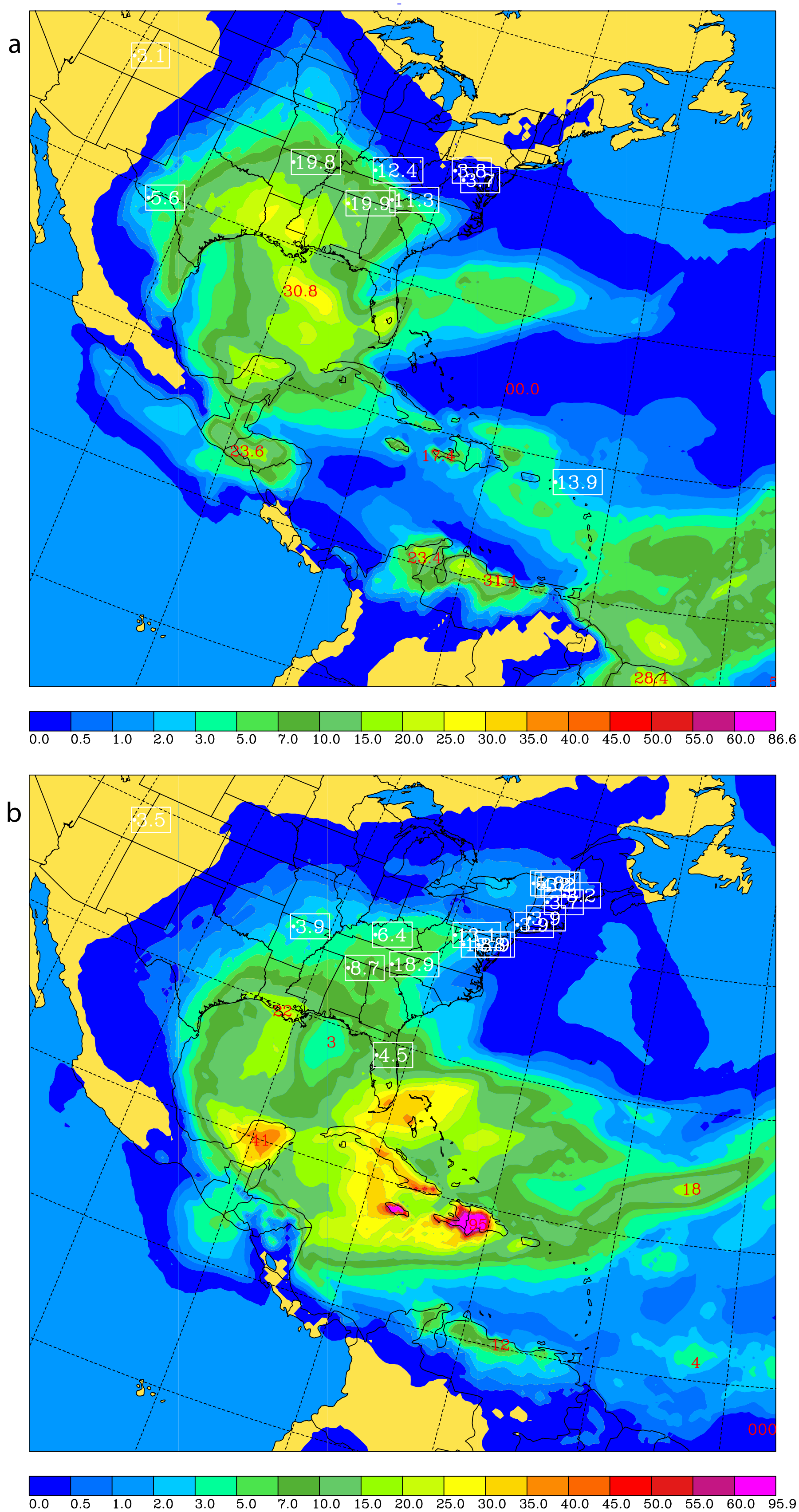

Figure 7. Daily averaged surface dust concentration (in μg m^{-3}) model-estimated (colored fields) and measured at IMPROVE observation stations (white values in borders) of dust particles with centered diameter of 1.5 μm for (a) 3 July and (b) 7 July 1993.

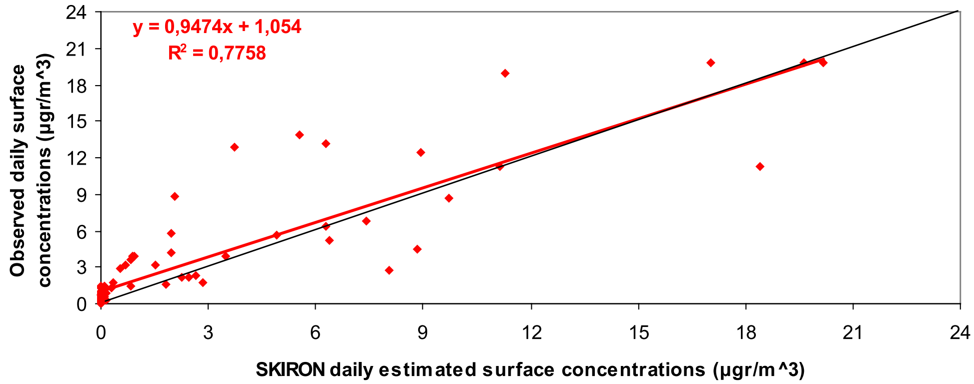

Figure 8. Correlation between observed and simulated daily averaged dust surface concentrations for the period 30 June to 7 July 1993.

[18] Further model analysis indicates that $PM_{2.5}$ particles reached the American coasts penetrating the central United States while the particles with larger diameters were not able to reach the Caribbean in appreciable quantity. In Figures 6a and 6b we have mapped the daily model estimated concentrations of the dust particles with centered diameters 1.5 and 12 μm for 30 June, respectively. The observed concentrations of $PM_{2.5}$ (white numbers in boxes) are plotted together with the simulated fields, highlighting the competent performance of the model.

[19] In the following days, the dust moved towards the continental United States with a maximum concentration of 20 μg m^{-3} at the southern and central parts of the United States on 3 July 1993 (Figure 7a). On 7 July, observations indicate that the dust plume had extended and covered the entire United States east of the Rocky Mountains (Figure 7b). During these last days of the 30-day simulation, the model does not exhibit the same accuracy in reproducing quantitatively the entire transcontinental dust transport. Dust concentrations recorded in western and southwestern parts of the United States were found to be higher than normal. This might imply that either Saharan dust plume progressed western than the areas indicated in model simulation or were locally produced. If the first hypothesis is true, the model failed to reproduce this feature. It is worth noticing that in the model setup no dust sources for the United States were considered. Despite this fact, the general characteristics of the dust plume support the argument that the model reproduced the basic patterns of the observed concentrations quite satisfactorily. In general the simulated quantities are in good agreement with the analysis discussed in *Perry et al.* [1997]. The level of agreement between the model estimations and observations is illustrated in Figure 8. As is shown, the correlation between observed and estimated values is at a good level (R^2 = 0.78), with slight model underestimation in smaller concentrations. It is noteworthy that this level of agreement has been achieved after several days of simulation (30-day simulation period). Since the regression illustrated in Figure 8 contains a number of very small concentrations that is considered as in favor of producing too good correlation, we repeated it by excluding concentrations lower than 0.1 μgr/m^3. In this case, the correlation coefficient was slightly smaller (R^2 = 0.70) as expected but the overall model performance remains high.

5. Concluding Remarks

[20] As previously documented by observational evidence, transatlantic transport of the Saharan dust can occur under certain meteorological conditions. The model simulations performed in the context of this work focused on studying the combination of the meteorological conditions that initiate desert dust mobilization and conditions that foster long-range transatlantic dust transport. In assessing the success of the performed dust transport simulation, it should considered that the specific study represents a quite complex test of the entire system (atmospheric and dust module components) due to the model integration for an extended period (30-days of continuous simulation) and over a large geographical area. According the qualitatively and quantitatively evaluation, the system has demonstrated its ability to reproduce the major features of the specific dust event since the deviations of the predicted values from the relevant observed data could be considered as acceptable. Nevertheless, this study provides insight into the features of the atmospheric dust cycle, especially for components for which there is not enough measurement evidence. The entire modelling system has some unique capabilities to capture the complex processes involved in the cycle of dust production-transport-deposition that makes it a useful tool for analysis and better understanding of the phenomenon as well as in real time applications. However, more frequent and denser remote-sensing and ground-based observations of dust parameters are considered as absolutely necessary in the future, in order to better validate the dust models, further improve and tune them.

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