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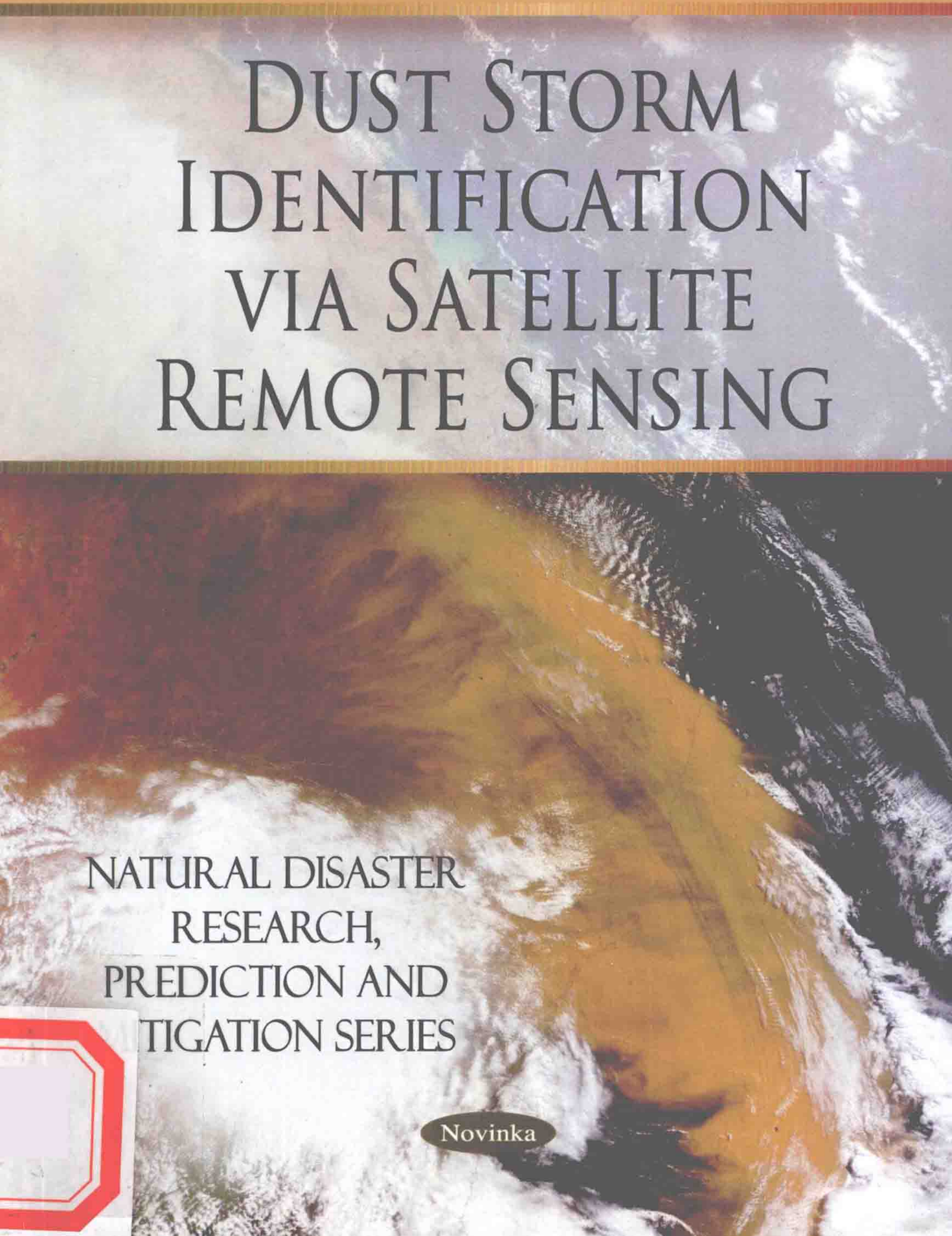
K. V. S. Badarinath · Shailesh Kumar Kharol

DUST STORM IDENTIFICATION VIA SATELLITE REMOTE SENSING



NATURAL DISASTER RESEARCH, PREDICTION AND MITIGATION SERIES

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NATURAL DISAS CTION AND
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DUST STORM IDENTIFICATION VIA SATELLITE REMOTE SENSING

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D.G. KASKAOUTIS
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PREFACE

Dust storms are considered natural hazards, which affect ecosystems for a short-time interval ranging from a few hours to a few days. Due to the significant impact of dust outbreaks on climate, human health and ecosystems, numerous studies have been conducted throughout the world with differing instrumentation and techniques focusing on the investigation about such events. The identification of the dust aerosol sources is a difficult process due to the complex natural and anthropogenic processes, which are involved in entraining soil particles into the atmosphere during a dust transport. Monitoring of these particles is only possible from satellites because ground-based measurements are very limited in space and time. Focusing mainly on the Sahara desert, this chapter provides a short review on the recent knowledge about the dust aerosol optical and physico-chemical properties, the seasonal variability of dust outbreaks, the dust source regions, the main pathways towards Southern Europe, which is mostly influenced, and the main results of similar studies. Furthermore, this chapter is looking forward to providing a new methodology to the scientific community for the dust transport monitoring using a combination of satellite data and back-trajectory analysis for the identification of coarse-mode aerosols, Sahara dust (SD) events and the analysis of the dust-transport mechanisms. The analysis covers a 6-year (2000-2005) period of daily aerosol optical depth at 550 nm (AOD_{550}) and fine-mode (FM) fraction values, derived from Terra-MODIS observations. Based on the AOD_{550}-FM relation, the cases satisfying the criterion $AOD_{550}>0.3$ and $FM<0.6$ refer to coarse-mode aerosols, probably dust particles. A focus is made on the Athens area. Back-trajectories ending at Athens at altitudes of 500, 1000 and 4000 m have been calculated by means of the HYSPLIT model. The majority of the SD events occur in April-May and July, while very few in November-December. The average number of the SD events per year is about 13, with a maximum of 20 in

2002 and a minimum of 7 in 2003. The Aerosol Index (AI) derived from TOMS was found to adequately characterize the dust load over Athens despite the fact that 35% of the dust cases conforming with the back-trajectory analysis do not correspond to high (above 0.5) AI values. As a conclusion, this chapter shows that the combination of remote-sensing measurements and back-trajectory analysis constitutes a powerful tool for the identification of SD events over Athens, and to a certain extend at other locations around the Mediterranean region, since the results are found to be in agreement with those of relevant studies.

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Chapter 1

INTRODUCTION

According to the Earth Observatory website http://earthobservatory.nasa.gov/ dust storms are considered natural hazards, which affect ecosystems for a short-time interval ranging from a few hours to a few days. Due to the significant impact of dust outbreaks on climate, human health and ecosystems, numerous studies have been conducted worldwide with differing instrumentation and techniques focusing on the investigation about such events. To this respect, in the last two decades, the research about the dust coming from north Africa has increased 3 times, i.e., from an average of 21 peer-reviewed papers per year between 1995 and 1997 to 61 between 2003 and 2005. These studies shed light into the dust source regions, the variability of dust emissions, the dust transport, the role of human impact and rainfall on dust emission, and the recent developments of global and regional dust models (Engelstaedter et al., 2006). In order to improve the scientific knowledge about dust aerosols, their source regions and their effect on global climate, a worldwide effort has been undertaken in the last two decades to produce a global aerosol climatology by combining satellite observations (e.g. TOMS, MODIS) and measurements from ground-based monitoring networks (e.g. AERONET, EARLINET). The TOMS sensor is able to map the global distribution of the major dust source regions with the goal of identifying common environmental characteristics. Another satellite product for the detection of dust distributions is the Infrared Difference Dust Index (IDDI), which uses reductions in atmospheric brightness temperatures derived from Meteosat IR-channel measurements (Legrand et al., 2001). Large quantities of mineral dust are carried over the oceans from arid regions around the world. Several aerosol studies have documented the temporal and spatial variability of dust transport over the oceans (Duce, 1995; Prospero et al., 1996a, b). Satellite imagery clearly shows that dust aerosols often cover very large ocean areas. Indeed, the aerosol load associated with dust transport is higher than that attributed to pollution plumes; furthermore the dust plumes cover much larger area, are more persistent, and occur more frequently that those associated with pollutant aerosols (Husar et al., 1997).

While progress has been made in characterizing the importance of mineral dust in global-scale processes, there has been less progress in identifying the sources of dust, the environmental processes that affect dust generation in the source regions and the meteorological factors that affect the dust transport. This can be achieved by the development of the regional and synoptic weather forecast models, also able to predict the emission, the amount, the transport as well as the deposition of the dust (Kallos et al., 2006, 2007). The identification of major dust sources will enable us to focus on critical regions and to characterize emission rates in response to environmental conditions. With such knowledge we will be better able to improve global dust models and to assess the effects of climate change on emissions in the future. While some satellite sensors have been useful in characterizing dust transport over the oceans (Husar et al., 1997; Antoine and Nobileau, 2006), they cannot be readily used to identify sources because of difficulties associated with the large spatial and temporal variability of the arid surface albedo. Some techniques based on measurements of upwelling thermal emissions (Ackerman, 1977), while useful, suffer from various difficulties including the effects of cloud and water vapor, so that it is difficult to detect coherent spatial patterns over dust source regions. The dust optical and physical properties (e.g. aerosol optical depth (AOD), Angstrom exponent, size distribution, single scattering albedo (SSA), asymetry parameter, refractive index, particle shape) are now well documented via both gound-based and satellite instruments. To this respect, except of the experimental campaigns, the standardized newtworks (e.g. AERONET, EARLINET) have helped in continuing monitoring and analysis of the dust optical properties. The NASA website (http://www.visibleearth.nasa.gov/Atmosphere/Aerosols/), has an achieve of images of spectacular aerosol events, most devoted to dust events. Also, the NASA website (http://earthobservatory.nasa.gov/NaturalHazards/) provides several images on the more intense dust events, which are referred as natural hazards along with floods, forest fires, cyclones, droughts, volcanoes, earthquakes. These figures can help the public and the scientists in developing their knowledge about the dust source regions, the dust transport and deposition and its optical properties.

Chapter 2

MAJOR DUST SOURCE REGIONS

The largest and most persistent dust sources are located in the northern Hemisphere, mainly in a broad "dust belt" that extents from the west coast of North Africa, over the Middle East, central and south Asia, to China. On the other hand, the southern hemisphere is devoid of major dust activity, except of some areas in South America (Atakama) and the Australian desert, north of lake Eyre. Dust sources, regardless of size or strength, can usually be associated with topographic lows; they are situated in close proximity to mountains and highlands with annual rainfall less than 200-250 mm. The largest and most active dust sources are located in remote areas where there is little or no human activity. Dust activity is extremely sensitive to many environmental parameters, such as topography, rainfall, surface winds, regional meteorology, boundary layer height, convective activity, etc. In general, dust mobilization is extremely sensitive to a wide range of factors, including the composition of the soils, their moisture content, the condition of the surface and wind velocity.

There have been many efforts in the past to identify dust sources in North Africa using various types of field and meteorological observations. These have resulted in a confused and conflicted picture which suggests that essentially all of North Africa could serve as a source (Middleton and Goudie, 2001), which in the broadest sense, is probably true. However, TOMS shows that there are dominant sources and that these present a remarkably consistent pattern both from the standpoint of the geometry of the individual sources and the seasonal changes in their shape and distribution. Furthermore, many of the intense sources are associated with regions where there are extensive alluvial deposits.

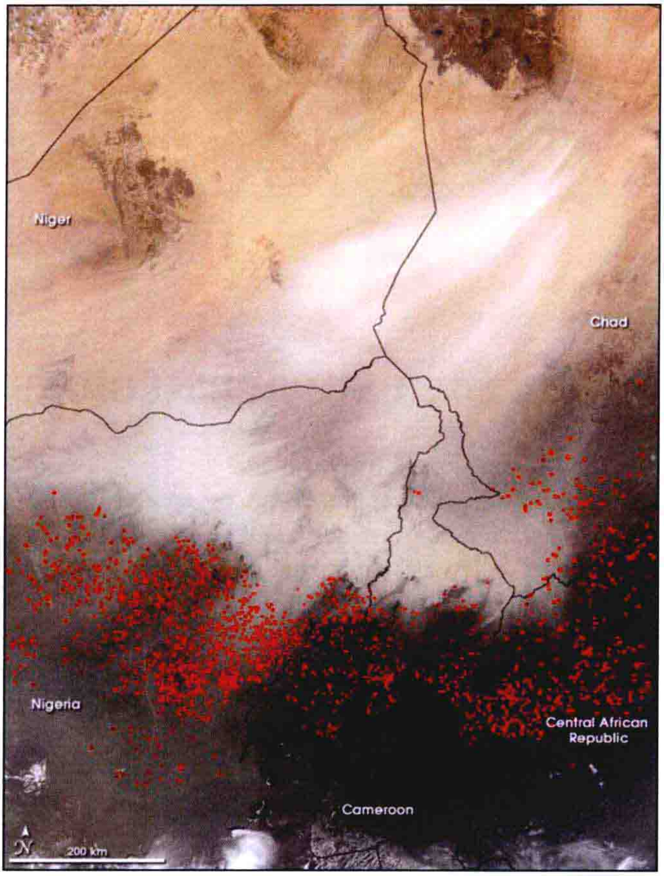

Figure 1. A dust storm in central Africa (Chad) that began in late December 2004 intensified in the first week of January 2005. The image was taken from MODIS on NASA's Terra satellite, captured on 6 January 2005. The red dots show the locations where MODIS detected active fires.

The Chad basin and the Bodélé depression is undoubtedly the most intense dust source in the world (Fig. 1). Large areas of the basin are filled with dust all year long. This is in agreement with visibility data from meteorological stations in the region (Mbourou et al., 1997), which show a high frequency of visibility reduction during all seasons except fall, when the rate decreases. The mean TOMS aerosol Index (AI) values are the highest of any region in terms of both the monthly and annual means. Adetunji et al. (1979) first identified this region as the likely source of Harmattan dust haze. Goudie (1983) identifies the region as an important dust source that is transported south during the winter Harmattan. In

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satellite imagery dust from this source is repeatedly visible during much of the year. Moreover, one can often see that the overall plume, which is typically hundreds of kilometers long, is comprised of many individual plumes that originate from sharply defined sources.

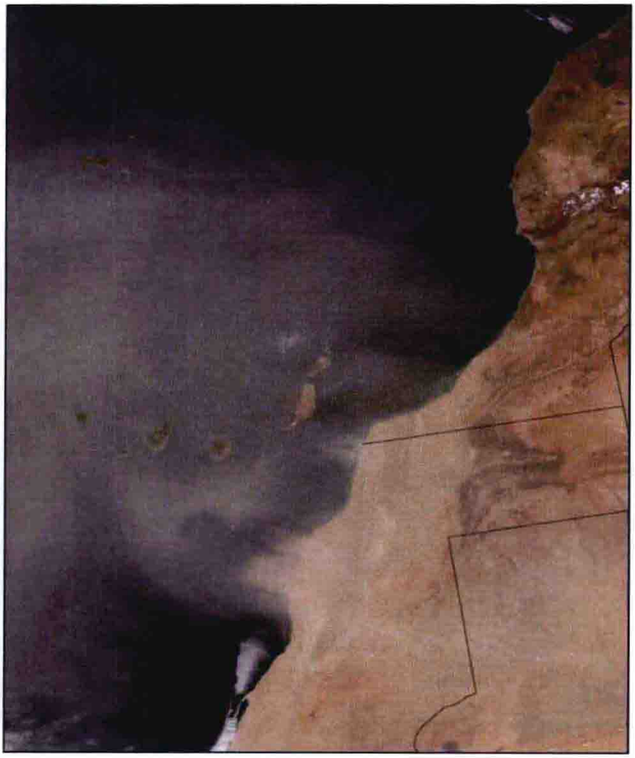

Figure 2. A thick plume of sand and dust (brownish pixels) blew out from the western Sahara over the Atlantic Ocean on 22 April 2002, engulfing the Canary Islands in the eastern Atlantic Ocean. This image was acquired by the MODIS flying aboard NASA's Terra satellite.

There is a complex distribution of the dust sources in areas in western North Africa (Mali, Mauritania and southern Algeria). These sources are active all year long, but in the summer they are completely obscured by blowing dust. There is a persistent active dust region located to the south of the northern Atlas Mountains in Tunisia and eastern Algeria. The greatest dust activity takes place near an extensive system of salt lakes and dry lakes found in the lowlands south of Atlas Mountains. The most intense dust activity starts in April-May and extends to

August-September. The dust emitted from these regions is mainly transported over the north and tropical Atlantic (Fig. 2) but in several cases it is transported over Mediterranean. A large area of dust activity extends over the eastern Libya desert into western Egypt. These sources are active during much of the year; the dust activity is most intense in May-June. The northern part of this feature lies over a low-lying region that is marked with a number of drainage features, which receive flow from the somewhat elevated coastal region to the north. The dust activity in the area of western Sudan and the flanks of the Ethiopian highlands peaks in the period May-July, while there is little activity during the remainder of the year.

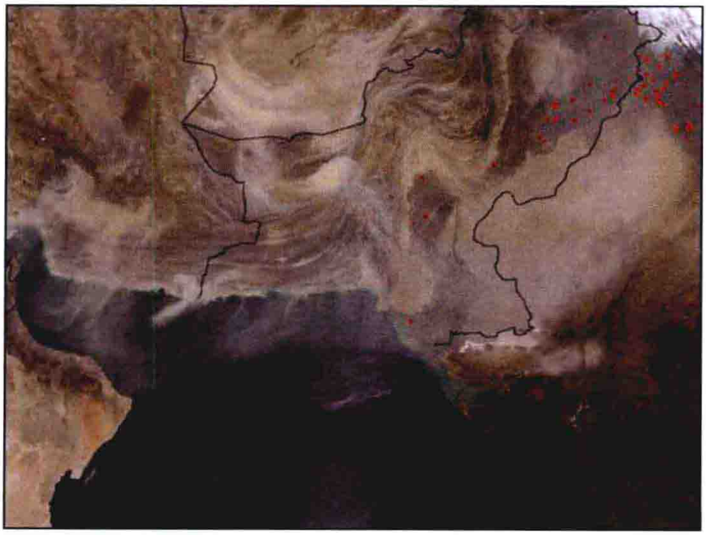

Figure 3. A number of jets of windblown desert dust (light brown plumes) were blowing over the Gulf of Oman and the Arabian Sea on May 2, 2003. Originating from the Arabian Peninsula as well as Iran, Afghanistan, and Pakistan, the dust obscures the surface over much of the region. This image was made using data from the MODIS sensors flying aboard NASA's Terra and Aqua satellites at hours apart on the same day.

Other active source regions are areas in the Arabian Peninsula along the Persian Gulf and on the Arabian Sea (Fig. 3) and the large area in central Asia (Taklimakan and Gobbi deserts) most active in March, May and July (Fig. 4). The accumulation of recent and ancient sediments in playas, often with salt, which enhances the weathering of sediments, makes them good sources of fine-grained mineral particles (Middleton et al., 1986). A detailed description about the major dust source regions can be found in the works by Prospero et al. (2002) and Engelstaedter et al. (2006).

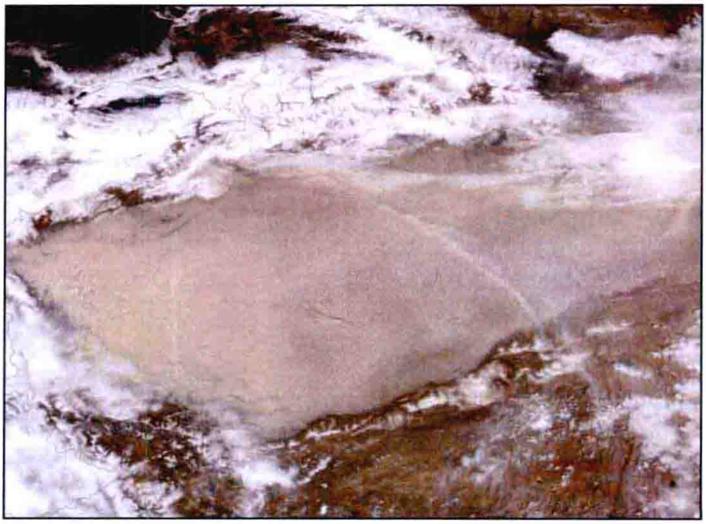

Figure 4. A large-scale dust storm blanketed the eastern Taklimakan Desert on 10 March 2004, draping the normally orange-colored sands with a swath of tan-colored dust. The Taklimakan is a great bowl of land ringed by rugged mountains to the north and south. The image was taken on 10 March 2004 by the MODIS aboard NASA's Aqua satellite.

Chapter 3

DUST CHARACTERISTICS AND EFFECTS

3.1. SAHARAN DUST EMISSIONS

Deserts are the main sources of aerosols injected into the atmosphere, with the mineral dust comprising more than 35% of the primarily emitted aerosol mass (IPCC, 2001). Half of this amount is attributed to the Saharan desert rendering it as the most important dust source in the world. Transport of dust plumes to the North Atlantic and the Mediterranean Sea occur throughout the year (Moulin et al., 1997). While most (about 60%) of the Saharan dust is transported westward, a significant amount reaches Europe. The dust vertical distribution is different for the two dust streams, since dust travels at an altitude of less than 5 km over the Atlantic (Karyampudi et al., 1999), while it often reaches 8 km over the Mediterranean (Gobbi et al., 2000; di Sarra et al., 2001; Alpert et al., 2004). Estimates of the dust emissions from Sahara range from 130 to 760 Tg yr^{-1} (Goudie and Middleton, 2001), while another study (Ozer, 2001) estimated the annual Saharan dust emissions to be about 1600 Tg yr^{-1}. For comparison purposes the global dust emissions range from 1000 to 3000 Tg yr^{-1} (Zender et al., 2004). On a regular yearly basis, about 80-120 Tg of dust are transported to the Mediterranean (d' Almeida, 1986). Barnaba and Gobbi (2004) found a total seasonal mean value of 119 ktons of desert dust per day to be injected into the Mediterranean atmosphere, corresponding to a total of 4.3×10^4 ktons of dust in 2001. Numerous estimates of mean annual dust emissions for Sahara and world are addressed in the review studies of Goudie and Midletton (2001) and Engelstaedter et al. (2006). The Saharan dust aerosols strongly affect the Mediterranean Sea and coastal Europe, since they can travel over long distances from their source region with a residence time varying from a few days to a few weeks (Pandis et al., 1995). In addition, the aerosol composition and concentration are highly variable depending on the removal mechanisms with the larger density and particle size to occur near the source. Dust can also come from anthropogenic activities although its contribution to climate is still poorly quantified (Haywood and Boucher, 2000). Zender et al. (2004) identify two ways in which human activities can influence dust emissions, (a) by changes in land use, which modify the potential for dust emission and, b) by perturbing local climate that, in turn, modifies dust emissions. Several studies using numerical dust models (Tegen and Fung, 1995; Sokolik and Toon, 1996; Tegen et al., 2004; Yoshioka et al., 2005) resulted in large uncertainties regarding the anthropogenic contribution to the global dust loads; this contribution was found to range from 0% to 50%. Due to increase in population, demand for food and deforestation, dust emissions have been increasing significantly during the drought periods of the last decades, as can be conducted by both satellite and surface observations (Goudie and Midletton, 1992; Ozer, 2001). However, deciding whether the natural processes or the human interventions be responsible for the dust-emission increase is not an easy task (Goudie and Midletton, 2001). The annual dust emissions may be partly explained by changes in the regional meteorology affecting the position of the Intertropical Convergence Zone (ITCZ) and further the rainfall distribution. Several studies cited in Engelstaedter et al. (2006) conclude that Saharan dust emissions are identified in regions where the annual rainfall amount is below 200 mm. Rainfall reduces the atmospheric dust amount by increasing the soil moisture and vegetation cover over the arid regions and by cleansing the atmosphere by removing dust (wet deposition). Several studies (Bertrand et al., 1979; Brooks and Legrand, 2000; Prospero and Lamb, 2003; Moulin and Chiapello, 2004; Chiapello et al., 2005) found a close relationship between dust load over North Africa and precipitation amount from previous years. Thus, the increase in the dust activity was observed after the years with intense drought. Other factors, such as changes in soil moisture or in the annual cycle of surface wind, may also play a significant role in the annual dust emissions, although the role of wind is still poorly quantified.

3.2. Dust Effects on Solar Radiation and Climate

Desert aerosols are probably the most abundant type of aerosol particles that are present in the atmosphere worldwide. Dust, which is the common aerosol type over the deserts (Smirnov et al., 2002a, Masmoudi et al., 2003) emitted from arid and semiarid areas, is considered to be one of the major sources of tropospheric aerosol loading, and constitutes an important key parameter in climate aerosol

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