CHAPTER 1

INTRODUCTION

1.1 Atmospheric aerosols

Atmospheric aerosols are suspensions of solid and/or liquid particles in the air from natural and anthropogenic sources. Natural background aerosols are present in the absence of human activity, while urban aerosols are dominated by anthropogenic sources. In both cases, the primary particles are continuously emitted into the atmosphere, while the secondary ones are formed via oxidation, photolysis and mixing processes. Aerosols are ubiquitous in the air and are often observable as dust, smoke and haze (Fig 1). On a global basis, aerosol mass derives predominantly from natural sources, mainly dust and sea salt. However, anthropogenic aerosols, arising primarily from a variety of combustion sources, can dominate in, and downwind of, highly populated and industrialized regions and over areas of intense biomass burning. Atmospheric aerosols might affect the global climatic system in many ways, i.e. by attenuating the solar radiation reaching the ground, by modifying the solar spectrum, by re-distributing the earth-atmosphere energy budget and by influencing cloud microphysics and even the hydrological cycle (IPCC, 2007). Although the optical properties of aerosols are well known, large uncertainties still occur about aerosol-climate interaction due to the variety of aerosol types, their changing optical and physico-chemical properties, the influence of dynamic and synoptic scale meteorology and the mixing (internal and external) processes in the atmosphere.

Table 1.1 summarizes the source strengths, production mechanism and amounts of natural and anthropogenic aerosols over the globe. Anthropogenic aerosols are emitted from densely populated and industrialized regions over the globe due to anthropogenic activities and having the greatest climate effect. These are short-lived and mostly fine particles (size $<1\mu m$). The main chemical components of anthropogenic aerosols are sulfate, nitrate, organic and inorganic carbonaceous compounds produced by several physical and chemical processes such as gas-to-particle conversion, biomass burning and fossil fuel burning. A substantial fraction of the organic aerosols is water soluble and constitute the efficient Cloud Condensation Nuclei (CCN) which is the important sink for organic aerosols. The marine aerosols are composed of both natural and anthropogenic constituents such as liquid sea water drops, dry sea-salt particles, dust and minerals transported from continental origin and from volcanoes, biological particles (bacteria, viruses), sulfate, nitrates, ship exhaust emissions, soot. The marine aerosols can be generated by several processes such as gas-to-particle conversion, nucleation, condensation and their size ranges from nanometers to millimeter. After emission in the atmosphere sea-salt particles can be internally and externally mixed with other aerosols. Sulfate particles are produced by the aqueous phase reaction within cloud droplets by oxidation of SO_2 via gaseous phase reaction with Oxide Hydroxides (OH) and by condensational growth onto pre-existing particles (Penner *et al.*, 2001). The dominant source of sulfate particles is fossil fuel burning with some small contribution from biomass burning. However, sulfate aerosols are also produced by natural sources, such as DiMethyl Sulphide (DMS), marine phytoplankton and volcanoes.

Table 1.1: The sources, source strength, production mechanism, and particle components of the natural and anthropogenic aerosols [Source: d'Almeida *et al*., (1991) and Hobbs (1993)].

Source	Production mechanism	Aerosol component	Source strength (Tg.yr-1)
Anthropogenic			
Direct-emission	Direct-injection	Dust/soot/water-soluble	10-90
Biomass burning	Combustion	soot	3-150
Gas-to-particle conversion	Nucleation	Sulfate/nitrate/organics	175-325
Natural			
Extraterrestrial	Cosmic dust	Meteoric dust	10
Biosphere	Direct-injection	Pollen/spores	80
Volcanoes	Direct-injection	Water-soluble	15-90
Biomass burning	Combustion	Soot	200-450
Gas-to-particle conversion	Nucleation	Sulfate/nitrate/organics	345-1100
Ocean/fresh water	Bubble bursting	Sea-salt	1000-2000
Crust/cryosphere	Weathering	Soil dust	2000
Cloud processing	Cloud evaporation	Water-soluble	3000

Finally, mineral dust is a mixture of carbonates, sulfates, organic material and soot particles constituting one of the largest sources of tropospheric aerosols with emissions of 2150 $Tg.yr^{-1}$, about 37% of the total production of primary atmospheric aerosols by both natural and anthropogenic sources (Penner *et al*., 2001). Mineral-dust aerosols are produced mainly by wind erosion of desert soils, lifted to high altitudes by convection and can be transported over long distances from their source regions and mixed with continental aerosols such as sulfate, nitrate, soot, playing an important role in the heterogeneous chemical reactions (Ginoux *et al*., 2001). Furthermore, Fig. 1.1 provides a schematic presentation of the major aerosol types, their sources as well as climate implications through the attenuating of solar radiation and their influence on microphysical properties of clouds.

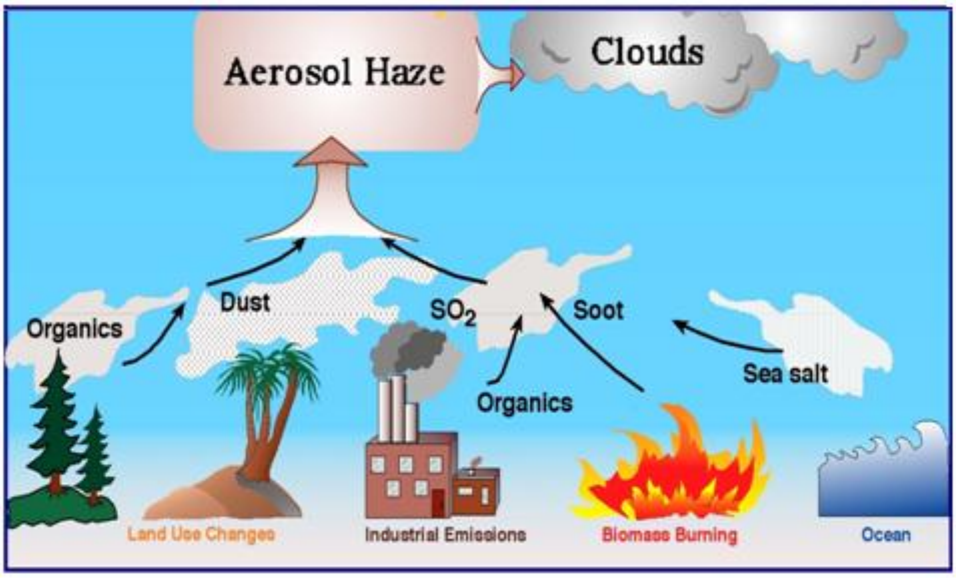


Figure 1.1: Various aerosol particle sources and their formation and removal mechanisms and distribution on the Earth's surface [source: D.G. Kaskaoutis PhD thesis, University of Ioannina, Greece 2008, reproduction with permission].

1.2 Definition of dust events

Dust events, according to the World Meteorological Organization (WMO), are defined by McTainsh and Pitblado (1987) as follows:

(1) *Dust storms* are the result of turbulent winds raising large quantities of dust into the air and reducing visibility to less than 1000 m above the surface.

(2) *Blowing dust* is raised by winds to moderate heights above the ground reducing visibility at eye level (1.8 m) but not to less than 1000 m above the surface.

(3) *Dust haze* is produced by dust particles in suspended transport which have been raised from the ground by a dust storm prior to the time of observation.

(4) *Dust whirls (or dust devils)* are whirling columns of dust moving with the wind and are usually less than 30 m high (but may extend to 300 m or more above the surface) and of narrow dimensions.

There is some confusion in the literature between ‘sand storms’ and ‘dust storms’. Sand storms tend to be low altitude phenomena of limited areal extent, composed of predominantly sand-sized materials. On the other hand, dust storms reach higher altitudes, travel longer distances and are mainly composed of silt and clay. In this thesis, the term dust storm refers to an atmospheric phenomenon in meteorology, where the horizontal visibility at eye level is reduced to less than 1000 m by atmospheric mineral dust. While aerosol in the Earth’s atmosphere may be derived from a number of different sources – including cosmic dust, sea salt, volcanic dust and smoke particles from fires – in this thesis I concentrate on the dust emitted from the Sistan desert that originates in Iran from surfaces at low latitudes (25º to 35º North Hemisphere).

1.3 Origin of Dust aerosols

Currently there are limited grain-size data available for dust particles. Bagnold (1941) defines such particles as having diameters of less than 0.08 mm (80 µm), but many others prefer to define them according to the silt/sand boundary (i.e. less than 62.5 µm). Below this cut-off, fine particles are commonly categorized into those of silt and clay sizes, with grain diameters of 4.0 to 62.5 µm and <4.0 µm, respectively (Wentworth, 1922). Whereas inorganic clay-size particles are generally agreed to be derived largely from chemical weathering, the processes responsible for silt formation in the desert environment remain a matter for debate. As Pye (1987) pointed out, many mechanisms of silt formation have been formulated but no clear picture regarding their relative importance has yet emerged. One major hypothesis is that silt can be formed by glacial grinding. This is an attractive theory to explain the great expanses of loess that occur on the margins of the former great Pleistocene ice caps (Smalley, 1966; Smalley and Vita-Finzi, 1968). Abrasion (sometimes called corrasion) during fluvial and aeolian transport may also produce silt. For example, numerous laboratory experiments have shown that abrasion of dune sand releases fines by spalling, chipping and breakage of particles and by the removal of grain surface coatings (Bullard et al., 2004; Bullard and White, 2005).

Moreover, many surfaces in both desert and Polar regions show clear evidence of wind abrasion at a variety of spatial scales. In the latter case, some of the abrasion is achieved by driven snow, though snow abrasion is less efficient than that by quartz grain impacts. The greater kinetic energy of windblown sand compared to water transported sand explains the greater abrasion achieved by wind transport (Kuenen, 1960). Furthermore, of potential importance to silt formation are various types of weathering, including frost action, salt attack, thermal fatigue weathering and chemical weathering (see, for example Goudie *et al*., 1979; Nahon and Trompette, 1982; Smith et al., 2002). For instance, deeply weathered granitoid rocks may contain a quite high silt percentage – up to 37.7% in eastern Australia (Wright, 2002). The role of salt weathering may also be important in producing what is often termed 'rock flour'. Goudie *et al.,* (1979) designed an experiment to test whether silt-sized debris could be produced by salt weathering of aeolian dune sand, and found that it could. Subsequently other successful experimental simulations of salt attack on sands and on rocks were undertaken by Pye and Sperling, (1983); Fahey, (1985); Smith *et al*., (1987) and Goudie and Viles, (1995). In addition, samples of salt-weathered rock collected in the field have shown that appreciable quantities of silt-sized material are produced (Goudie and Day, 1980; Mottershead and Pye, 1994). Although the relative importance of these mechanisms is difficult to assess, the important point to make is that silt can be produced in many ways, either singly, or more likely, in combination. Moreover, such mechanisms allow silt production in many types of environment, whether glacial, periglacial, arid or humid tropical (Wright, 2001a; Smith *et al*., 2002). In addition, complex pathways of silt production and transport may be involved (Wright, 2001b). As Smith *et al*., (2002) remark "Weathering mechanisms coupled with periods of sediment reworking and associated silt production by glacial, fluvial and aeolian systems may provide a feasible explanation for the provenance of a significant majority of total global quartz silt. In addition to releasing silt-size particles directly, weathering may release considerable quantities of partially flawed sand grains. These flaws may then be readily exploited during subsequent periods of transport within glacial, fluvial or aeolian systems".

Some dust may be derived from erosion of organic materials (such as diatomite), which were deposited in pluvial lakes that have now become desiccated. Diatomite is a very light substance that, if abraded, produces fine, easily carried debris. This has been proposed as a major dust source in the Bodélé Depression in the Central Sahara (Giles, 2005). Other dust may be provided by the winnowing of fines from reactivated sand dunes. Dunes that have long been stable, having been produced under earlier conditions of greater aridity in the late Pleistocene, contain silt and clay contents in reasonably substantial quantities. Such fines may be the result of penecontemporaneous deposition of clay aggregates within the dunes as they were formed, but also important are post-depositional weathering and accretion of dust. Data from Kordofan (Sudan), north-west India, Zimbabwe, Niger and north-west Australia suggest that silt and clay contents of stabilized dunes can range from 7.8% to 32.0% (Goudie *et al*., 1993).

Thus, if such dunes become mobile as a result of climate or land-cover changes, they can release silt and clay for dust storm generation. Given that there are so many mechanisms to produce silt-sized material (Smalley *et al*., 2005), It is not surprising that various geomorphological environments, in addition to old dunes, contain silt-sized material that is available for deflation. These include settings like outwash and alluvial fans, playa basins, weathered or unconsolidated rock exposures and areas of previously deposited loess (Fig. 2.2). Coudé-Gaussen (1984), whose work is largely based on the Sahara, has attempted to categorize desert surfaces that are highly favorable for producing dust:

– Dried-out salt lakes of internal drainage, the surface of which is disrupted and rendered mobile by salt crystallization

– Wadi sediments containing silt and the floodplains of great rivers, like the Niger

– Powdery areas (fech-fech) derived from ancient lake muds or on certain argillaceous rocks

– Desert clay soils (takyrs) with polygonal desiccation cracks

– Outcrops of materials like unconsolidated Neogene fine-grained sediments

Desiccation of lake beds, whether due to drought or to water diversion schemes, as in the Aral Sea in Turkmenistan, or the Hamoun lakes in Iran, can also lead to increased dust storm activity. Thus, some dust may be derived from dried lake beds and can be highly saline, while the finest aerosols can be injurious to health.

1.4 Physical properties of dust aerosols

1.4.1 Size distribution

Size distribution is a key parameter to characterize the aerosol chemical, physical and optical properties. The distributions of dust aerosol properties are shaped by several dynamical processes namely, advection, convection, turbulent mixing, humidification, condensation, cloud contamination, scavenging and long range transport. The power law distribution is valid for monodispersion, i.e. the value representing the concentration of aerosol particles decreases exponentially with the radius and shows narrow size distributions and lower geometric standard deviation values. However, nature does not support monodispersive distribution and, therefore, the aerosols in the atmosphere are polydispersive, i.e. wider size distributions and higher geometric standard deviation values due to wide sources that follow the lognormal distribution.

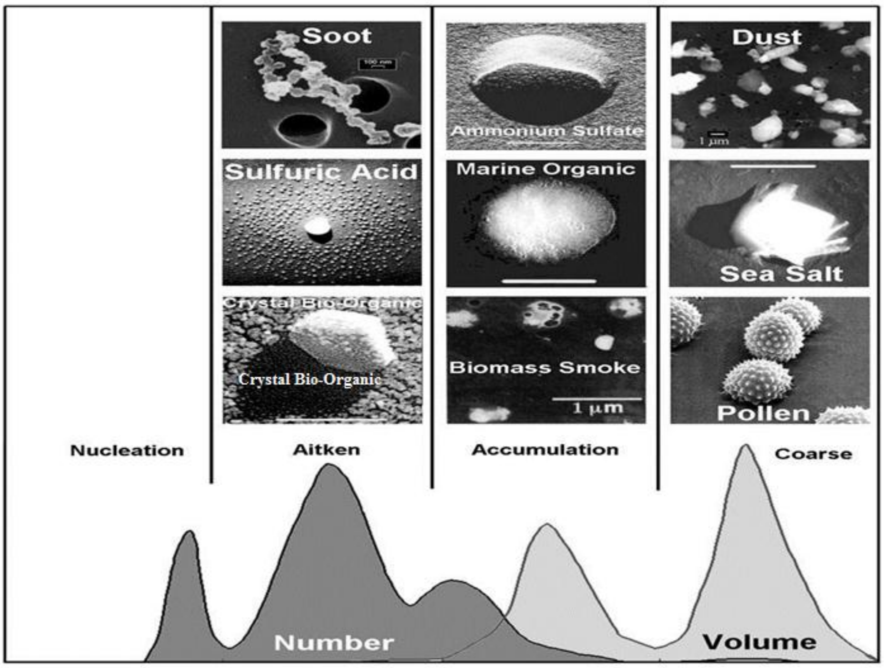


Figure 1.2: Morphology and size classification of aerosol and dust particles [S.N. Singh presentation at the COSPAR aerosol workshop 2011]

The lower and upper size limits of dust aerosols are from a few nanometers to ~100µm and aerosol properties change substantially over this size range. Depending on the size, dust aerosols can be classified into three categories i) Aitken nuclei mode (~0.001 to 0.1 µm), ii) accumulation mode (~0.1 to 1.0 µm) and iii), large mode/giant particle >

1.0 µm; or alternately, fine/sub-micron aerosols < 1 µm and coarse mode aerosols > 1 µm. The aerosol size distribution can be used as a proxy to infer the relative contribution of dust particles from different sources.

1.4.2 Refractive index

The refractive index is a key parameter which determines the scattering, absorption and size distribution of aerosols. The refractive index of hygroscopic aerosols changes with the additional amount of water that is absorbed in response to changing relative humidity. This alters the refractive index, including also the change in specific density, size and mass fraction.

1.5 Optical Properties of Dust

1.5.1 Aerosol Optical Depth (AOD):

Aerosol Optical Depth (AOD) is the degree to which aerosol particles prevent the transmission of light. It is defined as the integrated extinction coefficient over a vertical column of unit cross-section. It is an indirect measurement of the size and number concentrations of aerosol particles present in a given column of air. The spectral dependency of AOD contains information about the dominance of fine and coarse mode particles, the aerosol source regions, the modeling of aerosol radiative effects, the air quality (through monitoring of particulate matter) and the correction for aerosol effects in satellite remote sensing of the Earth's surface.

1.5.2 Extinction coefficient:

The attenuation of intensity (energy) of solar radiation by scattering and absorption of aerosol particles are ubiquitous phenomena in the atmosphere and take out the so called. The measurement of extinction coefficient related to extinction contains information about the particles' number concentrations and their size distribution.

1.5.3 Scattering coefficient:

The scattering coefficient is a significant optical property of aerosols that defines the distribution of scattering light around the particle. Scattering (excitation + re-radiation) is the process that a particle in the path of the electromagnetic wave (em) scatters the incident radiation in all directions around it. The distribution of scattering is a strong function of the size and shape of the particle and, therefore, the geometry of scattering is very different. The effect of particle size on scattering is inferred by a physical term called size parameter (i.e. number of wavelengths that is allowed to fit into a circle of given radius) defined as $x=2\pi r/\lambda$, where r is the particle radius and λ is the incident wavelength. The criteria for Rayleigh (molecular) and Mie (aerosol) scattering are $x < 1$ and $x\sim1$, respectively.

1.5.4 Absorption coefficient:

The absorption coefficient defines the capability of an aerosol particle to absorb and, then re-emit the energy, i.e. sun light and Thus absorption of light is the process by which sun light is absorbed by the particles, converted into another form of energy and, consequently, heats the atmosphere. The strong increase in atmospheric absorption of solar radiation could be due to the presence of large concentrations of absorbing mineral dust or soot (black carbon aerosols). In general, the aerosol absorption efficiency increases with the imaginary part of the refractive index and size of the particles, while it is a strong function of the aerosol chemical composition.

1.5.5 Single scattering albedo (SSA):

Single scattering albedo (SSA) infers the efficiency of the scattering nature of aerosol particles and is defined as the ratio of scattering optical depth to the total optical depth. It is a key variable for determining the aerosol climatic effects and retrieving the AOD from satellite radiances. The SSA contains valuable information about the chemical composition of aerosols in the atmosphere. An increase of SSA with wavelength can be associated with the dominance of coarse-mode desert dust particles in the aerosol size distribution. The value of SSA may vary from 0.2 for absorbing type aerosols, such as soot, to 1.0 for scattering type aerosols, such as sea salt.

1.5.6 Phase function (scattering function):

The Phase function (scattering function) is defined as the angle at which scattered light is distributed as a function of size, shape of the aerosol particle, wavelength and the incidence angle of the light. It is expressed as:

$$P(\theta) = \frac{\beta(\theta)}{\beta_{sc}/4\pi} \tag{1.1}$$

Where $\beta(\theta)$ and β_{sc} are the angular and total scattering cross-section of the aerosol particles respectively. Due to diverse sources and strength of atmospheric aerosols and the variety of size modes (nucleation, fine and coarse) and complex refractive index, the phase functions are quite different for different size particles, as clearly shown in Fig. 1.3.

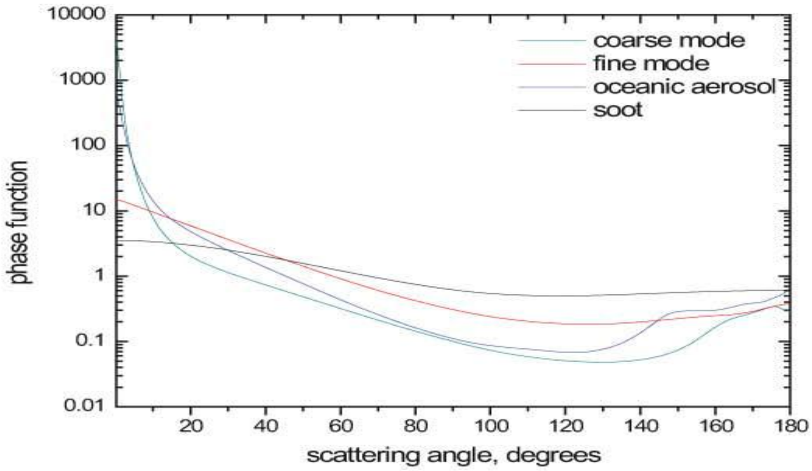


Figure 1.3: Phase function of various aerosol particles (source: Kokhanovsky, 2008).

1.5.7 Asymmetry Parameter:

The asymmetry parameter (g) is defined as the cosine weighted mean of the angular scattering phase function and is a measure of the amount of radiation scattered in the forward versus backward directions. It can be expressed as:

$$g = \frac{\int_{-1}^{1} P(\lambda,\theta)\cos\theta d(\cos\theta)}{\int_{-1}^{1} P(\lambda,\theta) d(\cos\theta)} \tag{1.2}$$

Where g is the asymmetry parameter, P is the phase function and θ the scattering angle. The value of g can vary in the range of -1 (for complete backscattering) to +1 (for complete forward scattering) and it is zero for isotropic or symmetric scattering.

1.6 Dynamics of dust aerosols

1.6.1 Dust emission

The dust emission process is mainly initiated by sand blasting. The mechanism interpreted in empirical formulations is that dust can only be emitted into the atmosphere over dry Earth surfaces when the surface winds exceed a threshold speed of wind erosion.

The formation and evolution of atmospheric aerosols are key processes in describing and determining their dynamics (Kulmala *et al*., 2000). Once the aerosol particles have formed they undergo various physical and chemical processes, namely nucleation, coagulation, transportation and scavenging (Fig. 1.4).

1.6.2 Nucleation

Nucleation is the ubiquitous process in the atmosphere that leads to the formation of freshly-created nanometer-sized particles and subsequent growth to larger size ranges. It plays an important role in several processes, such as cloud radiative properties, cloud lifetime and precipitation rates and, consequently, rain formation and freezing. The transition from one phase to another phase, i.e. from gas to particle during the nucleation processes does not occur instantly due to the enthalpy difference between these two phases. However, as the enthalpy barrier is crossed, the nucleation cluster is formed and it grows very rapidly. The nucleation can be homogeneous or heterogeneous. The homogeneous nucleation takes place by the condensation of precursor gases and creates new aerosol particles in the air with low aerosol concentration at high effective super-saturation. The heterogeneous nucleation takes place when gaseous molecules condense onto pre-existing solid or liquid particles at significantly lower effective super-saturation.

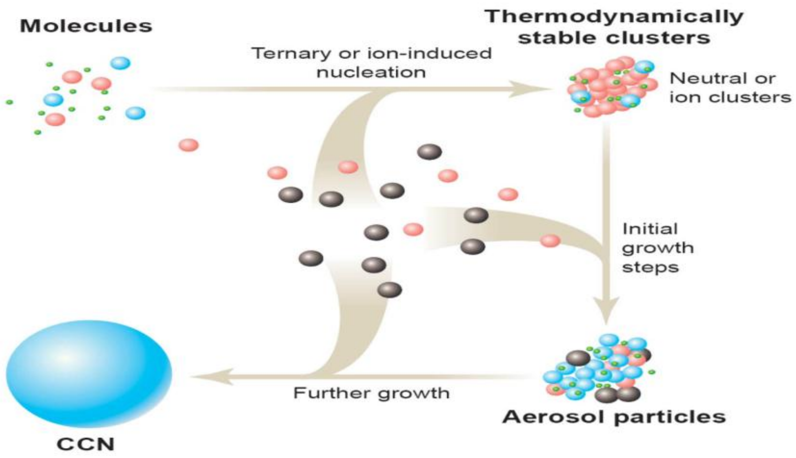


Figure 1.4: Growth of particles (Source: Kulmala *et al*., 2003)

The growth mechanism of aerosol particles, the so-called coagulation, results from the differences in the speed and direction of moment in the atmosphere. The coagulation of aerosol particles significantly modifies their shape and size distribution in the atmosphere and reduces the number concentrations, while the total mass of particles is conserved without changing the chemical compositions. Another important characteristic of coagulation processes is the change of mixing state of particles, since the particles originated from different sources, they often have different sizes and chemical compositions. Therefore, coagulation between unequally-sized particles will externally convert to internally mixed aerosols and to changes in the optical properties and hygroscopic growth characteristics of the particles (Levin and Cotton, 2009). The process of coagulation is the efficient mechanism for the formation of accumulation-mode aerosols in the atmosphere. If the distribution of particles is known, the coagulation rate is a function of the mechanism bringing the particles together. There are several coagulation mechanisms that affect the coagulation rate namely Brownian, gravitational, convective Brownian diffusion enhancement, turbulent inertia and turbulent shear coagulation. Coagulation with larger particles might serve as a significant sink for newly formed nuclei-mode particles.

1.6.3 Dust transportation

Mineral dust is transported in the atmosphere by advection, convection, and turbulent diffusion. The majority of the atmospheric dust falls back to Earth a short time after entrainment and not far from its source. However, intense dust storms are capable of transporting sediments over enormous distances, in many cases over some thousands of kilometers. In Texas, Sahara dust events with moderate to high fine particulate contents occur on three to six days annually, mainly between June and August, lasting for one to three days after travelling from their source over a period of 10 to14 days. Saharan dust also travels northwards to Europe, eastwards to the Middle East and even as far as China (Tanaka et al., 2005). Dust from Central Asia and China is regularly transported to Korea, Japan, the Pacific and North America (Rahn *et al*., 1977; McKendry *et al*., 2001). The distance traveled by dust particles depends upon many factors, including wind speed and turbulence, dust grain characteristics and their settling velocities. The latter is determined by the mass and shape of each particle.

1.6.4 Dust deposition

Atmospheric dust settles to the Earth's surface both through gravitational settling (dry deposition) and through wet deposition with precipitation. Deposition is the most efficient removal pathway for ultrafine (particle size (dp) <0.1 µm) coarse and mode (2.5µm<dp<10µm) particles. Deposition of the particles may be caused by gravitational settling and turbulent deposition. In wet deposition, particles are removed from the atmosphere by rain or fog, and it is the most efficient removal pathway for fine particles, especially particles in the size range 0.1 to 1µm. Wet deposition can occur either below a cloud, when raindrops, snowflakes or hailstones scavenge dust as they fall, or within a cloud when dust particles are captured by water droplets and descend to earth when the precipitation falls. There are two major wet deposition mechanisms, nucleation scavenging i.e. Cloud Condensation Nuclei (CCN), and occult i.e. deposition by the fog and cloud droplets. The removal rate through wet deposition is strongly dependent on the fall velocity, size distribution of the droplets and collision efficiency between droplets and aerosol particles.

Over land, dust is often subject to dry deposition when particles in suspension cross a boundary to terrain with a greater roughness. The presence of vegetation is thought to be important for trapping dust, while rock fragments also perform the same function, although such terrain probably retains less than 20% of settled dust (Goossens, 1995).

1.7 Major desert dust source regions

The largest and most persistent dust sources are located in the northern hemisphere, mainly in the broad "dust belt" that extends 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 for some areas in South America (Atacama) 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 to 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, and the condition of the surface and wind velocity.

The largest dust source region on earth is a zone that extends from the eastern subtropical Atlantic ocean eastwards through the Sahara Desert to Arabia and southwest Asia. In addition, there is a large zone within central Asia, centered over the Taklamakan Desert in the Tarim Basin. Central Australia has a relatively small zone, located in the Lake Eyre basin, while southern Africa has two zones, one centered on the Mkgadikgadi basin in Botswana and the other on the Etosha Pan in Namibia. In Latin America, there is only one easily identifiable zone. This is in the Atacama and is in the vicinity of one of the great closed basins of the Altiplano – the Salar de Uyuni. North America has only one relatively small zone, located in the Great Basin (Goudie and middleton., 2006).

Dust storms are also widespread in the northern part of the Indian sub-continent and neighboring areas (Léon and Le Grand, 2003; El-Askary *et al*., 2006). Middleton, (1986) used ground station observations to examine the frequency and seasonality of dust storms in southwest Asia. He showed that the highest frequencies occur at the convergence of the common borders between Iran, Pakistan and Afghanistan (Sistan Basin). Other high-frequency areas occur on the Arabian Sea coast of Iran (Makran) and across the Indus Plains of Pakistan (Hussain *et al*., 2005) and the Indo-Gangetic basin (Dey *et al*., 2004).

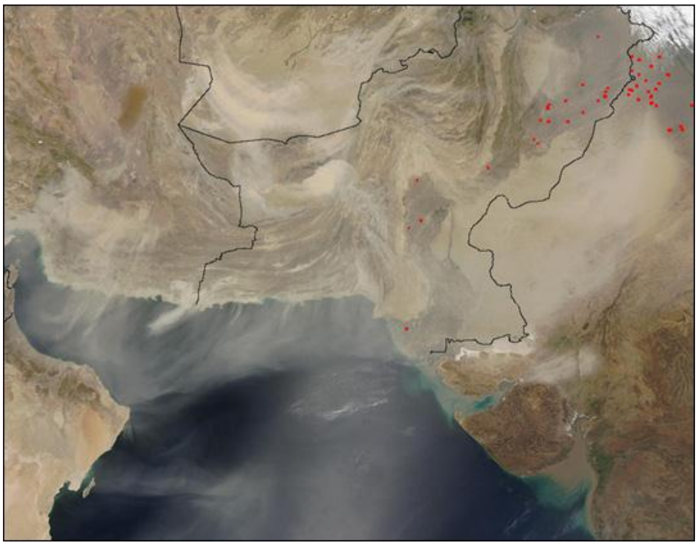


Figure 1.5: A number of jets of windblown desert dust (light brown plumes) were blowing over the Gulf of Oman and the Arabian Sea on May 2, 2003. Originating from the Arabian Peninsula as well as Iran, Afghanistan, and Pakistan, the dust obscures the surface over much of the region. This image was compiled using data from the MODIS sensors flying aboard NASA's Terra and Aqua satellites at hours apart on the same day.

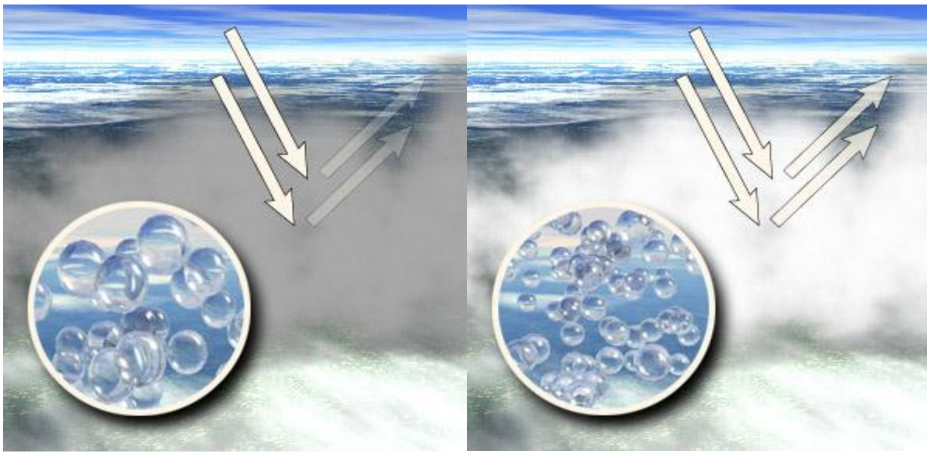
1.8 Effects of dust storms

According to the Earth Observatory website (*http://earthobservatory.nasa.gov/*) dust storms are considered natural hazards, which affect ecosystems for short time intervals ranging from a few hours to a few days. Dust outbreaks have a significant impact on climate, human health and ecosystems, and numerous studies have been conducted worldwide with different instrumentation and techniques to investigate of such events.

1.8.1 Dust effects on solar radiation and climate

Desert aerosols are probably the most abundant type of aerosol particles that are present in the atmosphere. Dust, which is the most common aerosol type that occurs over deserts (Smirnov *et al.*, 2002a; Masmoudi *et al*., 2003) or that is 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 forcing studies (Kaufman *et al*., 2002; Christopher and Zhang, 2002). The impact of mineral dust aerosols on the Earth's system depends mainly on particle characteristics such as size, shape and mineralogy (Mahowald *et al*., 2005), which are initially determined by the terrestrial sources from which the sediments are entrained. Mineral dust is believed to play a crucial role in climate, with an estimated global planetary radiative forcing in the range of –0.6 to 0.4 $W.m^{-2}$ (IPCC, 2001). Though poorly quantified, the impact of mineral dust on global radiative forcing is expected to be negative (Satheesh and Krishna, 2005), but still have large uncertainties. These uncertainties are mainly attributed to the mineral aerosol shape (Kalashnikova and Sokolik 2002), their spectral optical properties (Sokolik and Toon, 1999), their chemical and mineralogical composition (Claquin et al., 1998), their spatial, vertical and temporal distribution (di Sarra *et al*., 2001), their removal (dry and wet deposition) processes (Alpert *et al*., 2004) as well as the albedo of the underlying surface and the relative height between dust layer and clouds (Kinne and Pueschel, 2001; Abel *et al*., 2005). Dust particles scatter and absorb solar and thermal (outgoing) radiation (direct effect) and also, by acting as cloud condensation nuclei, change the microphysical properties of clouds (see Fig. 1.4), such as brightness, albedo, lifetime, structure, droplet size, precipitation rate and latent heat, thus affecting the hydrological cycle (Haywood and Boucher, 2000; Lohmann and Feichter, 2005).

Desert dust particles attenuate UltraViolet (UV) and visible radiation (Badarinath et al., 2007), thus causing cooling at earth surface (di Sarra *et al*., 2002; Meloni *et al*., 2003). The Sahara dust experiment (SHADE) campaign showed a net radiative forcing of -0.4 $W.m^{-2}$ at the Top-Of-Atmosphere (TOA), thus having a cooling effect (Myhre *et al*., 2003). Badarinath *et al*., (2007) found a 4.77% reduction in solar (0.3 to 3.0 μm) radiation over Hyderabad, India, due to a dust storm that originated from the Thar desert. It has been shown that the extent of solar attenuation is sensitive to the dust particles' source region (Meloni *et al*., 2004) and their vertical distribution and shape (Balis *et al*., 2004), because their optical properties are strongly dependent on their source, as well as through chemical and physical processes occurring along the trajectory. Thus, larger particles scatter solar radiation more. The most absorbing dust particles attenuate more solar radiation above the ground. Balis *et al*., (2004) compared the UV irradiances at 305 nm at Thessaloniki, Greece, for two days (one with and the other without a dust event), but with similar ozone levels and aerosol loading. The UV irradiance during the dust event was almost 5% lower after removing the contribution to the differences caused by small total ozone variation between these two days.



(a) *(b)*

Figure 1.6: The indirect aerosol effect through the modification of the cloud microphysical properties. [Source: *http://terra.nasa.gov/FactSheets/Aerosols/*]

1.8.2 Radiative effects of dust

Atmospheric aerosols play a vital role in the radiation budget of the Earth-atmosphere system by scattering and absorbing part of the incoming solar radiation (called direct effect) and by modifying the cloud droplet size distribution, thereby changing the radiative properties and lifetime of clouds (called indirect effect) (Twomey, 1977; Albrecht, 1989; Charlson *et al*., 1992; Ramanathan *et al*., 2001b; Koren *et al*., 2004). The aerosol direct and indirect effects are associated with the surface area and size of the particles, respectively. Direct scattering of solar radiation by dust aerosol particles may cause a change in the vertical temperature profile, cloud properties and precipitation. In addition, atmospheric heating due to dust can increase the atmospheric temperature and might cause "burning of clouds" i.e. evaporation of clouds, and therefore, absence of precipitation, which is an example of the semi-direct effect of dust aerosols (Ackerman *et al*., 2000). However the sole impacts of aerosols on the Earth radiation budget depend on the types of aerosols (i.e. scattering or absorbing properties), reflecting property of the surface, altitude distribution of aerosols, solar declination, geographical latitude and distribution of clouds.

The change in the amount of total solar radiation reaching the Earth's surface with and without the presence of aerosols is called Aerosol Radiative Forcing (ARF) at the surface. Similarly, the change in the amount of solar radiation going out of the Earth-atmosphere system due to the presence of aerosols is the ARF at the TOA. The difference between the ARF at the surface and that at the TOA gives the net amount of radiation trapped in the atmosphere due to aerosols, which is the ARF in the atmosphere, which increases with a decrease in the value of the (SSA).

1.8.3 Dust mineralogy, chemistry and environmental impacts

Little information is available about the potential environmental impacts of dust compounds. These impacts depend upon dust composition, application rates and interactions with other environmental components. Potential environmental impacts include: (1) surface and groundwater quality deterioration; (2) soil contamination; (3) toxicity to soil and water biota; (4) toxicity to humans during and after application; (5) air pollution; (6) accumulation in soils; (7) changes in hydrologic characteristics of the soils, and (8) impacts on native flora and fauna populations (Piechota *et al*., 2002).

Most of the dust mass in the world is composed of illite, kaolinite and montmorillonite minerals (Sokolik and Toon, 1999), as well as of hematite (Quijano *et al*., 2000). Hematite, which is a strong absorber of light at solar wavelengths, aggregated with the other three clay materials (relatively transparent at solar wavelengths) which results in stronger absorption, particularly at shorter wavelengths. Additionally, since dust particles absorb solar radiation, they heat the lower atmosphere and, as a consequence, for an average dust event, it is estimated that the lower atmosphere (1.5 to 3.5 km) is heated by ~0.2 K per day. For about 30 dust events per year, dust aerosols might lead to a regional atmospheric heating of up to ~6 K per year (Alpert *et al*., 1998).

Furthermore, it was found that an elevated Saharan dust layer may play a important role in suppressing tropical cyclone activity in the Atlantic ocean (Dunion and Velden, 2004). Several studies have underlined the importance of dust aerosols, not only to the global and regional radiative and energy balance (Satheesh and Krishna Moorthy, 2005 and references therein), but also to weather forecasting (Alpert *et al*., 1998), rain acidity (Levin *et al*., 1996), modification of cloud microphysical properties (Twomey, 1959), the hydrological cycle and dynamical processes in the atmosphere (Carlson and Prospero, 1972; Ginoux *et al*., 2001). Dust aerosols constitute one of the primary sources of minerals for oceanic life and influence the health of coral reefs. Desert-dust aerosols have also been associated with an increase in coral mortality and *Trichodesmium* blooming in the Caribbean (Lenes *et al*., 2001; Griffin *et al*., 2003; Shinn *et al*., 2000). In addition to its direct radiative effect, dust aerosols mediate ocean carbon uptake and the chemical cycles of other aerosols like sulfates. Trace metals on dust are essential to some marine biological processes. Dust is a source of Iron (Fe), which may be a limiting nutrient for phytoplankton (Falkowski *et al*., 1998; Fung *et al*., 2000). Consequently, dust could modulate the global carbon cycle. Perhaps, the most interesting aspect is the study of dust as a source of iron to High-Nutrient, Low-Chlorophyll (HNLC) oceans, where plankton productivity is limited because of the availability of soluble iron (Lenes *et al*., 2001). It was also found that desert particles carry pathogens from the Sahara desert over the Atlantic Ocean, a fact that may explain the migration of certain types of diseases (Falkowski *et al*., 1998). In addition, certain species of cyanobacteria that utilize Iron (Fe) could play a significant role in the nitrogen chemistry of the ocean. The rate of production of nitrate and ammonium by these organisms could be strongly controlled by the rate of input of mineral dust to the oceans (Falkowski *et al*., 1998).

Dust deposition in the Alps appears to affect the local climate by reducing the albedo of the glaciers, thus contributing to their melting (Franzen *et al*., 1994) and altering the chemistry of Alpine lakes (Psenner, 1999). Furthermore, harmful health effects are caused by elevated concentrations of desert dust particles. These effects have been investigated in several studies (Rodriguez *et al*., 2001; Sultan *et al*., 2005). Dust can serve as a reaction surface for reactive gas species in the atmosphere (Dentener *et al*., 1996) and for moderating photochemical processes (Dickerson *et al*., 1997). Dust also has an important role in paleoclimatic studies. The concentration of windblown mineral dust in deep-sea sediments (Rea, 1994; Kohfeld and Harrison, 2001) and ice cores (Yung *et al*., 1996) is often used as a proxy indicator of paleoclimatic aridity on the continents and of historical changes in global wind systems.

1.8.4 Health effects of dust storms

A number of medical conditions can be traced to the impact of desert dust, and the effects of fine wind-borne particles on human health have recently been the subject of considerable interest (Griffin *et al*., 2001; Garrison *et al*., 2003,). On 9 August 2005, a dust storm in Baghdad led to nearly 1000 cases of suffocation being reported to the city's Yarmuk Hospital, one of whom died (Goudie and Middleton, 2006). The straightforward inhalation of fine particles can cause and/or aggravate diseases such as bronchitis, emphysema and silicosis. High incidences of silicosis and pneumoconiosis have been reported in Bedouins in the Negev (Bar-Ziv and Goldberg, 1974), while dust blown by the Irifi wind in the Western Sahara is responsible for conjunctivitis that is common among the nomads of the region (Morales, 1946). High concentrations of atmospheric dust in many desert areas often exceed generally recommended health levels for particulate matter (see also Section 1.6 on PM_{10} values). In Mali, for example, Nickling and Gillies, (1993) found that the mean ambient air concentrations during April to June were 1176 $\mu g.m^{-3}$, exceeding the recommended international health standard by an order of magnitude. Similar concentrations can also occur during particularly severe long-range transport events. In certain parts of Spain, the levels of particulate matter associated with frequent incursions of dust from North Africa means that it is not possible to meet European Union (EU) directives on acceptable levels of air pollution (Querol *et al*., 2004). Rodriguez *et al*., (2001) indicated that these Saharan dust events can induce up to 20 days per year in which PM_{10} standards are exceeded in southern and eastern Spain. Intrusions of desert dust from the Hexi Corridor in northern China also make a significant contribution to particulate pollutants in the Lanzhou Valley, an urban area that is among the worst in China for its poor air quality (Ta *et al*., 2004).

Dust may also be otherwise contaminated by organisms, such as bacteria and fungi (Kellogg *et al*., 2004) and by toxic chemicals that can harm people when it settles on the skin, is swallowed or inhaled into respiratory passages. The increase in dust storm activity in Turkmenistan, for example, linked to the desiccation of the Aral Sea, has probably caused severe respiratory problems for children in the area, but the dust from the dry sea bed also happens to contain appreciable quantities of organophosphate particles (O'Hara *et al*., 2000). Dust blown from another former lake bed, that of the desiccated Owens Lake in California, contains arsenic derived from nineteenth-century mining operations (Raloff, 2001). Dust storm material in Saudi Arabia has been found to contain an array of aeroallergens and antigens which could trigger a range of respiratory ailments (Kwaasi *et al*., 1998). Other possible consequences of airborne dust include an increase in asthma incidence (Rutherford *et al*., 1999), as reported for Barbados and Trinidad when Saharan dust outbreaks occur (Monteil, 2002; Gyan *et al*., 2005) and also an increase in the incidence of meningococcal meningitis in the Sahel zone and Horn of Africa (Molesworth *et al*., 2002). The annual meningitis epidemics in West Africa, which affect up to 200 000 people between February and May, are closely related to the Harmattan season in their timing (Sultan *et al*., 2005). Coccidioidomycosis, a disease caused by a soil-based fungus (Coccidioides immitis) transported in airborne dust, is endemic to parts of the southwestern U.S (especially in the San Joaquin Valley of California, southern Arizona, southern New Mexico and west Texas) and northern Mexico (Gabriel *et al*., 1999). In the U.S, where it is known as Valley Fever, an estimated 50 000 to 100 000 people develop symptoms of the disease each year (Leathers, 1981), and a dramatic increase in the incidence of coccidioidomycosis during the early 1990s in California was estimated to have cost more than U.S.$66 million in direct medical expenses and time lost in one county alone (Kirkland and Fierer, 1996). Dust can also contain dried rodent droppings or urine which can cause the spread of Hantavirus Pulmonary Syndrome. In Ladakh and China, dust may contribute to a high silicosis incidence (Derbyshire, 2001). Fungal spores from China reach high ambient levels in Taiwan during dust events and may have health implications (Wu *et al*., 2004). Some recent epidemiological studies indicate that long-range dust transport events are closely associated with an increase of daily mortality in Seoul, Korea (Kwon *et al*., 2002) and Taipei, Taiwan (Chen *et al*., 2004) and have caused cardiovascular and respiratory problems (Kwon *et al*., 2002), including an increased incidence of strokes (Yang *et al*., 2005).

Given the great distances over which dust can be transported, it is not surprising to learn that the intercontinental dispersal of material may include pathogens of crop plants. Long-distance dispersal of fungal spores by the wind can even spread plant diseases across and between continents and reestablish diseases in areas where host plants are seasonally absent (Brown and Hovmøller, 2002). While monitoring aerosols on the Caribbean island of Barbados, Prospero (2004) reported that concurrent detection of bacteria and fungi only occurred in air that contained Saharan dust.

1.8.5 Economic effects of dust storms

The entrainment, transport and deposition of dust can present a variety of problems to inhabitants in arid desert areas, many of which have a deleterious economic impact. Folk (1975), for example, suggests that the ancient Macedonian town of Stobi, which flourished between 400 BC and 400 AD, was abandoned because of the severe effects of dust storms. Another example of the mix of impacts a dust storm can bring is provided for

China by Yang *et al*., (2001): "A major sand-storm on May 5th 1993 caused serious economic loss and was as hazardous as a disaster caused by an earthquake. According to ground observation and investigation made by the expert group of the Ministry of Forestry, a total of 85 people died, 31 people were lost and 264 were injured (most of these victims were children). Agriculture and animal husbandry were most severely hurt. In total, 373,000 ha of crops were destroyed. 16,300 ha of fruit trees were damaged. Thousands of greenhouses and plastic mulching sheds were broken. 120,000animals died or were irrecoverably lost. The fundamental agricultural installations and grassland service facilities were ruined. More than 1,000km of irrigation channels was buried by sand accumulation. Many water resource back-up facilities, such as reservoirs, dams, catchments, underground canals and flood control installations were filled up with sand silts. About 6,021 communication poles and electricity grids were pushed down and electricity transports and communication services in some regions were stopped for several days. Some sections of railway and highway were interrupted due to deflation and sand accumulation."

Another major dust and sandstorm event took place in April 2002 and led to airport closures in Mongolia and Korea. The total damage cost of this event in Korea alone was put at U.S. $ 4.6 billion (or about 0.8% of Gross domestic product (GDP); Asian Development Bank, 2005, pp. 1–5).

In a similar vein, dust storms have regularly been associated with deaths in India. In April 2005, ten people and 50 head of cattle were killed by fires fanned by dust storm winds in Uttar Pradesh. In March 2005, six people were killed and 40 injured in a dust storm in Bihar.

Some progress has been made in identifying the offsite costs of wind erosion. In South Australia, for example, the costs include damage to houses and the need for redecoration, the need to clean power transformers, deaths and damage caused in traffic accidents, road disruption, impacts on the costs of air travel and impacts on human health (especially because of raised asthma incidence(Williams and Young, 1999).

The reduction in visibility caused by dust storms is a hazard to aviation, rail and road transport. The severe pre-frontal storm of 7 November 1988 in South Australia, for example, caused road and airport closures all across the Eyre Peninsula (Crooks and

Cowan, 1993). In the United state (U.S), in November 1991, a series of collisions involving 164 vehicles occurred on Interstate 5 in the San Joaquin Valley in California (Pauley *et al*., 1996), while in Oregon a dust storm in September 1999 set off a chain reaction of 50 car crashes that killed eight people and injured more than 20 (State of Oregon, 2004). The loss of visibility may be very sudden when caused by the arrival of a dust wall associated with a dry thunderstorm. Such Haboob dust walls were responsible for 32 multiple accidents between 1968 and 1975 on Interstate 10 in Arizona (Brazel and Hsu, 1981). The seriousness of the problem inspired the development of a Dust Storm Alert System involving remote-controlled road signs and special dust-alert messages broadcast on local radio (Burritt and Hyers, 1981).

1.8.6 Impact of dust storms in the Sistan region

After the 1999 drought, dust storm activity appears to be increasing in both frequency and severity. Tens of thousands of people have been suffering during the months of devastating dust storms in the Sistan basin, especially in the cities of Zabol and Zahak and surrounding villages. A severe dust storm occurred in Sistan and its 80 surrounding villages on 30 June 2008 that resulted in the closing of schools and businesses. Dust storms lasted about five days and more than 3000 people suffering from allergies and respiratory diseases were admitted to hospital or health centers. Miri *et al*., (2007) showed that 63% of the people in Zabol city suffer from respiratory diseases with the majority coming from the surrounding villages. Miri *et al*., (2007) indicated that 132 people have been considered as patients suffering from respiratory conditions related to dust storms. Information obtained from hospitals indicated that most of the patients who visited hospitals suffered from Chronic Obstructive Pulmonary Diseases (COPD) and asthmatic diseases with the peak of incidences during the summer season (June to September) when the most severe dust storms occur (Rashki *et al*., 2011). It is estimated that ~90% of the population living in the region suffered from respiratory problems in the summer period. The health damages and medical costs for patients for the period 1999 to 2004 exceeded U.S. $166.7 million (Miri *et al*., 2007). According to the Asthma Mortality Map of Iran, the rate of asthma in Sistan is higher than in other regions of the world (Selinus *et al*., 2010).

On the other hand, dust storms affect horizontal visibility, causing accidents. In recent years, many accidents have been reported on dusty and stormy days in the Sistan region resulting in death and injury of travelers. Accidents involving trucks transporting cargo are costly and affect the local economy. A study showed that the greatest number of accidents during one complete 24 hours (day and night) occurred when the dust was at peak intensity. The maximum number of vehicle accidents also takes place in the summer period (Miri *et al*., 2007).

Particles arising from dust storms affect schools in several ways, causing teachers and pupils to take leave or cause late attendance, disrupting classes due to discomfort, hampering serious study and restricting movement. A total of 623 schools were closed because of dust storms and amounts of damage were about U.S. $ 325 000 during 2000 to 2004. Two hundred and twenty villages are located in the path of dust storms and sand movement in the Sistan region, which need intensive clean-up after dust storms. The cost of evacuating sand from residential areas is estimated at 1.3 to often 1.5 U.S. $/m^3 (Miri *et al*., 2007)·

Table 1.2: Cumulative damage costs of dust storms in the Sistan region during 2000 to 2004 (Source: Miri *et al*., 2007)

Damage centre	**Damage Percentage (%)**	**Damage costs (×1000 US$)**
Road	4.5	5636
Community health	24.99	31.2
School breaks(enforced holidays)	1.06	1324
Sand aggregation in residential area	8.66	10.789
House cleaning and repairs	60.79	75.9
Total	100	124.849

Dust that is shifted in a dust storm comes down on city surfaces. Some 30 to 40% of the dust that collects on the ground enters into houses which then need regular cleaning. Survey response showed that each person spends roughly four hours cleaning up his/her house after a dust storm, increasing the cost of cleaning by 50%. Some 74% of the respondents pointed to dust as the cause of decrease in household equipment life and damage to electronic equipment. According to Miri *et al*., (2007), the total damage costs from dust storms during 2000 to 2004 in the Sistan region were estimated at 1213.976 million U.S.$ (Table 1.2).

1.9 Satellite observation of dust storms

The identification of dust aerosol sources, properties and transportation mechanisms over a wide scale 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 event. Ground-based measurements of aerosol optical properties, such as spectral aerosol optical depth and column-mean particle size, are reported by the global sun photometer network AERONET (Aerosol Robotic Network). However, significant limitations of the surface observations are the single point measurements and the intermittency of the reported data. Data coming from surface stations are often unevenly distributed and are generally not available within active dust regions. Nonetheless, visibility measurements have been extensively used for the qualitative and quantitative characterization of dust loadings and transport routes (Sun *et al*., 2001; Zhang *et al*., 2003; Darmenova *et al*., 2005).

Monitoring of dust source region, transport pathways and plume characteristics is only possible from satellites because ground-based measurements are very limited in space and time (Kaskaoutis *et al*., 2008; 2010). Therefore, it is important to identify, also for prognostic purposes, the atmospheric circulation patterns facilitating the transport of dust particles from their source regions over distances of thousands of kilometers downwind. Compared to ground-based measurements, satellite observations offer a more efficient way of determining key characteristics of aerosols at temporal and spatial scales that are needed to study and monitor aerosol impacts upon the climate system. Traditionally, over land and, especially, over bright surfaces such as arid regions, retrieving aerosols from satellite observations is a challenging problem because one needs to separate the signal from the surface from that of aerosols, which requires precise characterization of the surface reflectance or emissivity. In addition, the aerosol products greatly depend on the correct discrimination between aerosols and clouds, because aerosol retrievals are only possible in cloud-free conditions.

The Total Ozone Mapping Spectrometer (TOMS**)** sensor is able to map the global distribution of the major dust source regions with the aim to identify common environmental characteristics (Prospero *et al.*, 2002). 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). Furthermore, Multi-angle Imagining Spectroradiometer (MISR) can retrieve aerosol properties over bright desert areas due to its unique capability of multi-wavelength observations at forward and backward directions (Kahn *et al*., 2005). Recently, the new algorithm (deep blue) is able to obtain AOD values from Moderate Resolution Imaging Spectroradiometer (MODIS) over desert areas (Hsu *et al*., 2004). Satellite imagery clearly shows that dust aerosols often cover very large areas. Indeed, the aerosol load associated with dust transport is higher than that attributed to pollution plumes. Furthermore, dust plumes that cover much larger areas, are more persistent, and occur more frequently than those associated with pollutant aerosols (Husar *et al*., 1997).

However, dust properties are hard to be measured and difficult to be represented realistically by satellite remote sensing because size, shape, composition and regional distribution of dust vary over a wide range of spatial and temporal scales. Therefore, simultaneous measurements of dust chemical, physical, optical properties and related effects on climate are needed in order to support the satellite retrievals (Sokolik *et al*., 2001; Kohfeld *et al*., 2005). However, such measurements are very limited and are rarely performed in a coordinated fashion. The bulk of available data originates primarily from ground-based observations (including meteorological stations and short-term field measurements), and short-duration field campaigns that include ground-based measurements, aircraft observations and satellite remote sensing. The dust optical and physical properties (e.g. AOD, Angstrom exponent, size distribution, SSA, asymmetry parameter, refractive index, particle shape) are now well documented via both ground-based and satellite instruments. To this end, except from the experimental campaigns, the standardized networks (e.g. AERONET, European Aerosol Research Lidar Network (EARLINET**)**) have helped in continuing monitoring and analysis of the optical properties of dust. The National Aeronautics and Space Administration (NASA) website (*http://www.visibleearth.nasa.gov/Atmosphere/Aerosols/*) has an archive of images of spectacular aerosol events, most devoted to dust events. Also, the NASA website (*http://earthobservatory.nasa.gov/NaturalHazards/*) provides several images of the most intense dust events, which are referred to as natural hazards along with floods, forest fires, cyclones, droughts, volcanoes, earthquakes, etc. These images can help the public and the scientists in developing their knowledge of the dust source regions, the dust transport and deposition and its optical properties. In order to improve the scientific knowledge on 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 dust aerosol climatology by combining satellite observations (e.g. TOMS, MODIS, MISR) and measurements from ground-based monitoring networks (e.g. AERONET, EARLINET). In this thesis, the satellite monitoring of dust storms over Sistan region is also used along with in-situ measurements to provide deeper knowledge on the dust source region, transport pathways and optical properties of dust.

1.10 Aim, objective and structure of the thesis

The thesis aims at providing knowledge for the first time about the dust events, their source regions, transport pathways, optical properties, mineralogy and effects on human health over Sistan region and Hamoun Basin, located in southeastern Iran close to the Iran-Pakistan-Afghanistan borders. The main objectives of the thesis can be summarized in the followings:

1) Identification and quantification of the grain-size distributions of the dust flux loading over the Sistan region;

2) Identification of the variability of PM_{10} and $PM_{2.5}$ levels and interpretation of their environment and health impacts over the Sistan region;

3) Assessment of the chemical and mineralogical properties of dust particles;

4) Identification of the optical properties of dust storms using satellite observations;

The scientific objectives of the thesis are achieved in seven principal steps (Chapters):

Chapter 1 gives the general introduction and facts about dust storms (i.e. origin, climate implications, and optical properties of dust aerosols), provides some previous results regarding dust in the Middle East, Iran and the Sistan region and highlights the aim, objectives and structure of the thesis.

In Chapter 2, the focus is on the geography, meteorology and climatology of the Sistan Basin based mainly on meteorological data from the Zabol station. In this Chapter firstly, the geography of the Sistan basin is covered. It encompasses large mountains with altitudes of about 5000 m above mean see level in west Afghanistan to an elevation of about 400 m in the Sistan region in the eastern part of Iran. In this Chapter are discussed changes of Hamoun water surface as a main factor affecting of dust storms.

In Chapter 3, the horizontal dust loading of dust events is analyzed via ground-based instruments established in Sistan region. In this Chapter the Hamoun basin is defined as a major dust source region by focusing on the assessment of dust loading at two nearby locations in the Sistan region. The grain size is used to provide useful information regarding the status of Sistan's dust storms.

In order to understand the extent of dust's effects on the atmospheric environment and health and in order to put in place effective remedial policies and strategies, the chemical (composition and mineralogy) characterization of the Sistan aerosols is investigated in Chapter 4. The chemical analysis has been performed in laboratory using airborne and soil dust samples collected in the Sistan region and Hamoun Basin. In this Chapter, an overview of the temporal occurrences and geological-geochemical characteristics of airborne dust in the Sistan region are given. The chemical and mineralogical constituents carried out during major dust storms are analyzed to determine the relationship between the chemical constituents of the dust storms and those of the inferred (Hamoun) source soils, and to investigate atmospheric modifications from anthropogenic causes related to the dust storms in this region.

In Chapter 5, a temporal assessment of PM_{10} and $PM_{2.5}$ concentrations in the atmosphere above the cities of Zabol and Zahedan, which are effected by Sistan dust storms, is performed. The PM concentrations at both cities were measured from and established dust-pollution monitoring network. This Chapter also includes an examination of the relationship between PM_{10} and $PM_{2.5}$ and the determination of the temporal variability of the Air Quality Index (AQI) over the region. The AQI is used to provide valuable information regarding the status of air quality and the associated health concerns for the public.

In Chapter 6 satellite remote sensing provides observational constraints for monitoring dust production and improving the understanding of the effects of regional-scale atmospheric processes on dust emission and transport over the Sistan as well as south west Asia. This Chapter analyses the aerosol patterns by means of multiple satellite platforms aiming to reveal the spatio-temporal and vertical distribution of dust aerosols. The dataset include records of Aerosol Index (AI) from the TOMS on board the Nimbus-7 (1979–92) and the Earth Probe (mid-1996 to 2005) satellites and 6-year AI records from OMI aboard Aura. Moreover, the AOD is analyzed through 11-year records from MISR aboard Terra (2000-2010) and from Deep Blue records from MODIS Terra (2000-2007) and MODIS Aqua (2002-2011). The main focus is to determine similarities and differences in dust climatology provided by these sensors over the Sistan region and surroundings.

The overall conclusions and future directions of research are summarized in Chapter 7.