Establishing a WMO Sand and Dust Storm Warning Advisory and Assessment System Regional Node for West Asia: Current Capabilities and Needs

Technical Report

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Background

Sand- and Dust Storms (SDS) are a major problem in West Asia, where their main characteristics – intensity, extent and frequency – are either not well known or have not yet been scientifically addressed. The growing concern of countries in the region about these phenomena has led to a number of high-level international meetings in recent years at which the creation of a system for SDS monitoring and forecasting has repeatedly been raised.

The Government of Turkey is also concerned about the occurrence of SDS and their impacts and convened a meeting of the Ministers of the Environment of Turkey, the Islamic Republic of Iran, Iraq and the Syrian Arab Republic in Ankara on 28 and 29 April 2010. Participants discussed a variety of transboundary environmental matters and issued the Ankara Ministerial Declaration on 29 April 2010, in which they expressed their desire to enhance cooperation in the areas of the environment and meteorology and discussed a number of issues, including SDS. The meeting proposed the development of a project to reduce pollution of the environment by dust and haze by taking measurements of dust formation, improving meteorological monitoring and forecasting, controlling soil erosion and establishing regional cooperation projects. The ministers committed to set up a task force consisting of experts from the related ministries or departments of the countries concerned, and nominated experts from relevant international organizations, including the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). The Islamic Republic of Iran led the formation of the task force.

Two subsequent meetings at both technical and ministerial levels were held in Tehran in September 2010 with the additional participation of Qatar. Both the Ankara Declaration and the Tehran Action Plan constituted a sound basis for building a regional SDS programme.

The Regional Conference on Dust and Dust Storms was held in Kuwait City, 20–22 November 2012, during which UNEP and WMO organized a special session on scientific aspects of the regional SDS programme. The Conference highlighted the following issues:

- The significant impact of SDS processes in West Asia and the consequences to transport, health and the environment in general.
- Changes observed in source areas for sand- and dust storms and how these have had an impact on the frequency and intensity of SDS events.
- Concern about how climate change may impact SDS events.
- Gaps in observations, understanding, modelling, prediction, user services and warnings related to SDS processes.

Some major issues and outcomes were agreed in the Kuwait meeting, including the two following recommendations:

- WMO would conduct a survey to identify the existing SDS observing and forecasting facilities in the region.
- A Sand- and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Regional Node for West Asia would be established, at the initiative of WMO, to satisfy needs for providing/improving SDS observation and forecasting capabilities.

In November 2012, WMO and UNEP agreed to collaborate in a detailed survey of sand and dust phenomena and related capabilities and signed an agreement under which WMO would perform a study of the SDS-WAS concept and future activities for the West Asia region, which would provide a detailed survey of the necessary human resources and observational, forecasting and computational facilities. The study would also recommend necessary action for developing an SDS-WAS Regional Node for West Asia, following the concept and best practices of the SDS-WAS Regional Node for Northern Africa, Middle East and Europe (NAMEE).

This report, *Establishing a WMO SDS-WAS Regional Node for West Asia: Current Capabilities and Needs*, has been elaborated under the overall supervision of the Director of the WMO Atmospheric Research and Environment Branch, with the support of the UNEP Regional Office for West Asia. It aims to perform an assessment of the capabilities in SDS monitoring, prediction and assessment and provide guidance for establishing an SDS-WAS Regional Node by presenting the essential elements to be taken into account.

The specific objectives of the report are to:

- Review published information on dust storm incidence in West Asia, including the Islamic Republic of Iran and Turkey.
- Compile existing information on dust sources, frequency/intensity of dust storms and the socio-economic and environmental impacts of dust
- Recommend a strategy for dust-model validation.
- Map regional and national institutions.
- Propose regional institutional collaboration mechanisms for the monitoring, prediction and delivery of dust-related products and services.
- Propose types and density of measurements, based on existing observation capacity;
- Propose a multiscale/downscaling dust-forecasting strategy, based on identified existing numerical modelling facilities.
- Propose a regional data-exchange policy.
- Advise on training and capacity-building programmes on the regional scale.

The WMO SDS-WAS mission is to enhance the ability of countries to deliver timely and quality sand- and dust storm observations, forecasts, information and knowledge to users through an international partnership of research and operational communities. It is proposed that the WMO SDS-WAS Regional Node for West Asia be established in collaboration with the UNEP Regional Programme to Combat Sand and Dust Storms. Through collaborative partnership with UNEP, the WMO SDS-WAS Regional Node for West Asia will provide SDS phenomena assessment and secure an SDS monitoring and early warning system.

A.1 INTRODUCTION

Mineral-dust loading in the atmosphere is the most abundant of all aerosol species, together with sea-salt aerosol in some coastal areas (*IPCC, 2001*). On the global scale, dust mobilization appears to be dominated by natural sources (*Tegen et al., 2004*) in arid regions (*Prospero et al., 2002*). Topographic lows in deserts are the predominant sources of atmospheric mineral dust because, in these regions, fine particles that have been transported by water after rainfall are easily eroded and transported by wind during the dry season.

Several factors determine whether soil particles can be aerosolized: wind velocity, physical properties of the soil (e.g. particle size distribution, soil moisture and particle cohesiveness) and land-surface conditions (e.g. surface roughness and vegetation cover).

Soils that are most sensitive to wind erosion and dust emission usually lack protection from vegetation, have low soil-moisture content (*Marticorena and Bergametti, 1995*) and contain readily erodible sediments of fine particles (*Prospero et al., 2002*). The most substantial sources of dust aerosols are therefore deserts and dry lakebeds, although dust emissions from vegetation-covered land and dunes are also commonly observed.

Conventionally, dust refers to soil particles with a diameter of < 0.6 mm. In practice, however, only those particles smaller than 0.1 mm (100 µm) can be lifted up, transported by suspension and be present in a dust cloud. Dust particles move in one of three modes of transport, depending on particle size, shape and density of the particle, designated as “suspension”, “saltation” and “creep” (see *Usher et al., 2003*).

- Suspension mode includes dust particles < 0.1 mm in diameter and also clay particles (2 µm). Through the suspension mechanism, the particles are transported upwards by turbulent wind currents. The fine particles may be transported to high altitudes (6–8 km) and over distances of thousands of kilometres.

- Saltating particles (i.e. 0.01 < diameter < 0.5 mm) leave the surface up to a height of 1 m, but are too large to be suspended, so they settle on the surface owing to the gravitational drag forces exceeding particle mass.

- Remaining particles (> 0.5 mm) are transported in creep mode. They roll or slide along with the wind, impacting particles on the land surface, favouring the movement of other particles.

These processes are illustrated in Figure 1.

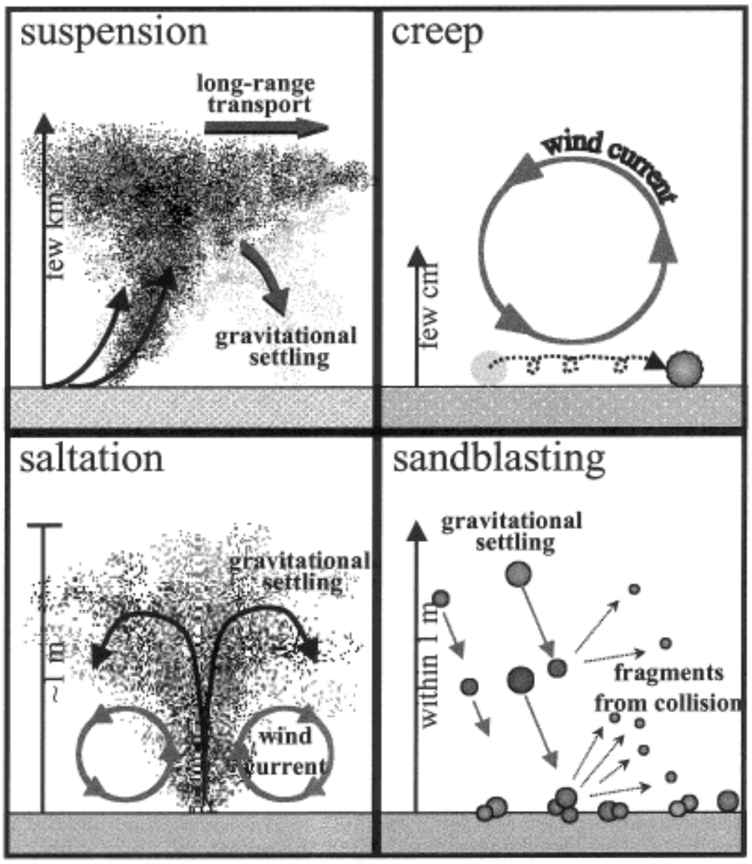


Figure 1 - Schematic representation of the possible wind-induced entrainment processes to move, emit and transport mineral dust particles from source into the troposphere (after *Usher et al., 2003*)

Dust particles that can be transported thousands of kilometres from their source regions – and thereby produce a substantial effect on weather and climate – mainly have diameters smaller than 20 µm (*Gillette and Walker, 1977; Tegen et al., 1996*).

Dust is moved by the prevailing winds and transported vertically by convective processes, as well as adiabatic vertical motion associated with frontal systems. Atmospheric dust settles on the Earth's surface through both molecular and gravitational settling (dry deposition) and wet deposition with precipitation (Figure 2). Large particles sediment out more quickly than smaller particles in dry deposition processes. 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 the surface in raindrops. Wet deposition is sometimes manifested in the phenomenon “blood rains”. Dust atmospheric lifetime depends on the particle size, ranging from a few hours for particles larger than 10 µm, up to several weeks for sub-µm size particles.

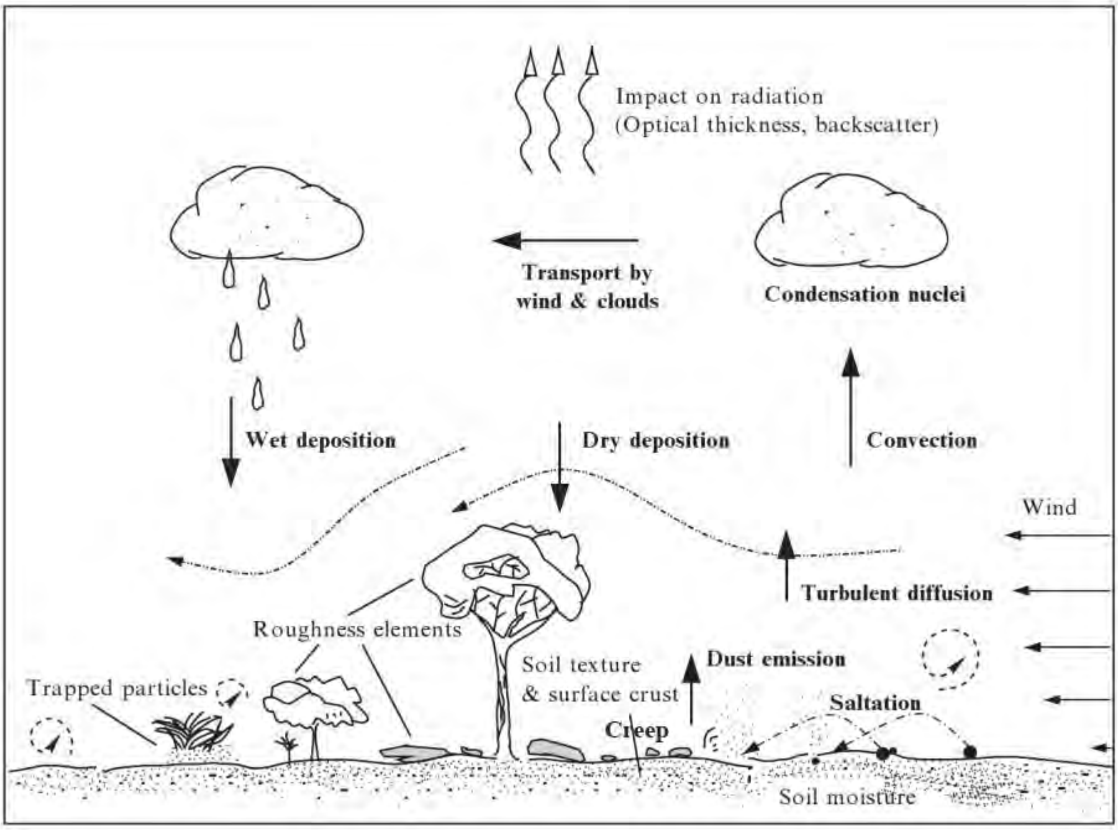


Figure 2 - Physics and modelling of wind erosion: entrainment, transport, deposition and impact on radiation and clouds of desert dust: atmospheric conditions, soil properties, land-surface characteristics and land-use practice control the erosion process (adapted from *Shao, 2008*)

A.2 SCIENTIFIC ASSESSMENT OF DUST STORMS IN WEST ASIA: SUMMARY REVIEW OF THE LITERATURE

This section covers various aspects of dust storms in West Asia (also known as the Middle East), such as dust sources and transport, types of dust storm, optical and physical properties of dust, vertical structure of the dust layer and a basic climatology of dust specifically produced for this report. Since, in the following sections, continuous geographic references are made, and in order to facilitate their identification, a map of the region under study is given (Figure 3), although it is likely that, for identifying certain areas cited in the report, the reader should consult national maps available online.

Figure 3 - Map of West Asia (Middle East)

A.2.1 Dust sources and transport

Dust events originate predominantly in arid or semi-arid environments, which account for some 33% of the total world land area (*Duce, 1995*). In fact, the northern hemisphere generates some 90% of global airborne mineral dust, where it is also deposited (*Duce, 1995*). Most "dust storm" occurrences are in the region beginning on the west coast of North Africa and extending through the Middle East into Central Asia. North Africa is the main dust source area, alone responsible for generating more than 50% of the total desert dust in the atmosphere and almost five times as much as the second main source, the Arabian Peninsula (see Figure 4).

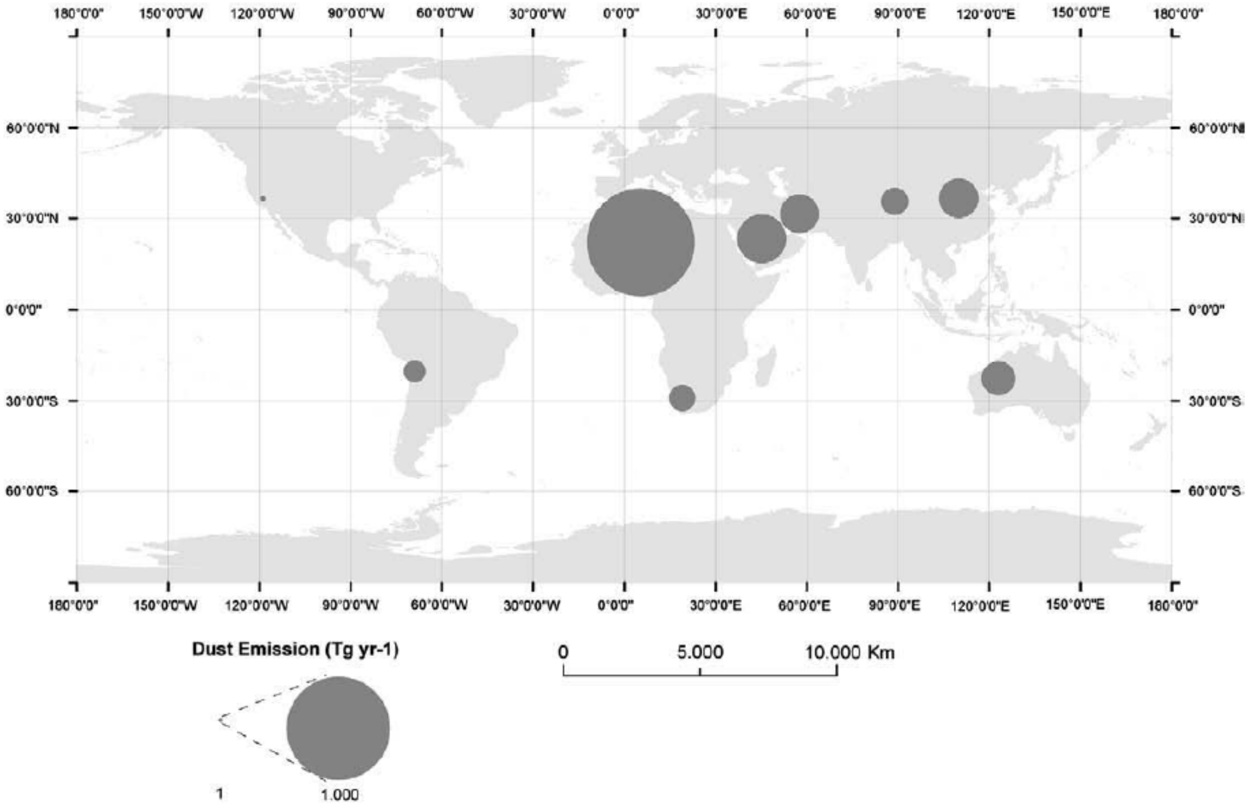


Figure 4 - Location of source areas and scale of dust emissions
(extracted from *De Longueville et al., 2010*, adapted from *Tanaka and Chiba, 2006*)

The climate in West Asia is mainly affected by three pressure systems (*Prospero et al., 2002*): the Siberian anticyclone in winter over central Asia; the monsoon depression in summer over the Indian subcontinent; and the depressions travelling from north-western Africa in the non-summer seasons. Severe dust storms are summertime phenomena associated with the shamal. Much of the dust entrained by the shamal is deposited in the Gulf and the Arabian Sea. In some areas (e.g. Negev Desert (Israel), Jordan, western and northern Iraq and the northern part of Saudi Arabia), the peak dust season occurs in spring and winter. In these seasons, dust storms are generated by depressions moving eastward from the Mediterranean.

When high winds at a threshold speed blow over areas with minimal vegetation cover, soils that lack snow and/or soil moisture content or soils that are vulnerable to disturbance, a dust storm has the potential to occur (Table 1). Other types of areas that can also be vulnerable to dust storms when threshold winds are present are those in which soils have dried out and been displaced after a flash flood (University Corporation for Atmospheric Research/Cooperative Program for Operational Meteorology Education and Training (*UCAR/COMET, 2010*) or areas with dried-out lakebed sediments.

Table 1 - Wind-speed thresholds for different desert environments: wind-speed threshold refers to the minimum wind speed required to lift suspended sediment in a certain environment (from *UCAR/COMET, 2010*)

Wind speed thresholds for different desert environments	
Environment	**Threshold wind speed**
Fine to medium sand in areas with sand dunes	16 to 24.1 kmph
Sandy areas with poorly developed desert pavement	32.2 kmph
Fine material in desert flats	32.3 to 40.2 kmph
Dry lake beds and/or crusted salt flats	48.3 to 56.3 kmph
Well-developed desert pavement	64.4 kmph

According to *Prospero et al. (2002),* the sources in the Middle East extend in a continuous band from the northern part of the Tigris-Euphrates basin to the coast of Oman. The seasonal variation of dust activity in the Middle East is complex and varies by region. Over much of the peninsula, dust is active all year long, but is relatively low in winter months. Dust activity strengthens in March and April, peaks in June and July and weakens in September.

A first rough estimation of potential dust sources in West Asia can be obtained from the type of soil. Silt and clay grounds present fine and very fine particles (< 0.07 mm in diameter) that are relatively easily lifted and transported by the wind. In poor vegetation regions, such as the Middle East, these particles are exposed to the wind and susceptible to transportation by atmospheric flows. The UCAR/COMET map of soil-grain sizes (*UCAR/COMET, 2005*) (Figure 5) shows that the Middle East is a region prone to dust storms.

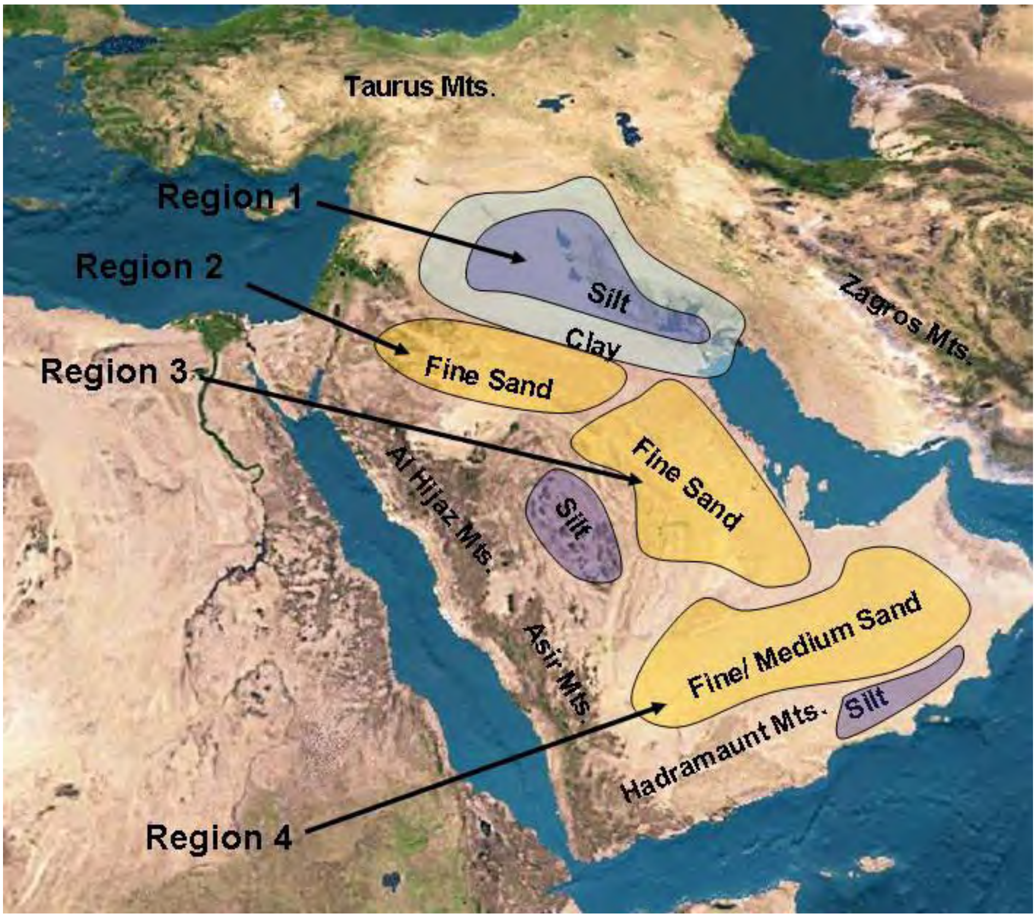


Figure 5 - Map of soil-grain sizes in the Middle East (from *UCAR/COMET*, adapted by *Anderson, 2004*): the authors defined different regions according to soil type

Ground-based aerosol detectors have been used for years to observe and measure mineral dust transport. Based on the WMO protocol, dust events are classified according to visibility into one of four categories (*Shao, 2008*). The first of these, *dust haze*, consists of aeolian dust particles homogeneously suspended in the atmosphere. These are not actively entrained, but have been uplifted from the ground by a dust event that occurred prior to the time of observation or from a considerable distance.

Visibility may sometimes be reduced to 10 km. *Blowing dust* is the state where dust is transported locally by strong winds – at the time of observation – reducing visibility to 1–10 km. A *dust storm* is the result of strong turbulent winds entraining large quantities of dust particles, reducing visibility to between 200 m and 1 km. Finally, a *severe dust storm* is characterized by very strong winds that lift up large quantities of dust particles, reducing visibility to less than 200 m.

The simplest approach to estimating dust-source zones and dust storm corridors in West Asia is, undoubtedly, to elaborate visibility climatologies from in situ visibility observations provided by SYNOP and METAR reports.

A previous study focusing on the delimitation of the regions in the Middle East according to the seasons of main dust activity was carried out by *Middleton (1986(a)).* He analysed the dust distribution over the Syrian Arab Republic, Lebanon, Jordan, Israel, Saudi Arabia, Yemen, Iraq and the Islamic Republic of Iran, using short periods of data recording, and other data collected over varying lengths of time from the 1950s and 1960s. He showed that the area of greatest dust-raising activity were the Lower Mesopotamian Plains, spring or summer being the main season of occurrence. He reported that the dust haze experienced off the south-eastern Arabian coast from June to August was related to a large-scale dust flow that is thought to originate over the Horn of Africa and is part of the south-west monsoon circulation. Moreover, central Saudi Arabia had a moderate level of dust storm activity, with Riyadh recording an average of 7.6 dust storm days per year and an average of 76 days when blowing dust reduced visibility to less than 11 km.

An extended climatology following the methodology proposed by *Middleton (1986(a))* analysed the visibility reduction in the region and was published by *Kutiel and Furman (2003)* (Figure 6). They used eight "three-hour" mean values for each month for a period of 21 years (1973–1993) and concluded that Iraq, Saudi Arabia and the Gulf, were the regions reporting the greatest occurrence of dust storms. Dust storms in the Islamic Republic of Iran, north-eastern Iraq and the Syrian Arab Republic, the Gulf and southern Arabian Peninsula were more frequent in summer, while, in western Iraq and the Syrian Arab Republic, Jordan, Lebanon, northern Arabian Peninsula and southern Egypt, they occurred mainly in spring.

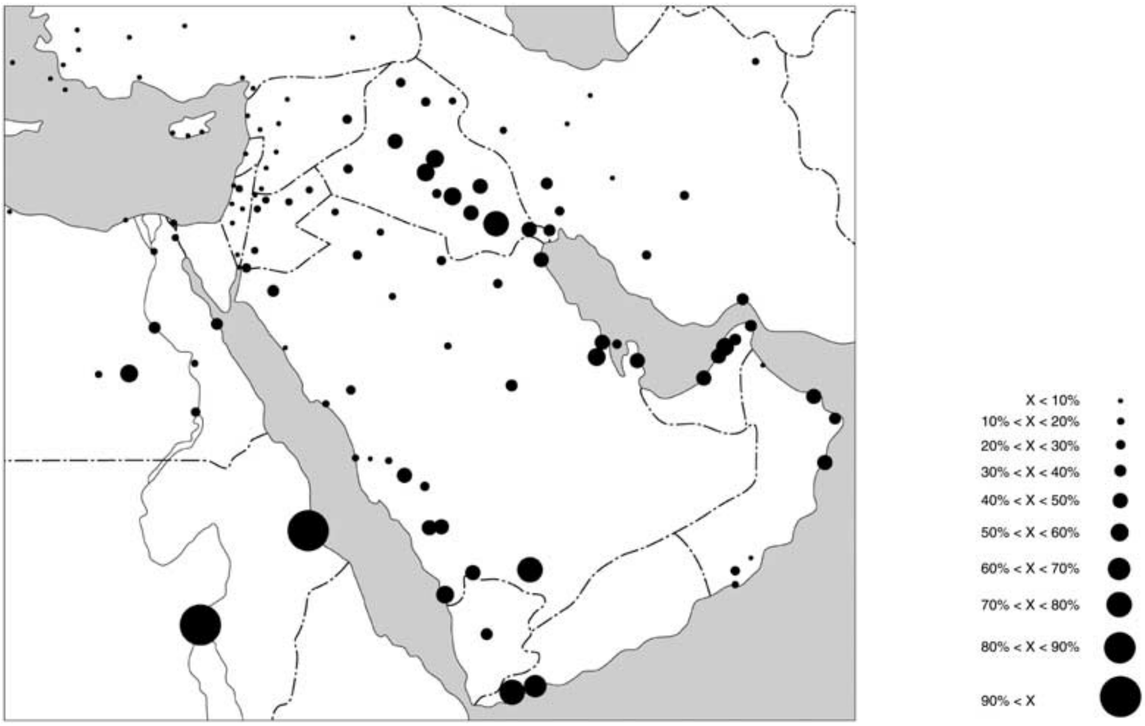


Figure 6 - Spatial distribution of maximum visibility reduction occurrence (in percentage of time): circle sizes are proportional to the percentage of visibility reduction (after *Kutiel and Furman, 2003*)

Idso (1976) identified Arabia as one of the five regions of the world where dust storm generation was especially intense. *Prospero and Carlson (1981)* reported that a major zone of dust haze was observed in the Arabian Sea during June, July and August and high levels of dust had been found off the Omani coast (*Tindale and Pease, 1999*).

In a second paper in 1986, *Middleton (1986(b))* focused his attention on a region located further east of West Asia, showing that the highest frequencies occurred at the convergence of the common borders between the Islamic Republic of Iran, Pakistan and Afghanistan (see Figure 7, after *Middleton, 1986(b))*. Another area with a high frequency of dust episodes was located on the Arabian Sea coast of the Islamic Republic of Iran (Makran) and across the Indus plains of Pakistan into north-west India. These data suggest that this region is one of the most important dust-raising areas in the world, exceeded in importance only by the Sahara, Arabia and the Taklamakan Desert of China (*Washington et al., 2003*).

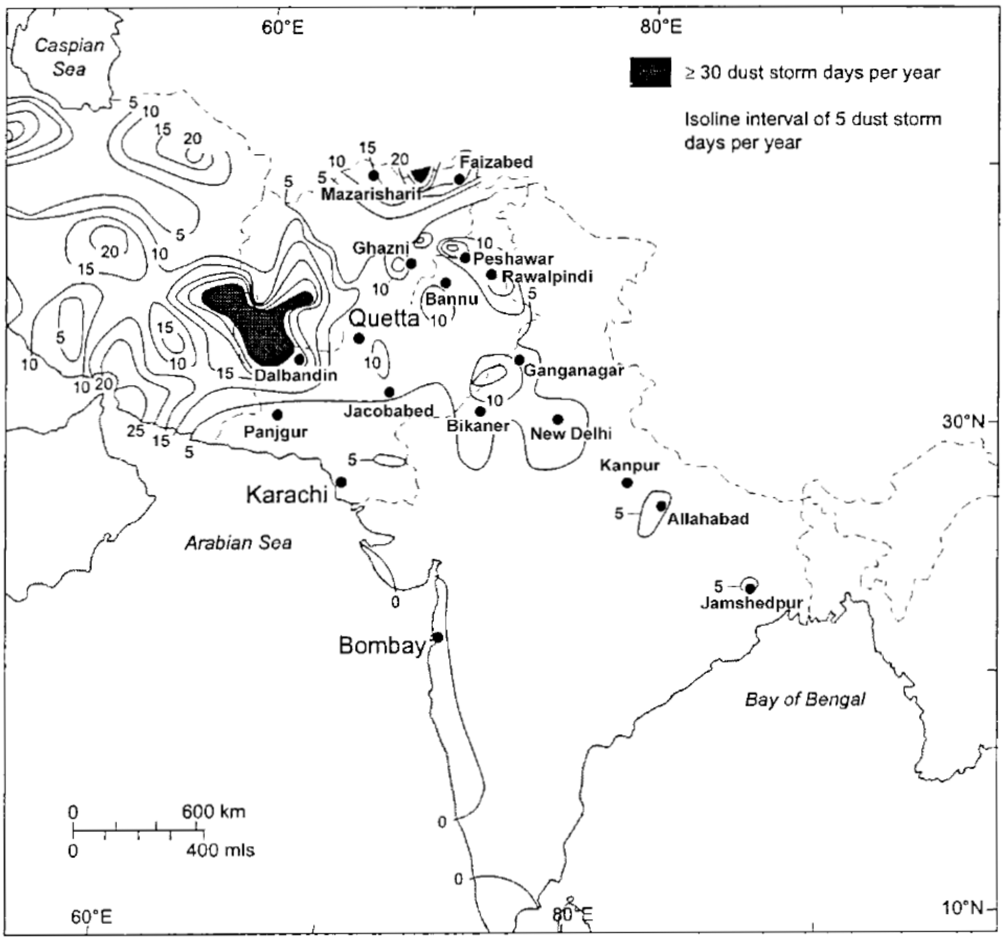


Figure 7 - The number of dust storm days per year, based on ground observations (after *Middleton, 1986(b))*

A global picture of dust concentration over Asia based on visibility reports is given in Figure 8. It stretches from the Arabian Peninsula to Mongolia and China (*Middleton, 1986(a); Leon and Legrand, 2003).* Within this dust belt, major dust activity is evident in the Arabian Peninsula, the Middle East and south-west and central Asia, including the Islamic Republic of Iran, Turkmenistan, Afghanistan, Pakistan, northern India, the Gobi Desert in Mongolia and the Tarim basin in China (*Shao and Dong, 2006*).

Tegen et al. (2002) calculated the difference between the simulated maximum lake areas and those of the present day, surmising that it was an indication of the extent of paleo-lake deposits formed under wetter climatic conditions. These areas are shown in Figure 9, as well as some major global dust sources in West Asia or nearby.

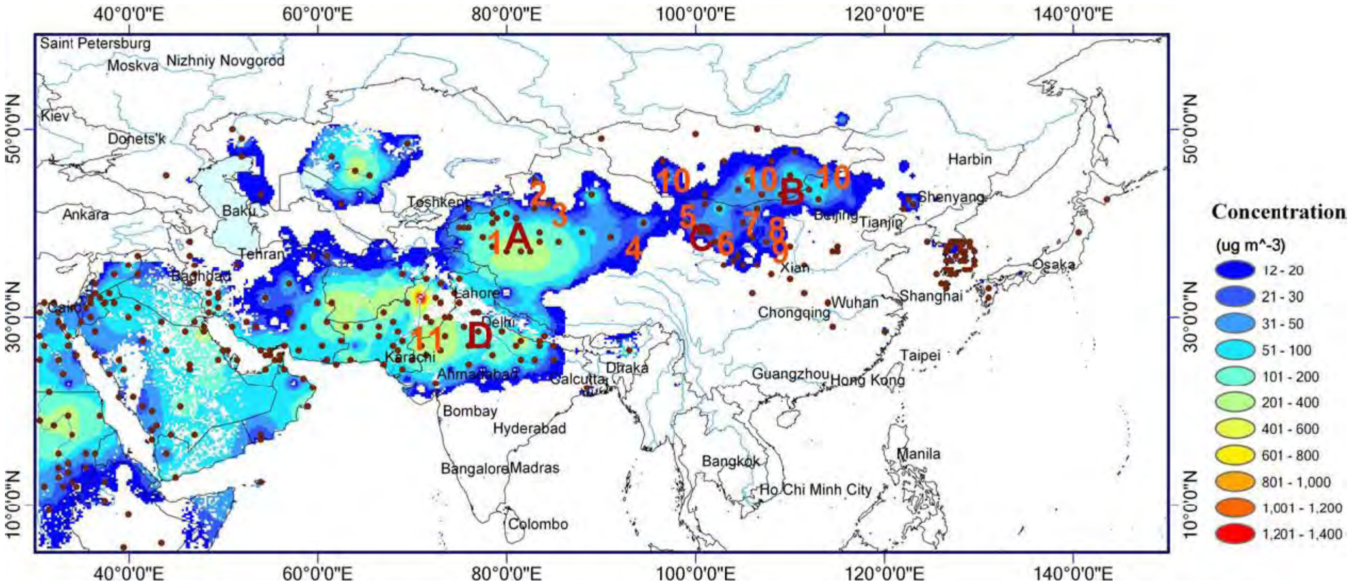


Figure 8 - Mean dust concentration (averaged over time) for Asia: data used for this graph are derived from visibility observations from 27 May 1998 to 26 May 2003 (reprinted from *Shao and Dong, 2006*)

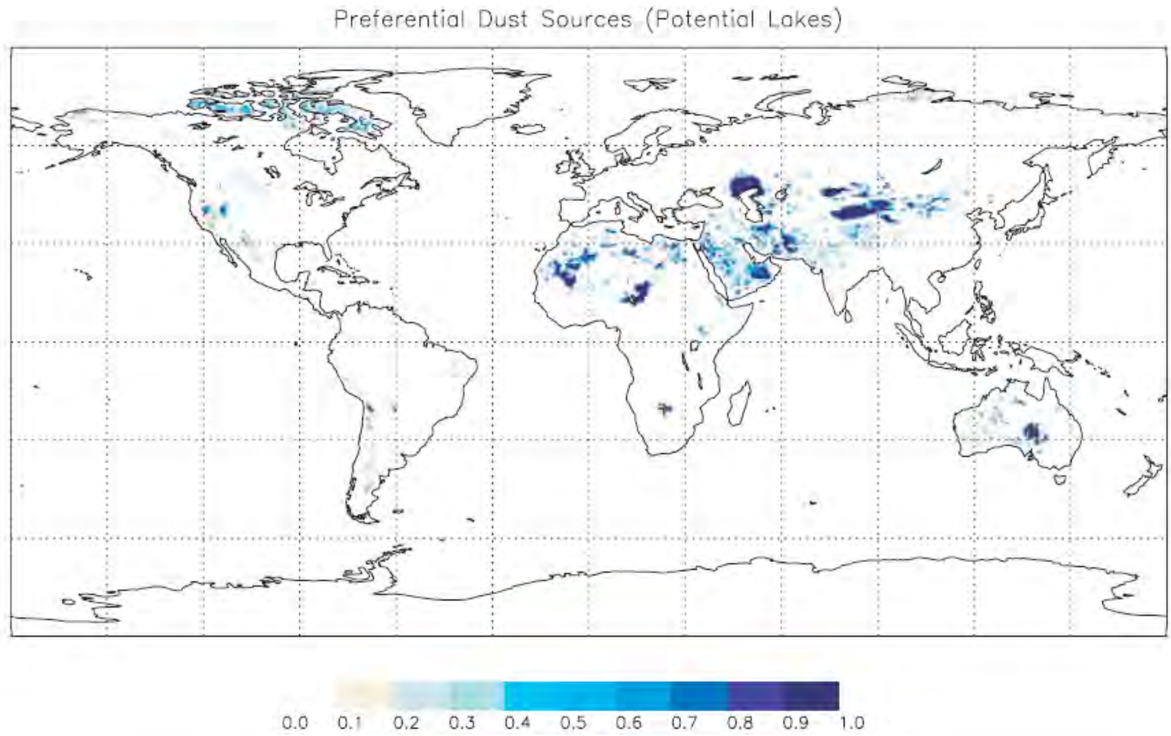


Figure 9 - Areal coverage of predominant dust sources, calculated from the extent of potential lake areas, excluding areas of actual lakes (modified from *Tegen et al., 2002*)

This first approach, using in situ observations, tends to be insufficient because it includes only a few, scattered observation sites throughout specific regions, as in the Middle East. The magnitude and geographic coverage of individual dust storms were not fully assessed until satellite imaging provided pictures of these events. Remote-sensing instruments have been incorporated into dust storm analysis and monitoring, mainly over the oceans: the Advanced Very High-Resolution Radiometer (AVHRR) (*Fraser, 1976; Husar et al., 1997; Durkee et al., 2000; Ozsoy et al., 2001; Díaz et al., 2001); Meteosat (Coudé-Gaussen et al., 1987; Moulin et al., 1997; Legrand* *et al., 2001*); Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) (*Husar et al., 2001; Falke et al., 2001; Moulin et al., 2001; Viana et al., 2002*) and Moderate Resolution Imaging Spectroradiometer (MODIS). Other sensors allowed the researchers to obtain semi-quantitative estimations of dust storm intensities and dust sources over land. The first instrument to provide unique and valuable information on atmospheric mineral dust over continental surfaces was the Total Ozone Mapping Spectrometer (TOMS) (*Herman and Celarier, 1997; Chiapello et al., 2000; Torres et al., 2002*). The Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board Meteosat Second Generation (MSG) (European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)) satellites provides 20 times more information than former Meteosat sensors. A key feature of SEVIRI-MSG is its continuous imaging of the Earth in 12 spectral channels with a baseline repeat cycle of 15 minutes. The imaging sampling distance is 3 km at the sub-satellite point for standard channels, down to 1 km for the high-resolution visible (HRV) channel. It constitutes a unique platform for monitoring and tracking dust storms and is extremely valuable for dust nowcasting, point-dust source identification and research analysis (*Schepanski et al., 2007; Martínez et al., 2009; Ashpole and Washington, 2012; Eissa et al., 2012*).

Figure 10 shows the global distribution of dust sources as derived from TOMS (*Engelstaedter et al., 2006*), which indicates that the major dust-sources are in the desert regions of the northern hemisphere, in the so-called "dust belt" that extends from the eastern subtropical Atlantic eastwards through the Sahara Desert to Arabia and West Asia. In fact, the latter is considered the second source of atmospheric dust, on the global scale, after the Sahara.

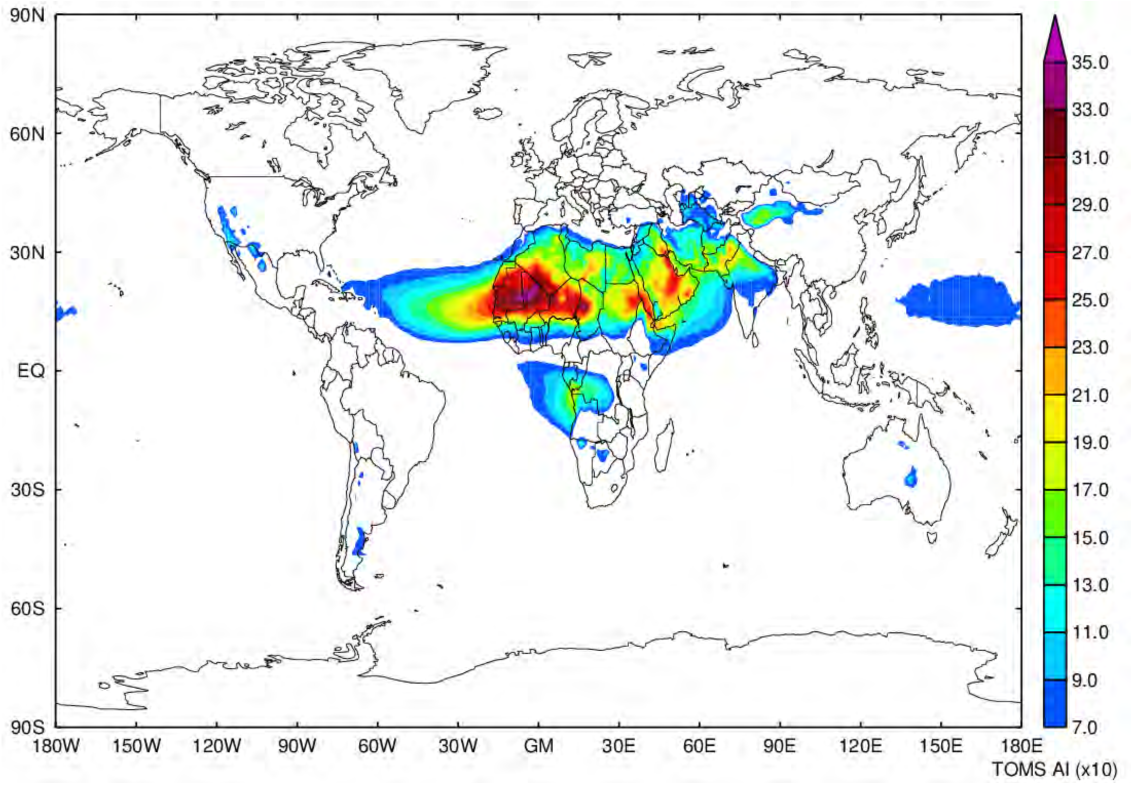


Figure 10 - May–July seasonal mean for the period 1980–1992 of aerosol index (AI) derived from TOMS satellite observations, showing the main dust sources on the global scale forming the dust belt (after *Engelstaedter et al., 2006*)

Prospero et al. (2002) found good agreement between the absorbing aerosol index (AAI) derived from TOMS-AI and topographic depressions (Figure 11), which is a further indication of the importance of dry lake areas for global dust emissions. Using TOMS-AI, they showed that dust sources, regardless of size or strength, can usually be associated with topographical lows located in arid regions with annual rainfall less than 200–250 mm. Although the source regions themselves are arid or hyper-arid, the action of water is evident from the presence of ephemeral streams, rivers, lakes and playas. Most major sources have been intermittently flooded through the

Quaternary period, as evidenced by deep alluvial deposits. Some dust sources in West Asia are associated with areas where human impacts are well documented, e.g. the Caspian and Aral Seas and the Tigris-Euphrates basin.

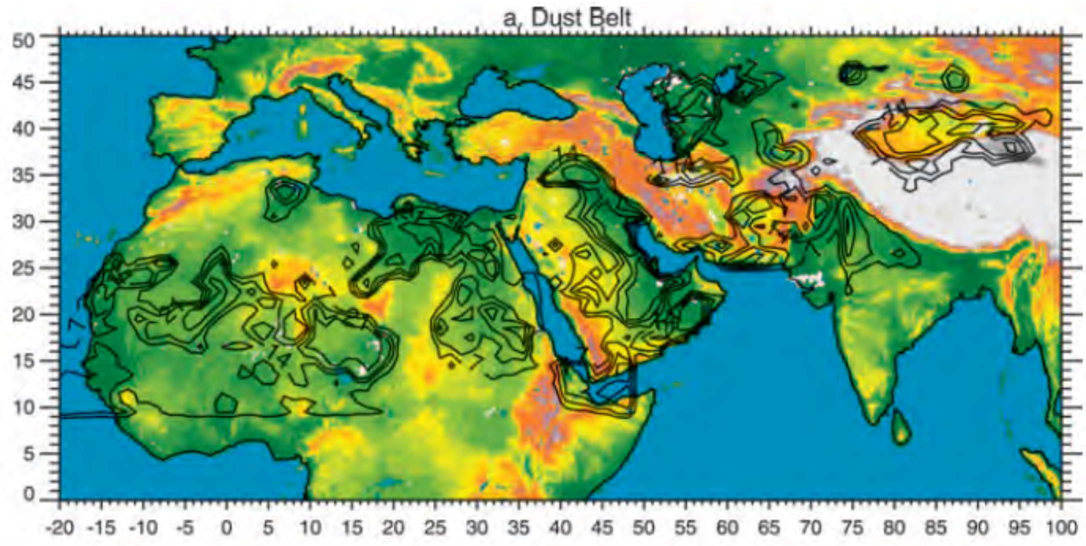


Figure 11 - Dust sources in the global dust belt and their association with topographic relief. This figure is a composite of selected monthly mean TOMS-AAI frequency of occurrence distributions (days per month when AAI equals or exceeds 1.0), shown as isolines on a topographic map (10-min resolution dataset from the US Navy Fleet Numerical Oceanography Centre, Monterey, California. Salt and dry lakes are shown in white (after *Prospero et al., 2002*)

Hickey and Goudie (2007), using TOMS and MODIS data, later identified two additional sources in the Middle East and South-West Asia: the Sistan basin and the Tokar Delta (Sudan). The Sistan basin is an internal endorheic basin with active deflation of lake and deltaic sediments encompassing large parts of south-western Afghanistan and the south-eastern Islamic Republic of Iran: one of the driest regions in the world and one subjected to prolonged droughts. The Tokar Delta is a large alluvial system produced by the Baraka River and is also in an arid area. Both areas are associated with rivers that carry exceptionally heavy silt loads and have a highly seasonal and vigorous dust regime which occurs in the dry, hot and windy summer. The Sistan basin and the Tokar Delta highlight the importance of wind funnelling and contribute substantially to dust intrusions over Pakistan/ Islamic Republic of Iran and the Red Sea, respectively.

In some cases, a combined strategy of satellite-based information and in situ observations has been used to determine high-resolution dust sources as performed by *Pease et al. (1999).* They used sand samples and Landsat imagery to characterize the spatial distribution of sand mineralogy, and to evaluate potential sources and transport pathways of sediment in the Wahiba Sand Sea in Oman.

Through mesoscale atmospheric modelling over the Red Sea, *Jiang et al. (2009)* identified two types of coastal mountain-gap wind jets that frequently blow across the longitudinal axis of the Red Sea: (a) a summertime eastward-blowing daily wind jet originating in the Tokar Gap on the Sudanese Red Sea coast; and (b) wintertime, westward-blowing wind-jet bands along the north-western Saudi Arabian coast, which occur every 10–20 days and can last for several days. Both wind jets can attain speeds of more than 15 m/s, driving dust storms/plumes over the Red Sea surface and thus contribute to dust transport in the Middle East.

Abuduwaili et al. (2010) emphasized the importance of saline dust storms, a kind of chemical dust storm originating in dry lakebeds in arid and semi-arid regions, whose characteristics are different from common dust intrusions in deposition flux and chemical composition. They identified the following areas of saline dust sources that might affect West Asia: the Aral Sea (Uzbekistan), Kara Bogaz Gol (Kazakhstan), Dead Sea (Israel/Jordan), seasonal salty wastelands (Iraq), Gulf sabkha (Saudi Arabia) and Hamun-i-Mashkel (Islamic Republic of Iran).

Walker et al. (2009) constitutes probably the most comprehensive and detailed approach to the identification of dust sources in South-West Asia. Numerous high-resolution (1 km or better) images from satellite remote-sensing platforms (i.e. space shuttle, SeaWifs and MODIS) show that dust plumes on the scale of 100 km originate from the merging of a multitude of point source plumes. The derived 1-km dust enhancement product (DEP) allows dust elevated over land to be readily distinguished from other components of the scene and the identification of many small, eroding point sources that form the heads of point source plumes. On the basis of this approach, a high-resolution (1 km) dust source distribution (DSD) database has been created, using five years (2001–2005) of DEP imagery for West Asia.

Figure 12 shows the US Naval Research Laboratory (NRL) DSD expressed as a grid erodible fraction (0.0–1.0) on a 27-km grid. Nearly all the major dust-source regions that have been identified for West Asia by station data analysis and in annual mean TOMS-AI values are present in the NRL DSD. The following three areas, not highlighted by *Middleton (1986(a) and (b)), Prospero et al. (2002)* and *Washington et al. (2003),* have been identified by *Walker et al. (2009):* (a) the eastern slopes at the foot of the Sarawat Mountains of Yemen; (b) along the slopes and at the foot of the Beyanae Kerman and Pir Shoran mountain ranges of the Kerman Desert, Islamic Republic of Iran; and (c) east and west of the Sarlath and Khwaja Amran mountain ranges in Afghanistan.

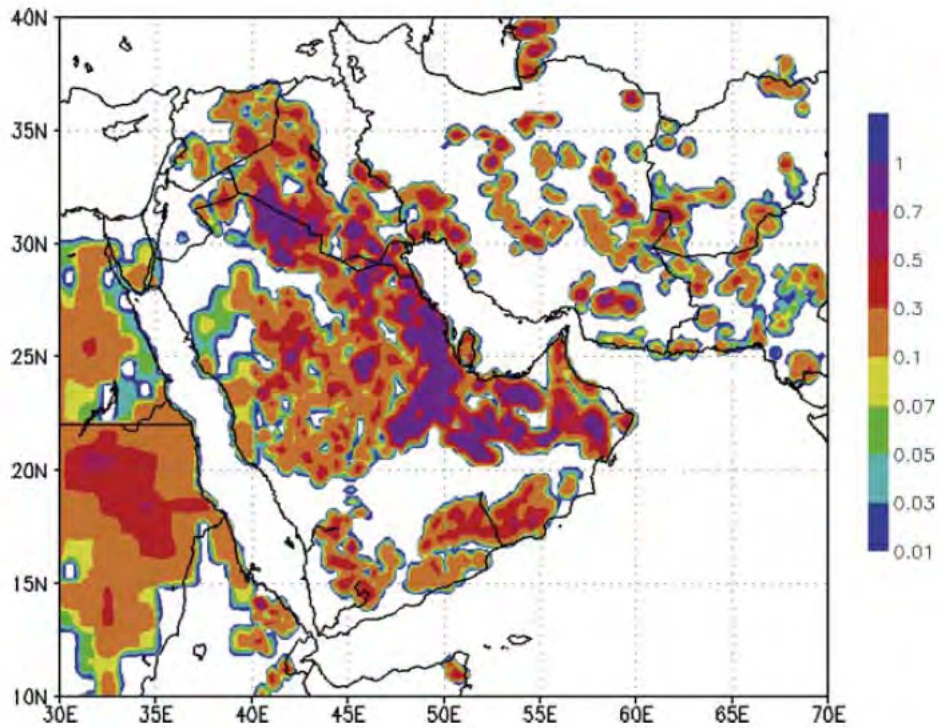


Figure 12 - US NRL DSD for the 27-km grid domain expressed as grid erodible fraction (0.0–1.0): African dust sources derived from TOMS DSD (after *Walker et al., 2009*)

Ginoux et al. (2012) performed a global-scale, high-resolution (0.1°) mapping of sources based on MODIS Deep Blue (DB) estimates of dust optical depth (DOD) in conjunction with other datasets, including land use (Figure 13). This high-resolution dust-source mapping, together with better mapping of threshold wind velocities, vegetation dynamics and surface conditions (soil moisture and land use) will facilitate the accurate estimation of dust emission in West Asia.

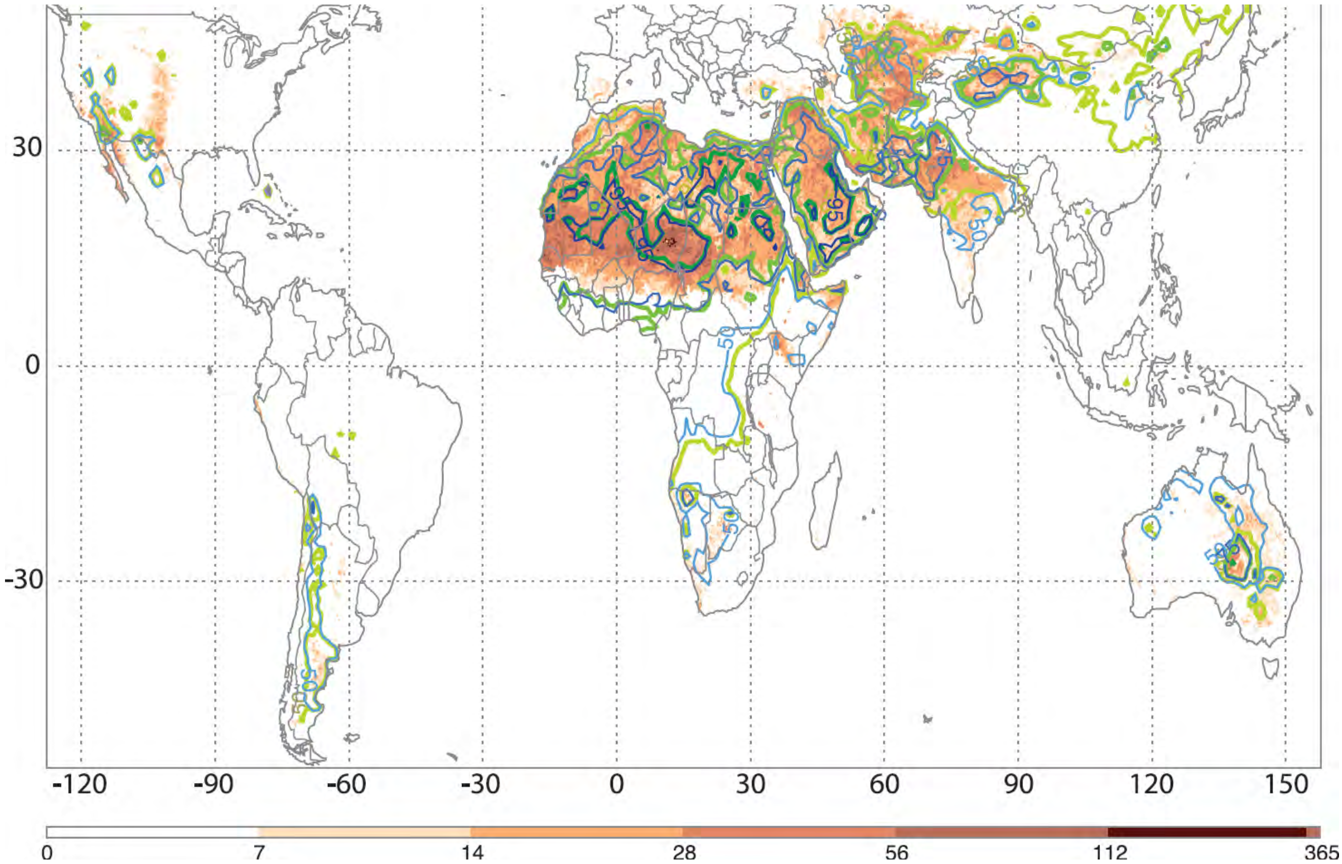


Figure 13 - Annual mean frequency distribution of MODIS DB (2003–2009) aerosol optical depth (AOD) (red field), TOMS (1980–1991) AI > 0.5 (blue) and Ozone Monitoring Instrument (OMI) (2004–2006) AI > 0.5 (green). The isocountours of TOMS and OMI have been removed over oceans for clarity (after *Ginoux et al., 2012*)

Focusing on the Middle East, *Ginoux et al. (2012)* identified the dust sources given in Figure 14. As shown below, in Section A.2.6, most of them fit quite well with AOD climatology derived from Multi-angle Imaging Spectroradiometer (MISR) satellite sensor observations and with AOD/DOD climatologies obtained with model (MACC and NMMB/BSC-Dust) reanalysis.

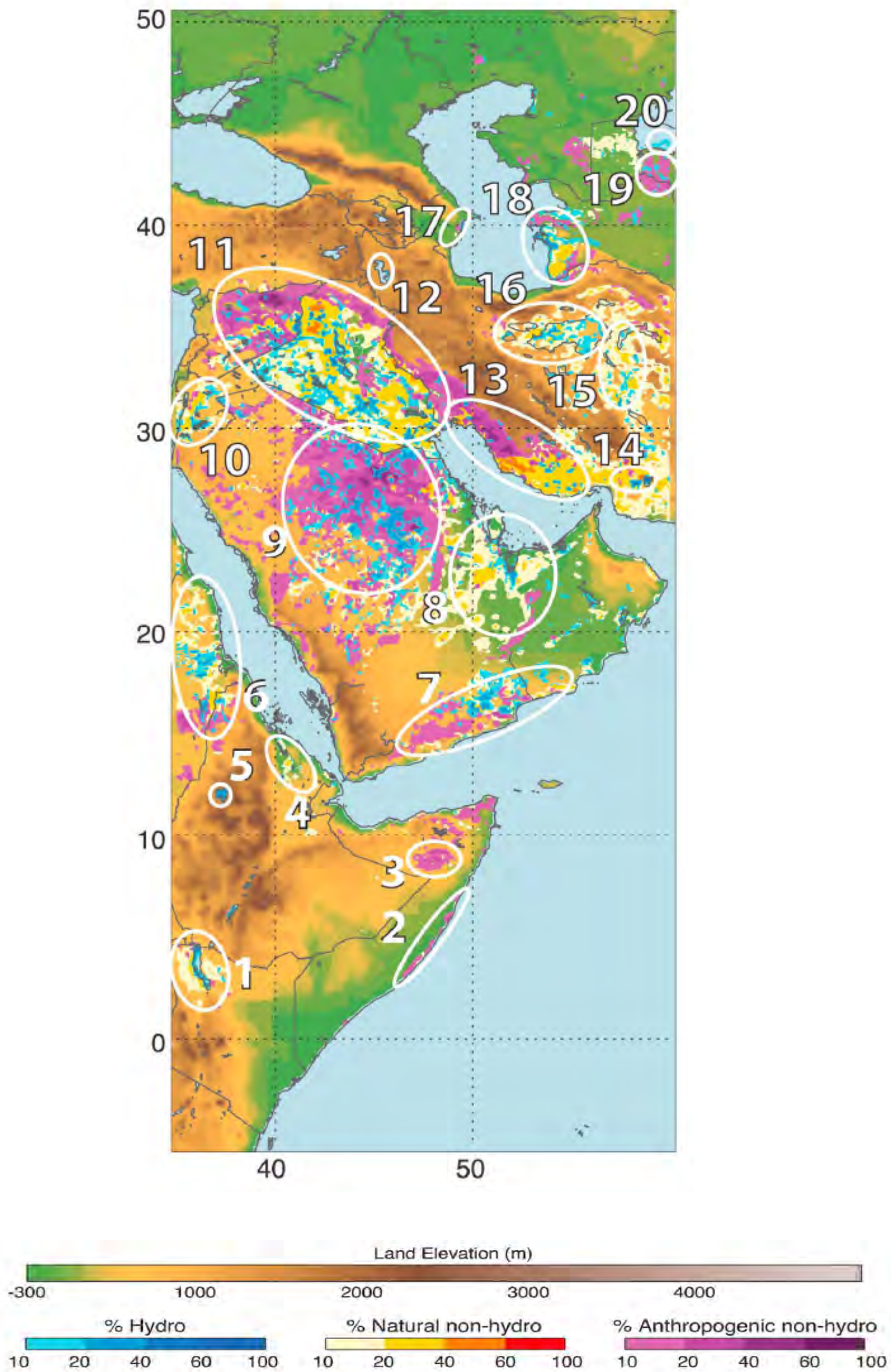


Figure 14 - Distribution of the percentage number of days per season (March, April and May) with DOD from MODIS DB > 0.2 over the Middle East: the sources in white circles are numbered as follows: 1 – Chalbi Desert (Kenya); 2 – coastal desert of Somalia; 3 – Nogal Valley (Somalia); 4 –Danakil Desert (Ethiopia); 5 – Lake Tana (Ethiopia); 6 – north-eastern Sudan; 7 – Hadramawt region (Yemen); 8 – Empty Quarter (Saudi Arabia); 9 – highlands of Saudi Arabia; 10 – Jordan River basin (Jordan); 11 – Mesopotamia; 12 – Urumia Lake (Islamic Republic of Iran); 13 – coastal desert of Islamic Republic of Iran; 14 – Hamun-i-Mashkel (Pakistan); 15 – Dasht-e Lut Desert (Islamic Republic of Iran); 16 – Dasht-e Kavir Desert (Islamic Republic of Iran); 17 – Qobustan (Azerbaijan); 18 – Atrek delta (Turkmenistan); 19 – Turan plain (Uzbekistan); and 20 – Aral Sea (Kazakhstan-Uzbekistan) (after *Ginoux et al., 2012*)

The global picture of high-resolution dust sources can be validated, complemented and enriched with country-scale studies, such as that of *Al-Dabbas et al. (2011),* using statistics of suspended dust observations. In Figure 15, the monthly mean number of days with dust storms in the period 1971–2000 and the monthly mean of deposited dust (g/m^2) in the period 1993–2007 in Iraq are shown. Lower Mesopotamia is the most affected region. The origin of high atmospheric dust in Iraq is caused by local/regional dust resuspension, confirming that Lower Mesopotamia is one of the most significant dust sources in the Middle East.

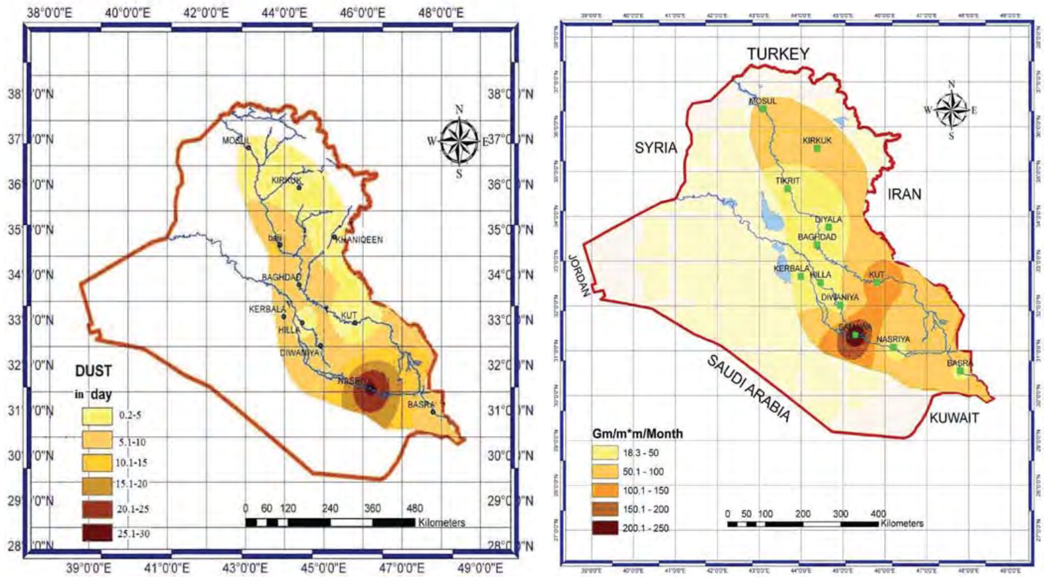


Figure 15 - Monthly mean number of days with dust storms in the period 1971–2000 (left) and monthly mean of deposited dust (g/m^2) in the period 1993–2007 period (right) in Iraq (after *Al-Dabbas et al., 2011*)

Keramat et al. (2011) showed an increase in dust sources over the Syrian Arab Republic and Iraq in the 20th century. In the period 1994–1999, the number of dust sources over this region was 14, which increased to 50 in the period 1999–2009. They do not explain the methodology followed for the identification of dust sources, however.

Recently, *Al-Dousari and Al-Awadhi (2012)* published an article in which the main sources of mineral dust and the path of dust storms in the north-west region of the Gulf are described (see Figure 16).

Gerivani et al. (2011) conducted a zoning of areas susceptible to dust sources in the Islamic Republic of Iran and Iraq, using geological maps and precipitation climatologies. Concerning eastern Islamic Republic of Iran, the comprehensive study performed by *Rashki (2012)* describes the dust sources in detail. The Sistan region is located in the south-east, close to the borders with Pakistan and Afghanistan. Severe droughts during the past decades, especially since 1999, have caused desiccation of the hamoun lakes that are located in the northern part of Sistan, leaving a fine layer of sediment that is easily lifted by the wind, thus making the basin one of the most active dust sources in South-West Asia. *Khoshhal Dastjerdi et al. (2012)* analysed the synoptic systems (western Islamic Republic of Iran) on dusty days at 11:00 UTC to identify the dust sources impacting this region, concluding that dust is mainly transported from Syrian Arabic Republic, Iraq and Saudi Arabia. *Ranjbar Saadatabadi and Azizi (2012)* obtained similar results from the case study of a strong dust storm. *Darvishi et al. (2013)* found two main dust storm sources affecting western Islamic Republic of Iran. The first is the area between the west bank of the Euphrates and the east bank of the Tigris and the second is the eastern and south-eastern Arabian Peninsula, a region called Rub' Al Khali (Empty Quarter). They determined how these dust sources impacted the western Islamic Republic of Iran using a combined approach of dust detection with remote-sensing techniques, hybrid single particle Lagrangian integrated trajectory (HYSPLIT) modelling, soil-texture, land-cover and wind-velocity data.

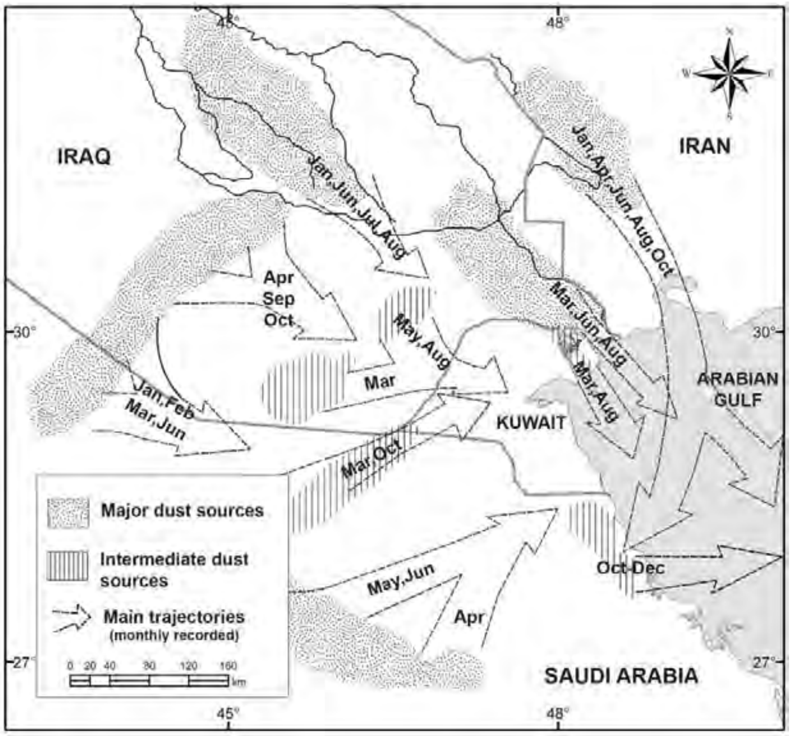


Figure 16 - Major and intermediate sources of dust and their corresponding trajectories over north-western areas of the Gulf (after *Al-Dousari and Al-Awadhi, 2012*)

Turkey must be treated separately, since most of the dust intrusions impacting this country originate in the Sahara. According to *Kubilay and Saydam (1995)* and *Kubilay et al., 2000; 2003; and 2005*), most of the dust outbreaks recorded in Turkey originated in different regions of the Sahara, the most important being observed in spring. Dust flows from the south-east (northern Middle East) are infrequent, as can be seen in Figure 17 (right). No significant dust sources are found in Turkey.

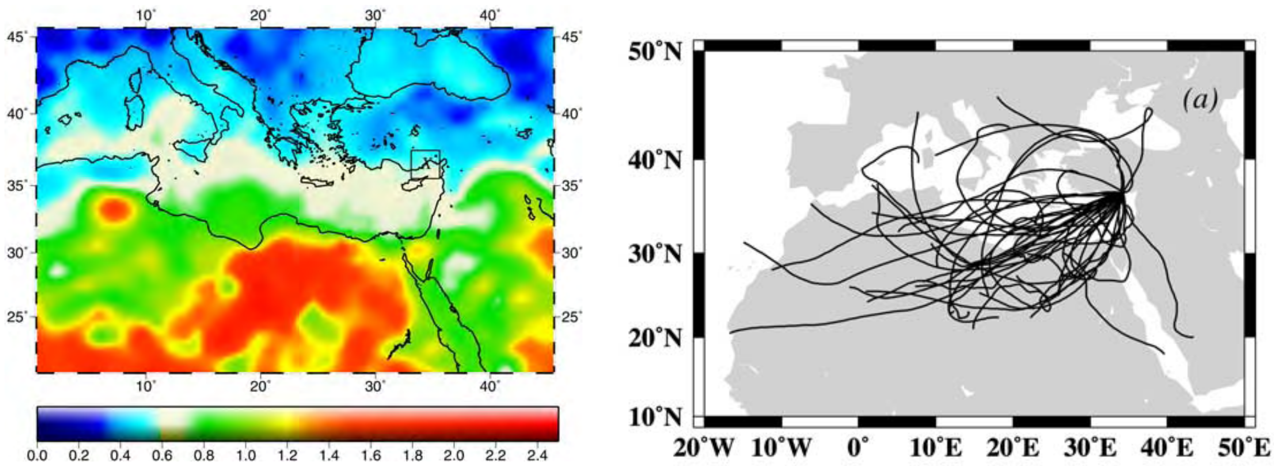


Figure 17 - April mean TOMS-AAI distribution obtained by averaging 21 years of daily data at each pixel of the analysis region (left). Three-day back trajectories for high-altitude transport events arriving at 700-hPa and 500-hPa pressure levels at Erdemli, Turkey represent selected events out of a total of 67 during 1991–1992 and 1996–2002 (right) (after *Kubilay et al., 2005*).

A.2.2 Types of dust storm

The atmospheric phenomena that produce dust events are on a variety of scales, including synoptic, regional, local, as well as turbulent, scales and can take a variety of forms. In West Asia, however, most of them can be classified within one of the following three types: shamal, frontal and convective. A detailed description of the different types of dust storm is given by *Wilkerson (1991).* A brief summary of this work and others follows.

A.2.2.1 The summer and winter shamal

The term *shamal* means "north" in Arabic (*Middleton, 1986(a)* and refers to the prevailing wind direction from which this type of dust storm comes. They are common across Iraq, Kuwait and the Arabian Peninsula. The shamal produces the most widespread hazardous weather conditions known in the region. They can be observed in summer and winter but the characteristics of the two are quite distinct.

The summer shamal is also known as the "wind of 120 days", since it blows almost daily during the entire summer from June to September. It has different names in different countries. For example, in Kuwait, the shamal is known as *simoon*, which means "poison wind" (*Middleton, 1986(a)).* It is basically generated by the following meteorological patterns: high pressure over northern Saudi Arabia, low pressure over northern Afghanistan and thermal low pressure associated with the monsoon over southern Saudi Arabia, producing and enhancing winds over the Gulf. A feature of summer shamal is that visibility on the ground rapidly (a matter of minutes) drops to near zero for one to three hours before increasing slowly. Another interesting feature of dust storms associated with summer shamal is that they move like giant walls of dust. The height of the walls can vary between 1 km and 2.5 km but, in some strong dust storms, can reach 4.5–5.5 km. Summer shamal dust storms can last from one to 10 days but, as they are caused by synoptic pressure systems, normally last three days. The most affected region by summer shamal is central and southern Iraq.

The winter shamal normally originates from cold post-frontal systems and the associated dust storms are given local names such as *blat* (*Soltani, 1990)* or *belat* (*Middleton, 1986(a))* in southern Saudi Arabia. These dust storms are normally very strong and the dust is the best way of locating the leading edge of the cold front. They are well observed by infra-red imagery, which frequently shows a dome of dust covering a large part of the Arabian Peninsula. Dust storms from winter shamal also cause a severe reduction in horizontal visibility and near-zero visibilities are not uncommon. Typical surface winds of these dust storms are 30–60 km/h, but gusts can be higher than 75–90 km/h. The persistence of dust storms associated with winter shamal varies, depending on the frontal system movement, and is generally either 24–36 hours or 3–5 days. The 24–36 hour shamal occurs when a frontal system migrates across the region (Figure 18: the associated dust outbreaks move across the length of the Gulf in 12–24 hours and can arrive at the southern coast of the Arabian Peninsula and Islamic Republic of Iran within 48–72 hours (*Wilkerson, 1991*). The "short-time" winter shamal is relatively common and occurs 2–3 times a month. When a cold front becomes stationary over the region, however, the dust outbreaks can last 3–5 days (*Perrone, 1979*). These "long-time" winter shamal episodes occur 1–3 times each winter, producing the strongest winds and highest seas in the Gulf.

A few winter shamal events are not associated with frontal systems but are caused by the funnelling of very cold air masses from Turkey or the Syrian Arab Republic southwards along the Tigris/Euphrates River valley in Iraq and over the Gulf (*Wilkerson, 1991*). They result in a narrow tongue of cold, dry and gusty winds, known as a "density current head" (*Lawson, 1971*), forcing warmer air and dust in its path aloft.

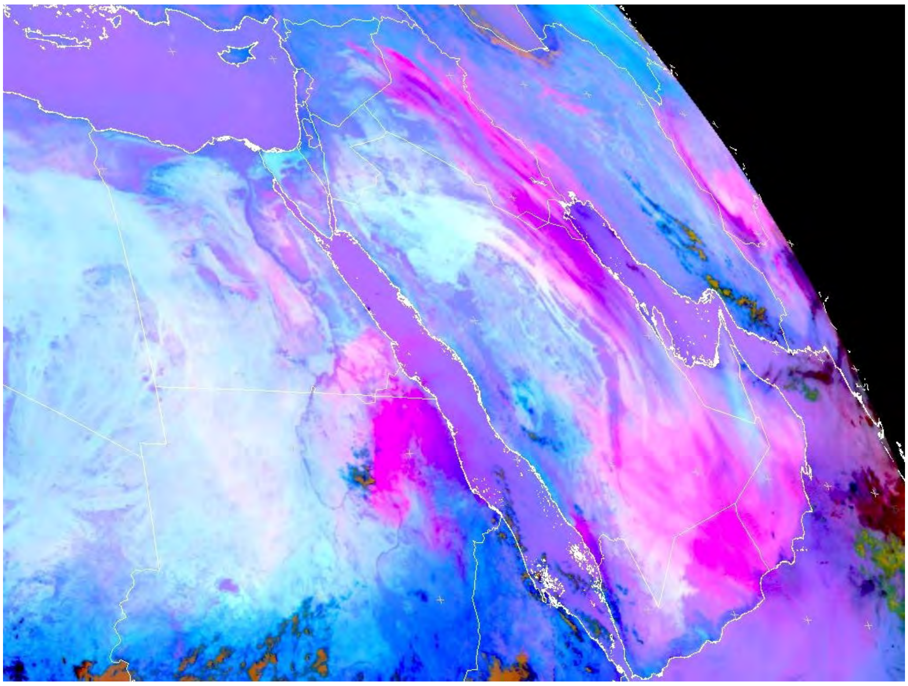


Figure 18 - A three-day summer shamal dust storm over Iraq and the Arabian Peninsula: dust is observed in pink with a tone more intensive the higher the dust content in the atmospheric column (17 June 2008, 08:00 UTC, Meteosat-9, EUMETSAT)

A.2.2.2 Frontal dust storms

Frontal storms mix the dust in the air and transport it great distances. There are three types of frontal dust storms: prefrontal, postfrontal and shear-line.

Prefrontal dust storms take place across Jordan, Israel, the northern Arabian Peninsula, Iraq and western Islamic Republic of Iran as low-pressure areas move across the region (Wilkerson, 1991). The polar jet (PJ) and the subtropical jet (STJ), associated with a front, play an important role in lifting dust aloft (Figure 19). The PJ behind the front and STJ in front of it often converge into a single maximum jet. The overlapping of the jet scores and coupling of secondary circulations in the right rear of the PJ and left front of the STJ enhance upper vertical velocities and increase lifting of the blowing dust (Figure 20). A good example is given in Figure 21.

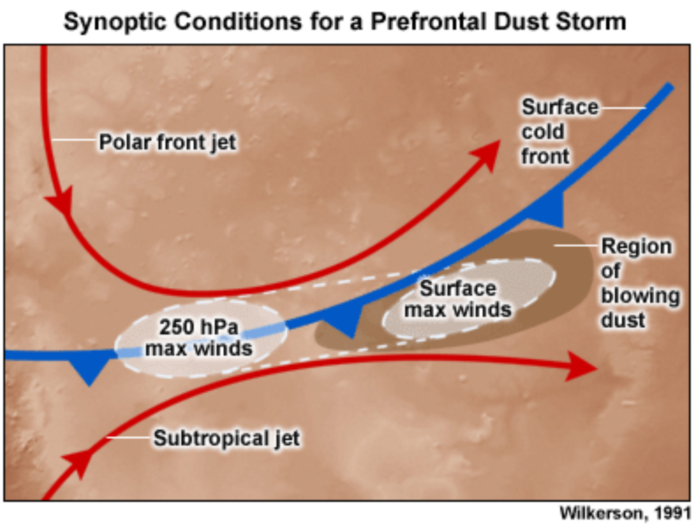


Figure 19 - Polar jet and subtropical jet in a prefrontal dust storm (from *Wilkerson, 1991*) (COMET project: www.meted.ucar.edu/mesoprim/dust/print.htm)

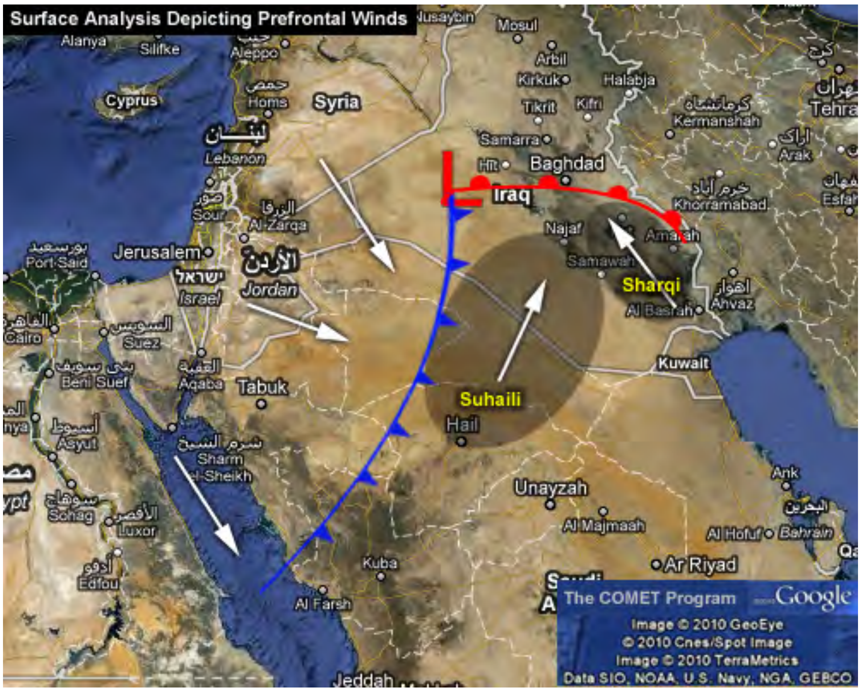


Figure 20 - Prefrontal dust storm over the Arabian Peninsula
(COMET project: www.meted.ucar.edu/mesoprim/dust/print.htm)

Prefrontal winds are known as *sharqi* in Iraq, *kaus* in Saudi Arabia, *shlour* in Syrian Arab Republic and Lebanon and *khamsin* in Egypt (*Middleton, 1986(a)).* Most of these winds are south-easterly. *Soltani (1990)* reported on the dry south-westerly *suhaili*, which occurs after the *kaus*, and extends across Jordan, northern Saudi Arabia, Iraq and Kuwait. Wind speeds associated with prefrontal dust storms are 20–40 km/h with occasional gusts of 45–55 km/h, normally lower than those of the summer and winter shamal (postfrontal winds) (*Wilkerson, 1991*).

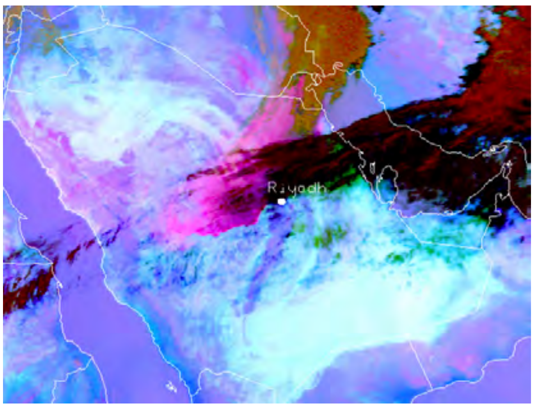


Figure 21 - Dust storm outbreak affecting Riyadh, Saudi Arabia, on 10 March 2009 at 09:00 UTC, showing the presence of PJ and STJ (left) (source: Meteosat-9): the dust storm disrupted flights at the city's King Khalid International Airport and the weather authorities announced that visibility dropped to zero (photograph: *Jad Saab/AP*)

Postfrontal dust storms (Figure 22) occur during the winter months, when shamal conditions exist behind a cold front. As the front moves across the dust-source regions of Iraq or Saudi Arabia, widespread dust is generated by the winds behind it.

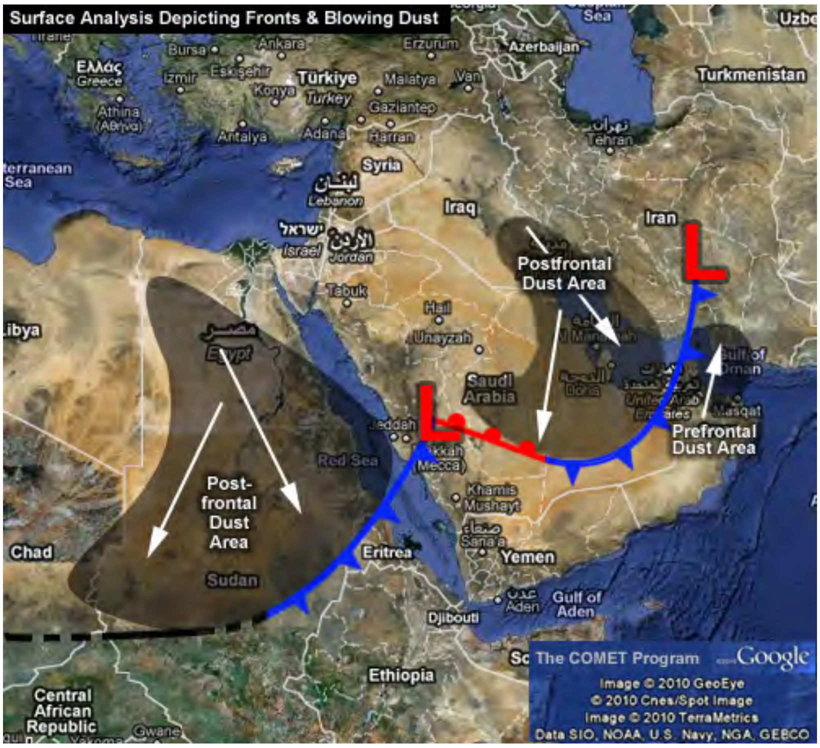


Figure 22 - Postfrontal dust storm over the Arabian Peninsula and North Africa (COMET project: www.meted.ucar.edu/mesoprim/dust/print.htm)

Another mechanism that causes dust storms is that of shear lines, which are frequent in winter across the Arabian Peninsula and the Red Sea. Shear lines are the result of the convergence of north-easterly wind flow to the south of a polar high-pressure cell and the easterly trade-wind flow. A narrow band of maximum winds that lifts dust into the air is found along the shear line as it moves slowly southward. Wind speeds along a shear line typically fall within the 20–45 km/h range with gusts of 55–75 km/h. Sometimes, moisture creates narrow clouds along the convergent frontal zone, with blowing dust to the northern side of the cloud (*Wilkerson, 1991*).

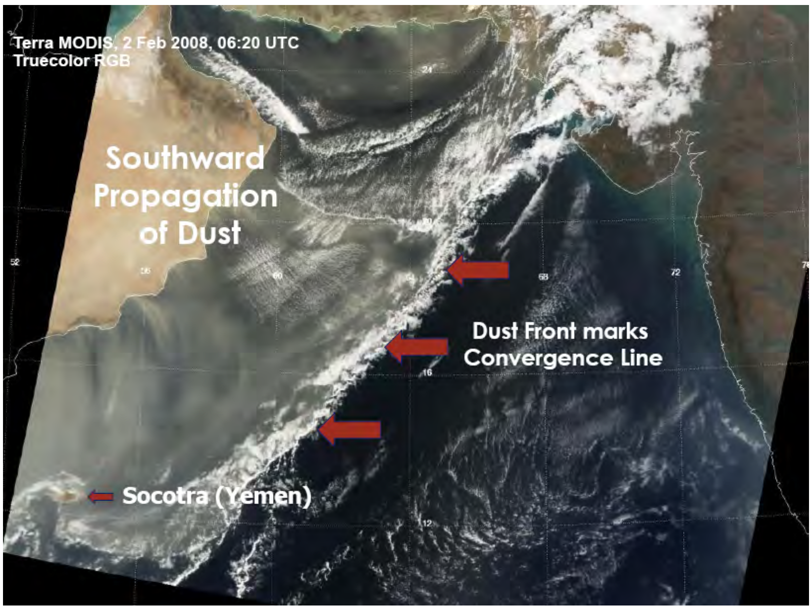


Figure 23 - Example of a shear-line dust storm over the Arabian Peninsula and the Arabian Sea as a cold front weakens across Pakistan/north-western India (source: Jochen Kerkmann (EUMETSAT), presentation of the EUMETSAT/WMO Virtual Training Week on Detecting/Nowcasting/Forecasting Dust Clouds using Satellite Data (March 2010))

A.2.2.3 Convective dust storms

There are basically three types of convective dust storms: haboobs, dust devils and inversion downburst storms. Of a much smaller spatial scale than frontal and shear-line storms and occurring on much shorter temporal scales, convective dust storms are difficult to monitor and forecast.

Haboobs are essentially strong dust storms generated by downward rush winds from a thunderstorm, resulting in a giant wall of dust associated with the outflow boundary (Figures 24 and 25). A typical scenario is a severe thunderstorm developing over Saudi Arabia and moving towards the Gulf. The mechanism of a haboob is the following: as cool air sinks and heavy rains bubble out under a thunderstorm, a zone of stronger winds in the mesoscale high-pressure area is created. Because of the very dry desert environment, the raindrops evaporate before reaching the ground. The strong winds of subsiding air form a "blast wave" lifting up large amounts of dust – even sand – and rapidly rising and changing dust towers can be seen at the same time along the leading edge of the haboob (*Powell and Pedgley, 1969*). This mechanism is similar to that of the density currents described earlier in winter shamal events. The formation and propagation of density currents are well-studied processes in fluid dynamics. Normally, a haboob moves at 45 km/h, but wind inside can reach 90 km/h.

Figure 24 - A sandstorm enveloping a gas rig near Dammam in eastern Saudi Arabia (source: http://www.desertaquaforce.com)

Figure 25 - Haboob at Al Asad, Iraq, 2007 (*James Gordon, Flickr*)

The formation of a convective cool pool and the associated dust mobilization, as well as the physical processes involved in the mobilization of dust, are well described for a representative event over the western part of the Sahara by *Solomos et al. (2012).*

Haboobs are relatively small (usually covering no more than 100–150 km) and move quickly. Their average height ranges from 1.5 to 2.5 km, but much higher ones (3-4 km) have been reported in North America (*Idso et al., 1972*). Visibility is drastically reduced to 200 m – even less inside the haboob (*Lawson, 1971*) – increasing some three hours (average duration) after the gust front passes. Most of the dust particles range from 10 to 50 µm (*Lawson, 1971*), but larger particles (up to several millimetres) can be blown about (*Foster, 1969*). The larger particles settle rapidly by gravity after the wind subsides, whereas the finer ones settle at about 300 m/h, when the haboob finally dissipates. Haboobs are much more difficult to forecast than synoptically forced dust storms and rely largely on nowcasting. *Miller et al. (2008)* analysed in detail the haboob activity common in this region. They used multidisciplinary observations (satellite, radar, lidar and meteorological station network observations) from the United Arab Emirates Unified Aerosol Experiment (UAE^2), an extensive field programme conducted over the south-eastern Arabian Peninsula during the summer of 2004. They provided an idealized model of haboob dust production, concluding that haboobs could be responsible for a significant component of the total regional-scale dust production (up to 30% over a 1 000 × 1 000 km domain).

Dust devils are small cyclonic circulations formed in arid climates when a strong lapse rate coincides with strong surface heating. Dust devils lift dust, sand and even small bushes up to heights that range from a few metres to 1–2 km. Dust dissipation is quite fast. They are quite small, ranging from a few metres to several hundred metres in diameter with a short lifetime and occur sporadically across the desert, making it impossible to forecast them (they can be easily avoided, however, since they are clearly visible). The only solution is to determine the most favourable conditions for their formation. Surface conditions must be very dry and air temperature must reach about 27°C. A weak gradient, with light and variable wind is most favourable. Skies are normally clear or with high cloud. Over slightly sloping ground, dust devils tend to move towards higher terrain.

Inversion downburst storms are convective windstorms that occur on sloping coastal plains with a strong sea breeze. As this intensifies, convergence along the front can generate sufficient lift to break a capping inversion. This potential instability results in the downward mixing of cool air aloft, which flows downslope and out over the water. The descending air produces roll vortices and potentially severe local dust storms along the coast. The inversion is then re-established and the event dies out (COMET project: www.meted.ucar.edu/mesoprim/dust/print.htm). Inversion downburst storms are formed in coastal terrain where slopes are at least 3 m/km, such as those found along the Red Sea and the Gulf. They occur when the sea breeze exceeds 30 km/h and there is inversion aloft, but not a particularly strong one. The downburst winds last 15–45 minutes and reach speeds of typically 40–45 km/h. These storms are limited in size, although they can still reduce visibility to less than 2 km, depending on local surface-soil conditions. Inversion downburst storms typically lead to a narrow streamer of dust out over the Gulf.

Interesting case studies of different dust storms that have occurred in West Asia countries can be found. *Alharbi et al. (2012)* analysed a huge dust storm over Saudi Arabia in March 2009, which was triggered and sustained by a cold front passage coincident with the propagation of a pre-existing intense upper-level jet stream. *Monikumar and Revikumar (2012)* analysed the meteorological causes for the occurrence of unprecedented widespread dust followed by a thunderstorm over Qatar and neighbouring areas of the Middle East on 4 February 2010. In this case, a cold-air high over Saudi Arabia initiated a north-westerly shamal, which triggered a dust event over parts of the Arabian Peninsula.

In general, environmental conditions favourable for the generation and transport of dust are potentially predictable at long lead-times (*Bartlett, 2004*):

- Wind at low levels (high speeds, direction that favours high speeds and turbulence, occurrence over and direction away from dust sources)
- Low precipitation
- Low relative humidity
- Low soil moisture
- High temperature at surface and low levels
- Turbulence at low levels
- Little land-surface vegetation
- Human disruption of the land surface.

A.2.3 Aerosol/dust concentration, size distribution and chemical composition

Modaihsh (1997) obtained some of the first results on the composition of aerosols in Saudi Arabia, especially in Riyadh. He analysed dust samples on a monthly or bi-monthly basis at eight different locations in Riyadh from March 1991 to February 1992 and concluded that fallout sediments are mainly represented by two textural classes – loam and silt loam – of which silt is the dominant fraction. Quartz and calcite were the dominant minerals in the dust samples. All the dust samples presented a high calcium-carbonate ($CaCO_3$) content ranging from 22% to 47% with an average of 32%. High values of $CaCO_3$ are typical of soils rich in limestone and dolomite, which are abundant in the calcareous soils of Saudi Arabia, particularly in the Arabian shelf. According to the author, similar results were reported in Iraq by *Kukal and Saadallah (1973),* who found that $CaCO_3$ was as high as 69% in dust storms. *Khalaf and Al-Hashash (1983)* also found that calcareous silt was the most abundant and frequent size class in Kuwait dust fallout. Another significant finding of *Modaihsh (1997)* was the elevated concentrations of heavy metals, such as lead, zinc, cadmium, nickel and cobalt, detected in the fallout sediments, that were caused by dense local vehicular traffic and also by the burning of oil fields in Kuwait. Researchers in Saudi Arabia (*Al-Tayeb and Jarrar, 1993*) reported similar results and conclusions. A mixture of mineral dust with heavy oil-derived components is therefore a permanent feature of aerosol/dust composition in much of Saudi Arabia.

UAE^2 undoubtedly provided an enormous amount of valuable scientific information about the composition of atmospheric aerosol in the Arabian Peninsula, although the results correspond only to summertime (Reid et al., 2005). Aerosol particle loadings provided by UAE^2 showed a clear dominance of airborne dust, with an important admixture of pollution aerosols. Typically, total suspended particulate (TSP) matter was of the order of 100–300 μg/m^3, with concentrations of particulate matter with diameter less than 10 μm (PM10) being about two-thirds of these values. Although dust in general is composed of clays and alumina-silicates, the authors reported that dust was enriched by shallow oceanic deposits, with oceanic carbonate deposits underlying most of the region. They recorded extremely high carbonate concentrations during some of the dustiest days. PM with diameter less than 2.5 μm (PM2.5), a key air-quality index, averaged 35 μg/m^3 during UAE^2 with a maximum value of up to 80 μg/m^3. In other pollution episodes, a co-existence of pollutants and mineral dust was observed. Another notable result was that pollution composition was surprisingly free of organic matter (Reid, 2005). According to these authors, simple ammonium sulphate accounted for nearly 60% of PM2.5 dry mass, followed by ~25% from coarse-mode dust. Only ~20% of mass can be contributed to black carbon (soot) or particulate organic matter. These results are consistent with the fact that most of the pollution comes from the petroleum industry and, in particular, from flares and power plants. The interaction of mineral dust with fresh pollution from petroleum-derived industry is a singular characteristic in aerosol samples and many areas of the Arabian Peninsula. Averaged apportionment of PM2.5 is shown in Figure 26.

According to *Reid et al. (2005),* although measured values for PM2.5 pollution are considered high compared to those in the USA and Europe, they are better than most other polluted regions of the world. We must take into account that these samples were taken in one of the worst air-quality months of the year when there is also a significant dust contribution. They also found a diurnal variation driven by the land-/sea-breeze regime, which influences significantly the relative vertical distribution of dust and brings, in turn, more complexity to the aerosol characterization.

Ross et al. (2005) provided information about the fine mode of aerosols from measurement stations on the UAE coast during UAE^2. They reported that ammonium sulphate is the most prevalent constituent of the fine-mode aerosol in the region (57% of the mass), followed by organic matter (13%), alumina-silicates (11%), calcium carbonate (9%) and black carbon (4%) (Figure 26). On the other hand, they concluded, from source apportionment, that most of the fine aerosol mass is derived from fossil-fuel combustion (72%), while mineral dust (20%) and local vehicle emissions (9%) also contribute to the fine aerosol loading. They argued that the dominance of sulphates means that the fine-mode aerosol in the region is probably responsible for a negative radiative forcing and that the polluting emissions significantly elevate the concentration of cloud condensation nuclei (CCN).

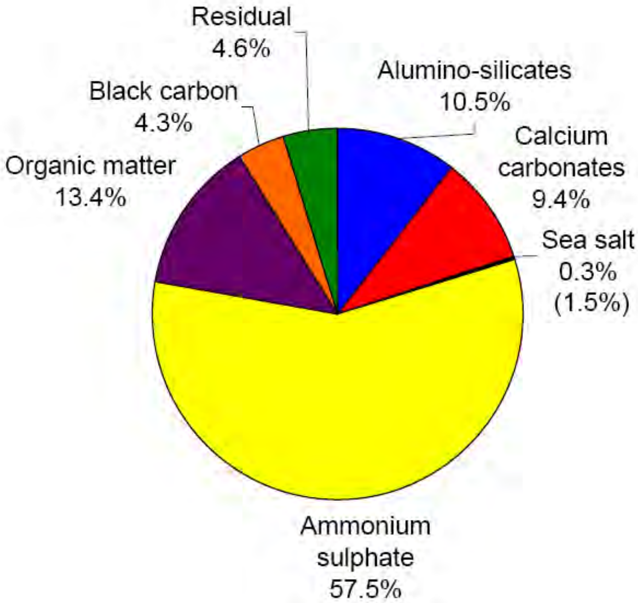


Figure 26 - Average apportionment of PM2.5 pollution during UAE^2 (from *Reid et al., 2005*)

Reid et al. (2008(b)) examined the characteristics of common mode dust (0.8 < diameter < 10 µm) finding experimental evidence that, on regional scales, common mode dust is not functionally impacted by production wind speed, but rather influenced by soil properties, such as geomorphology or roughness length. Similarly, they found that transport processes, from the mesoscale to near-synoptic scale, do not significantly impact common mode dust size, either. They found that coarse-dust mode had a median diameter in the order of ~3.5 µm ± 30%.

Elassouli (2011) found that the PM10 averages in Arafat and Muzdalifa near Jeddah (western Saudi Arabia) were 158 µg/m^3 and 444.5 µg/m^3, respectively, which exceeded the maximum daily threshold of 150 µg/m^3 established by the air-quality authority.

Khodeir et al. (2012) conducted a multi-week, multiple-site sampling campaign in Jeddah between June and September 2011 and analysed samples by X–ray fluorescence. The overall mean mass concentration was 28.4 ± 25.4 µg/m^3 for PM2.5 and 87.3 ± 47.3 µg/m^3 for PM10, with significant temporal and spatial variability. They found an average ratio of PM2.5/PM10 of 0.33. Concerning chemical composition, they found components from heavy oil combustion in both PM2.5 and PM10, characterized by high nickel and vanadium concentrations, re-suspended soil (mineral dust) characterized by high concentrations of calcium, iron, aluminium and silicon and a mixture of industrial source components. In PM2.5 they found lead, bromine and selenium – pollution typical of road traffic. In PM10, marine aerosol components were also present.

In Saudi Arabia, *Hyvärinen et al. (2013)* performed measurements of particle-size distribution from 7 nm to 850 nm at Hada Al Sham (21.8°N, 39.7°E, 254 m asl), situated about 60 km east of Jeddah, on the Red Sea coast. These measurements revealed a diurnal variation of the different particle-size modes, indicating that aerosols in Hada Al Sham have many sources, contributing to different sized particles. They concluded that new particle-formation events might be related to sulphate emissions from heavy oil combustion in western Saudi Arabia, such as from oil refining. These anthropogenic aerosols, mixed with mineral dust particles, are found during dust events.

Results from chemical composition of dust in Iraq, one of the major dust sources of the region, performed by *Al-Dabbas et al. (2011),* indicate that dust samples are composed mainly of silt (53%) and sand (19%). Most of the dust content was clay and silt with lower quantities of sand. The wind speed associated with a dust storm is critical for transporting dust particles of less than 63 µm in the dry season. Their results of the analysis with the X-ray diffraction method reflect that the recognized minerals are quartz, feldspar, calcite and gypsum. Clay minerals for the different slides were palygorskite, illiteillite, kaolinite, chlorite, montmorillonite and smectites. The presence of palygorskite and kaolinite reflects the arid and semi-arid climatic conditions. The formation of chlorite reflects an arid or semi-arid climate with an alkaline environment, while illite is common in desert soils.

In the Islamic Republic of Iran, *Keramat et al. (2011)* suggest the possibility of dust contamination with chemical, biological and radioactive components during the period 1980–1988. They indicate, for example, that the amount of elements such as uranium, thorium, arsenic, lead, zinc, nickel and cobalt in these samples is slightly higher than normal. They do not, however, provide a scientific reference supporting this assessment. *Shahsavani et al. (2012)* studied the average concentrations of PM10, PM2.5 and PM1 from April to September 2010 in Ahvaz, a city influenced to a considerable degree by dust transported from southern Iraq by the shamal. They reported average concentrations of PM10, PM2.5 and PM1 in Ahvaz over the study period of 320-407 $\mu g/m^3$, 70-83 $\mu g/m^3$ and 37-35 $\mu g/m^3$, respectively, but a peak concentration of 2028 $\mu g/m^3$ in July, indicating the huge dust concentrations that may be recorded in the region. *Shirkhani-Ardehjani (2012)* presented typical PM10 concentration values in several cities (Table 2). The annual PM10 concentration in most of the cities was >75 $\mu g/m^3$, representing a potentially high impact on human health.

Table 2 - PM10 concentrations in several Iranian cities in 1999 and in the period 2008–2009 (after *Shirkhani-Ardehjani, 2012*)

Dust Data

PM10 concentrations (micro grams per cubic meter)

City	city population 2000	PM10 Concentration 1999	PM10 Concentration 2008-2009	Max PM10 (In Dust Phenomenon 2009)
Ahwaz	943,666	81	301	9360
Bandar-e-Abbas	436,889	100	165	482
Bushehr	160,184	61	126	1348
Dezful	230,117	63	---	---
Ilam	155,792	52	---	2600
Kermanshah	758,273	59	---	1154
Khoramabad	315,972	66	---	2623
Masjed Soleyman	124,425	75	---	---
Orumiyeh	451,558	75	---	1425
Sanandaj	309,073	57	---	2603
Tabriz	1,328,504	69	---	923

The work of *Rashki (2012)* focused on the Sistan region (south-eastern Islamic Republic of Iran) but the results can be extrapolated to large areas of West Asia. He showed that, in descending order, quartz, calcite, muscovite, plagioclase and chlorite were the main mineralogical components of the dust present in all the selected airborne dust samples. In contrast, significantly lower percentages for enstatite, halite, dolomite, microcline, gypsum, diopside, orthoclase and hornblende were found, with these elements occurring in only some of the samples. On the other hand, silicon dioxide, calcium oxide, aluminium oxide, sodium oxide, magnesium oxide and iron (III) oxide were the major elements characterizing the dust, while large amounts of fluorine, chlorine and sulphur were also found as trace elements. *Rashki* illustrates how aerosols/dust sampled at two adjoining stations were quite similar but showed some differences in their composition as well as in the composition of the soil (Figure 27). These two stations are located to the south of Hamoun and to the north of Zabol city. Thus, chemical analysis of aerosols/dust is essential for knowing the origin of atmospheric dust and potential contamination with anthropogenic emissions. *Nabi Bidhendi and Halek (2007)* used six-stage high-volume cascade impactors to measure PM at 20 sites in the area of Tehran and obtained detailed measurements of aerosol size distribution in Tehran's atmosphere during 2004 at five sites. Results showed an interesting mix between mineral dust and city pollution, mainly from traffic.

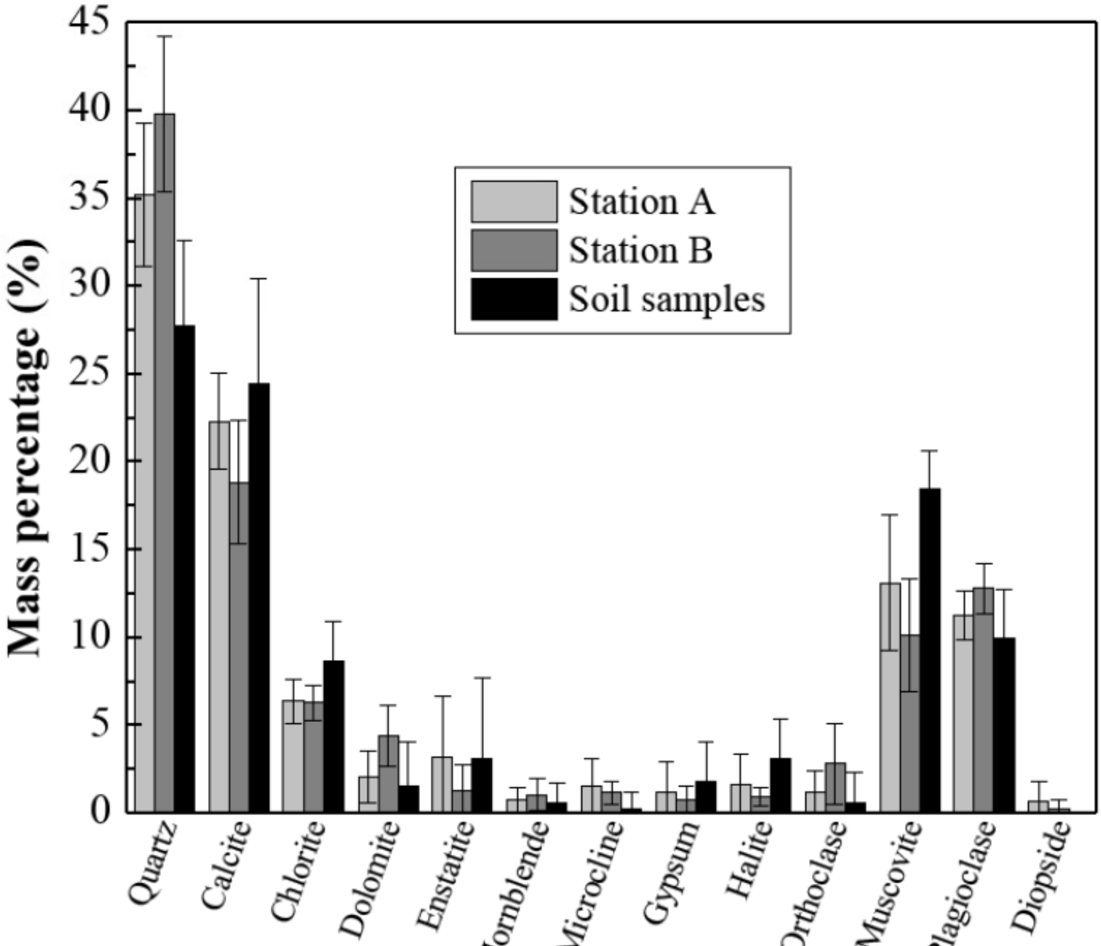


Figure 27 - Average mineralogy components for airborne dust samples at stations A and B and for soil samples obtained at various locations in the Hamoun basin: the vertical bars express one standard deviation from the mean (after *Rashki, 2012*)

Güllü et al., (2000) assessed the concentrations of elements and ions measured in aerosol samples collected between March 1992 and December 1993 in Antalya (Turkey), to understand temporal variability of elemental concentrations. They reported that strong, short-term variations of crustal elements, such as aluminium, calcium, potassium, scandium, titanium, manganese, iron, cobalt, rubidium, caesium, barium, lanthanite, samarium, cerium, ytterbium, lutetium and thorium are observed during spring and autumn. Two components of soil-related material are found in the eastern Mediterranean atmosphere, namely, dust transported from North Africa and re-suspended local soil. Episodic transport of dust from the Sahara Desert and arid regions of the Middle East are other important sources of crustal material observed in the eastern Mediterranean. *Koçak et al. (2007)* analysed PM2.5 and PM10 data at Erdemli, a rural site in Turkey. They observed that the highest levels of PM10 occurred in spring (March, April and May) due to mineral dust transported from North Africa and during winter from sea-spray generation. From source-apportionment analysis, they indicated that PM10 exceedances originated as a consequence of natural events (mineral dust ~40%; sea salt ~50%), whereas PM2.5 exceedances were accounted primarily by pollution events (in 90% of cases).

Nickovic et al. (2012(a)) developed a global dataset consisting of the mineral composition of the current potentially dust-producing soils. Because of the lack of sufficiently resolved information on the mineral content in sources, the current dust numerical models either do not simulate, or poorly simulate, the ways in which mineral fractions evolve and transform during atmospheric transport. The authors have mapped soil-mineral data to a high-resolution, 30-s grid (GMINER30; see Figure 28), including several mineral-carrying soil types in dust-productive regions that were not considered in previous studies (yermosols, haplic yermosols and xerosols). They also supplemented the table with phosphorus fractions in soils. When applied in atmospheric dust models, the GMINER30 data could be used to specify the emissions of mineral fractions in potential dust-producing soils.

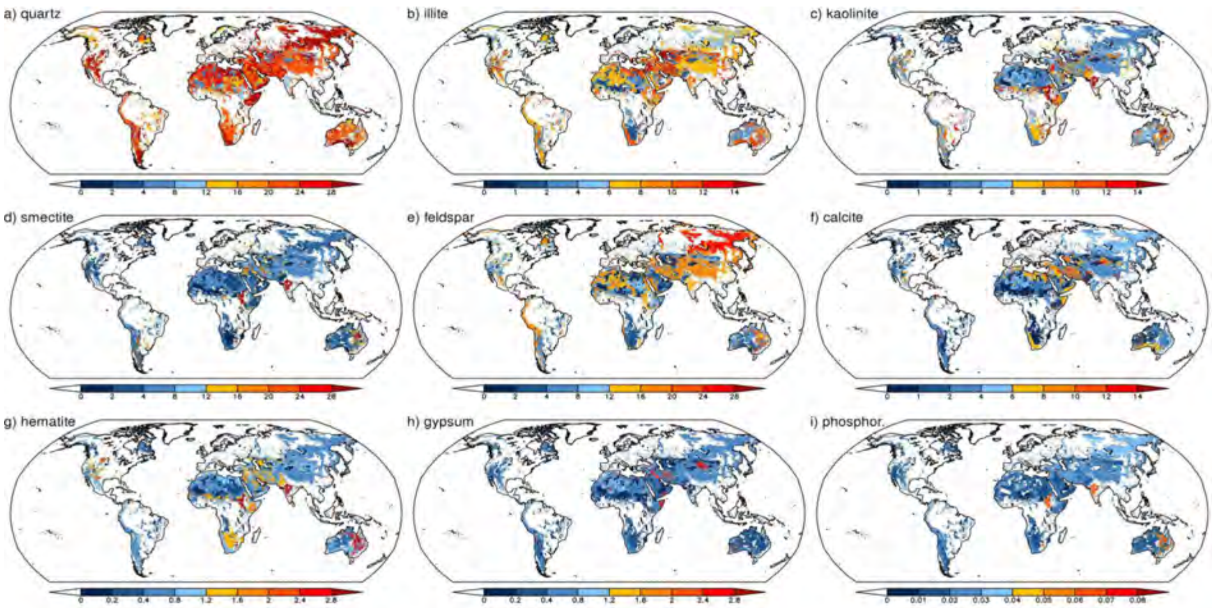


Figure 28 - Global distribution of the effective mineral content in soil in percentages for (a) quartz, (b) illite, (c) kaolinite, (d) smectite, (e) feldspar, (f) calcite, (g) hematite, (h) gypsum and (i) phosphorus: the mineral fraction is weighted with the clay and silt content in soil; for minerals that are present in both clay and silt, the weighted values are summed (after *Nickovic et al., 2012(a)*).

A.2.4 Optical properties of atmospheric dust

In order to facilitate interpretation of the results in this and following sections, some simple definitions and explanations of the most important optical properties of aerosols are briefly introduced.

Aerosol optical depth (AOD) is defined as the integrated extinction coefficient over a vertical column of unit cross-section, and provides information about the degree to which aerosol particles prevent the transmission of light.

Ångström exponent (AE) is the name of the exponent in the formula that is usually used to describe the dependency of AOD on wavelength. AE is inversely related to the average size of the particles in the aerosol: the smaller the particle, the larger the exponent. AE is therefore an indirect measurement of the size of aerosol particles present in a given column of air. AE provides information about the dominance of fine- and coarse-mode particles.

Extinction coefficient is a parameter that accounts for the attenuation of intensity (energy) of solar radiation by the scattering and absorption of aerosol particles.

Scattering coefficient is an optical property of aerosols that defines the distribution of scattering light around the particle. Scattering is the process by which a particle in the path of the electromagnetic wave scatters the incident radiation in all directions around it. The distribution of scattering is dependent on the size and shape of the particle.

Absorption coefficient defines the capability of an aerosol particle to absorb and then re-emit energy, i.e. sunlight. The strong increase in atmospheric absorption of solar radiation could be due to the presence of high concentrations of absorbed mineral dust.

Single scattering albedo (SSA) is defined as the ratio of scattering optical depth to the total optical depth and represents the efficiency of the scattering nature of aerosol particles. It is a key variable for determining aerosol climatic effects and retrieving AOD from satellite radiances. SSA gives 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.

Phase function is defined as the angle at which the scattered light is distributed as a function of size, shape of the aerosol particle, wavelength and incidence angle of the light.

Asymmetry parameter is defined as the cosine weighted mean of the angular scattering phase function. It is the ratio between forward- and backward-scattered radiation.

A first climatology of optical properties of aerosols over the Arabian Peninsula was provided by *Smirnov et al. (2002)* using AOD measurements over Bahrain acquired through the Aerosol Robotic Network (AERONET). A maximum dust aerosol loading was observed during the March–July period. They found a rather narrow AOD probability distribution with a modal value of about 0.25. The AE frequency distribution has two peaks. One peak, around 0.7, characterizes a situation when dust aerosol is more dominant; the second peak, around 1.2, corresponds to relatively dust-free cases. They also found that the correlation between AOD and water-vapour content in the total atmospheric column was strong (correlation coefficient of 0.82) when dust aerosol was almost absent (AE > 0.7), suggesting possible hygroscopic growth of fine-mode particles or source region correlation and much weaker correlation (correlation coefficient of 0.45) when dust was present (AE < 0.7). Diurnal variability of AE (20%–25%) was evident during the April–May period, when dust dominated the atmospheric optical conditions. Variations in the aerosol volume-size distributions are mainly associated with changes in the concentration of the coarse aerosol fraction. Geometric mean radii for the fine- and coarse-aerosol fractions are 0.14 m (standard deviation = 0.02) and 2.57 m (standard deviation = 0.27), respectively. Concerning SSA, they concluded that, in dust-free conditions, it decreased with wavelength, while, in the presence of dust, either stayed neutral or increased slightly with wavelength.

The only intensive campaign of measurements focused on optical properties of aerosols and, especially, desert dust in West Asia, was the UAE^2 field campaign in 2004. A detailed description of the activities and results of this campaign is provided by *Reid et al. (2005).* It focused on the characterization of fundamental physical and optical properties of atmospheric aerosol particles and on the interaction of regional/local meteorology with aerosol radiative impacts. It should be taken into account, however, that the results of this campaign, although extremely interesting, are representative only of summertime in a small region of West Asia.

During UAE^2 a dense network of Cimel sunphotometers was deployed (Figure 29) on an ad hoc basis (Eck et al., 2008) and integrated into AERONET (*Holben et al., 1998*). It was observed that the average diurnal variability of AOD at 500 nm varied between sites (from 0.4 to 0.53), with the largest diurnal changes (from values lower than 0.2 to higher than 1) occurring at some coastal and island sites (probably associated with land-/sea-breeze circulation). The two-month average of AE increased, moving from the desert region: 0.50–0.57 at inland desert sites, 0.64 at coastal sites and 0.77 over the Gulf island sites. This indicates that the observed dust particles are, on average, close to the source region. Correspondingly, the average fine-mode fraction increased from ~35% in the inland desert sites, up to ~48% in the Gulf island sites.

Figure 29 - Location of AERONET sites in the UAE and southern Gulf during the UAE^2 field campaign (from *Eck et al., 2008*)

Basart et al. (2009) provided an atmospheric aerosol characterization for North Africa, north-eastern Atlantic, Mediterranean and Middle East, based on the analysis of quality-assured direct-sun observations of AERONET, which include at least an annual cycle within the 1994–2007 period. They provide statistical values of AOD, AE and its spectral curvature (δα = AE (440, 613)–AE (613, 1003). *Kaufman (1993)* pointed out that negative values of δα indicate the dominance of fine-mode aerosols, while positive differences reflect the effect of two separate particle modes. In the Middle East, all sites show high extinctions (AOD up to 3), mainly clustering in the coarse mode. These extinctions are lower than those observed at African sites.

According to *Basart et al. (2009),* UAE and the Gulf include strong regional desert dust sources of predominately coarse-mode-size particles, as well as important fine-mode pollution particle sources from petroleum extraction and processing facilities, which are located on islands, sea-platforms and coastal regions of the Gulf. Thus, as shown in Figure 30, the coastal sites in the north-eastern part of the UAE, such as Mussafi, Dhabi and Dhanah, as well as Bahrain in the Gulf, attain positive δα values for most of the year (~0.2), which indicates the co-existence of two particle modes. At the coastal sites of Mussafa, Dhabi, Dhanah and Bahrain, they observed desert dust with AOD maxima of 1.5, AE < 0.75 and δα ≥ 0. On the other hand, small particles from petroleum-industry emissions are associated with fine mode (AE ~1.6 and δα ~–0.2) and AOD < 0.7. The interaction of mineral dust and pollution is strong at these coastal sites. Conversely, they reported that at inland desert sites, such as Hamim and Solar Village, desert dust is the main aerosol constituent associated with high AOD (> 0.7 ranging up to > 2), clustering mainly in the coarse mode (AE < 0.75 and δα variable). Records at Hamim show a contribution of small particles from industrial emissions, probably as a result of the land-breeze circulations in this area (Eck et al., 2008), which produce occasional increases of fine-mode particles from offshore petroleum operations. In Solar Village, far away from the Gulf or other industrialized areas, the records present the highest extinctions (AOD > 1) in the coarse mode (AE < 0.75 and δα < 0.1). This station also presents an expanded particle-size range, suggesting significant variations in the particle-size distribution, from almost pure coarse-mode dust particles to a mixture of coarse particles and fine-mode pollution aerosols. As shown in Figure 30, the contribution of large particles is maximal in spring and summer. In spring, all sites present similar AOD and AE values, associated with maximum local desert-dust activity (*Smirnov et al., 2002*).

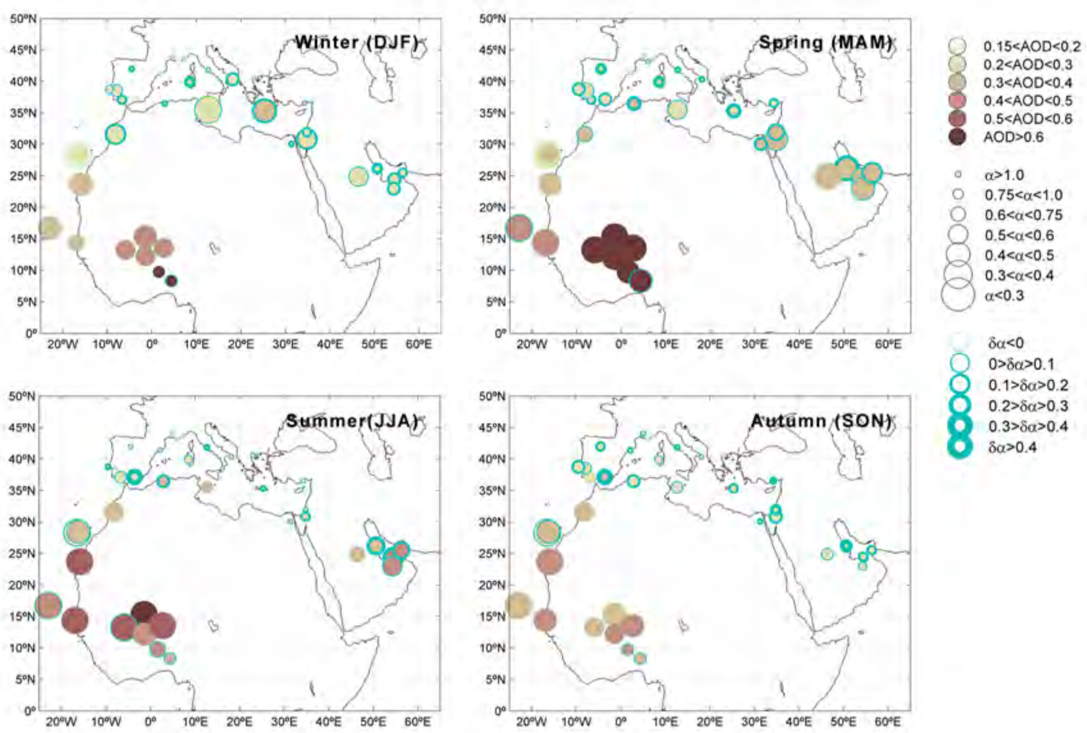


Figure 30 - Seasonal mean of measurements with AOD > 0.15 for each AERONET station: the colour code indicates the seasonal mean of AOD at 675 nm, the size code is associated with the seasonal mean of AE calculated between 440 and 870 nm and the blue contour code is associated with the seasonal mean of δα = AE (440, 675)–AE (675, 870)

Kim et al. (2011) used 14 AERONET stations (10 in North Africa and four in the Arabian Peninsula) to derive dust optical properties. They selected data with large AOD (≥ 0.4) at 440 nm and small AE (AE ≤ 0.2) for assuring pure mineral-dust aerosol characterization, reducing interference of non-dust aerosols. They found that the annual mean and standard deviation of SSA, asymmetry parameter, real refractive index and imaginary refractive index for Saharan and Arabian desert dust was 0.944 ± 0.005, 0.752 ± 0.014, 1.498 ± 0.032 and 0.0024 ± 0.0034 at 550 nm wavelength, respectively. They also found that, using the above above-mentioned data-selection criteria, dust aerosol is less absorbing than previously reported values. *Maghrabi et al. (2011)*, analysing a strong dust storm over Saudi Arabia, found sharp changes in aerosol optical properties before and after the intrusion. They found that AOD at λ = 500 increased by 330% immediately after the storm and remained very high: 429%, 144% and 52% for the three subsequent three days after the start of the storm, while AE fell to negative values. Another outstanding result was a remarkable decrease in broadband global and direct irradiances on the ground: 42% and 68%, respectively, in comparison with the previous clear day. The storm also caused an increase in atmospheric emissions in the atmospheric window (8–14 μm); the emissions in this window resembled those of a black body and, consequently, the atmospheric window was almost closed.

In the Islamic Republic of Iran, *Masoumi et al. (2010)* attributed the maximum value of AOD and noticeable increase of very coarse aerosols to the transport of dust from the Tigris-Euphrates basin. They also found a mixture of urban-industrial and dust aerosols during most of the year, with maximum AOD values, when AE values suggested the presence of supermicron aerosols (during spring and summer), typical of desert regions, and minimum AOD values when AE showed its largest values (December and January), indicative of an atmosphere mostly loaded with fine and very fine aerosols as a result of a mixture of urban-industrial dust with that transported from the Tigris-Euphrates basin and Qom Lake to Zanjan (*Masoumi et al., 2010*).

Using measurements from AERONET at the IMS-METU site at Erdemli (36°33'N, 34°15'E) on the north-eastern Mediterranean Turkish coast, *Kubilay et al. (2003)* characterized the predominant regional aerosol optical properties, with an emphasis on mineral-dust intrusions. As explained in previous sections, dust storms affecting Turkey originate primarily from the central Sahara in spring, the eastern Sahara in summer and the Middle East/Arabian peninsula in autumn. According to the authors, the dust episodes were characterized by: (a) a sharp drop in the Ångström coefficient to values near zero; (b) high-scattering with SSA greater than 0.95 ± 0.03 and the real part of the refractive index around 1.5 ± 0.5; (c) lower absorption given by the imaginary part of the refractive index less than 0.002; and (d) almost-neutral spectral dependence of these parameters.

A.2.5 Vertical structure of the dust layer

There is little information about the vertical structure of the dust layer in West Asia. The only intensive campaign of measurements with lidar was held during the UAE^2 field campaign. This campaign incorporated remote-sensing measurements of heterogeneous aerosol properties over water and bright desert surfaces.

The Micropulse Lidar Network (MPLNET) is a federated network of single-channel (523 nm), autonomous, eye-safe, micropulse lidar systems, designed to measure aerosol and cloud vertical structure (*Welton et al., 2001*). During UAE^2, MPL systems were deployed at the Al Ain international airport (SMART site) and a site on the coast, north of Abu Dhabi City (MAARCO site) (*Spinhirne et al., 1995*). Datasets and more information on MPLNET are available on the MPLNET-National Aeronautics and Space Administration (NASA) website (http://mplnet.gsfc.nasa.gov). Raw MPL data were acquired at a one-minute time resolution, and 75 m vertical resolution. The raw data were converted into signals to infer the altitude of aerosol and cloud heights (*Welton and Campbell, 2002*).

Aerosols were present from the surface to 5–6 km at both UAE^2 sites during the experiment. Figure 31 shows a dust layer between 1 km and almost 6 km above ground. The top of the aerosol layer is visible as the purple and pale blue-green layer bordering the free troposphere. Some middle clouds, probably altocumulus (around 5 km altitude), are observed at the top of the dust layer. Some cirrus clouds are also observed between 0 km and 12 km altitude. White indicates periods of intense apparent backscatter due to temperature fluctuations in the trailers (*Reid et al., 2005*).

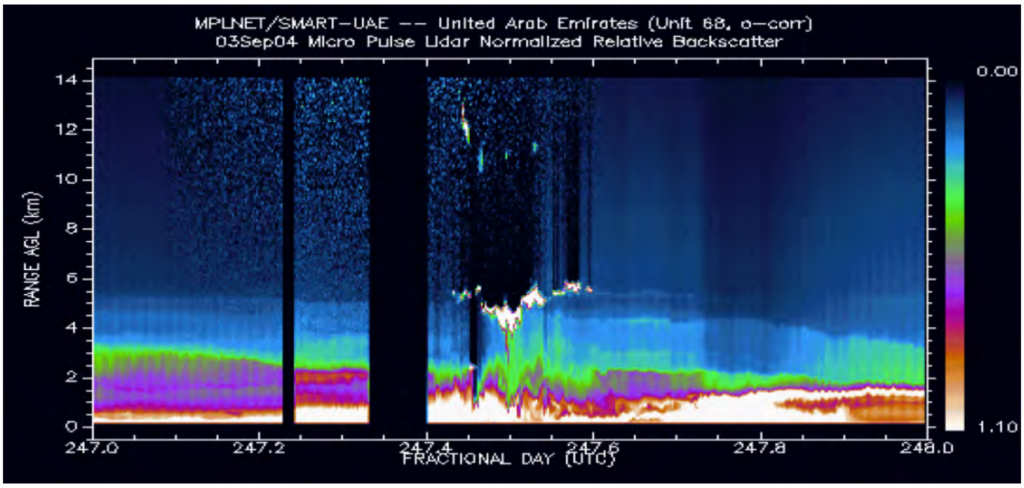


Figure 31 - Example of MPL normalized relative backscatter during UAE[2] (after *Reid et al., 2005*)

A permanent lidar station located at a strategic site in West Asia is Zanjan (36.7°N, 48.5°E, 1 700 m asl), a city located in the Iranian north-west (Figure 32, left). At present, the lidar is operated at a single wavelength and no polarization (*Khalesifard et al., 2004, 2005*). Its main objectives are environmental issues (*Bidokhti et al., 2008*) and atmospheric radiative budget, since the Zanjan region is subject to frequent dust storms.

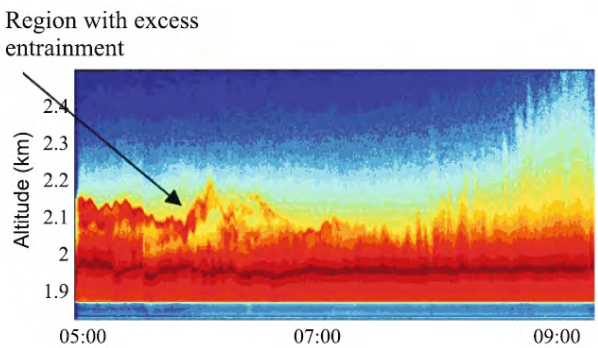


Figure 32 - Position of lidar in Zanjan (Islamic Republic of Iran) (left) and an example of vertical aerosol-layer structure monitoring at Zanjan (right), with an increase of mixed-layer height after sunrise reaching a maximum value between 05:00 and 11:00 UTC (after *Bidokhti et al., 2008*)

This lidar station permitted, for example, assessment of the impact of dynamic processes leading to dust emission over the Syrian Arab Republic and Iraq and north-western Islamic Republic of Iran, in response to a strong winter shamal (*Abdi Vishkaee et al., 2012*). Using ground-based lidar measurements acquired in Zanjan, this paper showed that, in the wake of the front, dust from Syrian Arab Republic/Iraq was transported in an elevated 1–1.5 km thick plume separated from the surface during the night/morning (Figure 32, right). After sunrise and strong turbulence in the developing convective boundary layer, dust was mixed into the boundary layer, leading to a sharp reduction in horizontal visibility.

The vertical distribution of the dust layer during Saharan-dust outbreaks in Turkey is, probably, quite similar to the vertical structure found over Greece by *Papayannis et al. (2009).* They performed systematic observations of the vertical aerosol with a multi-wavelength (355-532-1 064-387-607 nm) Raman lidar system of the National Technical University of Athens operated in Athens. They found multiple aerosol dust layers of variable thickness (680–4 800 m), with a centre of mass of these layers in altitudes between 1 600 m and 5 800 m. The mean thickness of the dust layer typically stayed around 2 700 m, however, and the corresponding mean centre of mass was of the order of 2 900 m. The top of the dust layer ranged from 2 000 m to 8 000 m, with a mean value of the order of 4 700 m.

Given the scarcity of in situ lidar measurements in West Asia, the information provided by the new-generation lidars aboard satellites is extremely useful. The primary instrument aboard the Cloud-Aerosol Lidar and Infra-red Pathfinder Satellite Observations (CALIPSO) satellite is the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) sensor, which is designed to acquire vertical profiles of elastic backscatter at two wavelengths (1 064 nm and 532 nm) from a near-nadir-viewing geometry during both day and night phases of the orbit (*Winker et al., 2007).* CALIOP also provides profiles of linear depolarization ratios at 532 nm. The depolarization measurements enable identification of non-spherical aerosol particles such as dust (Omar et al., 2009).

Liu et al. (2008) provide the most representative features of the vertical structure of the dust layer in West Asia by using the first year of CALIPSO measurements under cloud-free conditions. They provided zonal and meridional mean vertical structures of dust aerosols over the Arabian Peninsula (Figure 33). The mean dust-layer top is close to 5 km during the summer and below 3 km during the winter. As shown in Figure 33, intense dust plumes can be lifted up to 6 km during the winter. It is well known that dust generated over the Arabian Peninsula can be transported to the Gulf and the Arabian Sea (*Husar et al., 1997; Herman et al., 1997*). According to *Liu et al. (2008),* dust aerosols are mainly transported above 1 km during summer and autumn, while significant dust aerosols are transported below 1 km during the spring, which may be due to the local monsoon circulation.

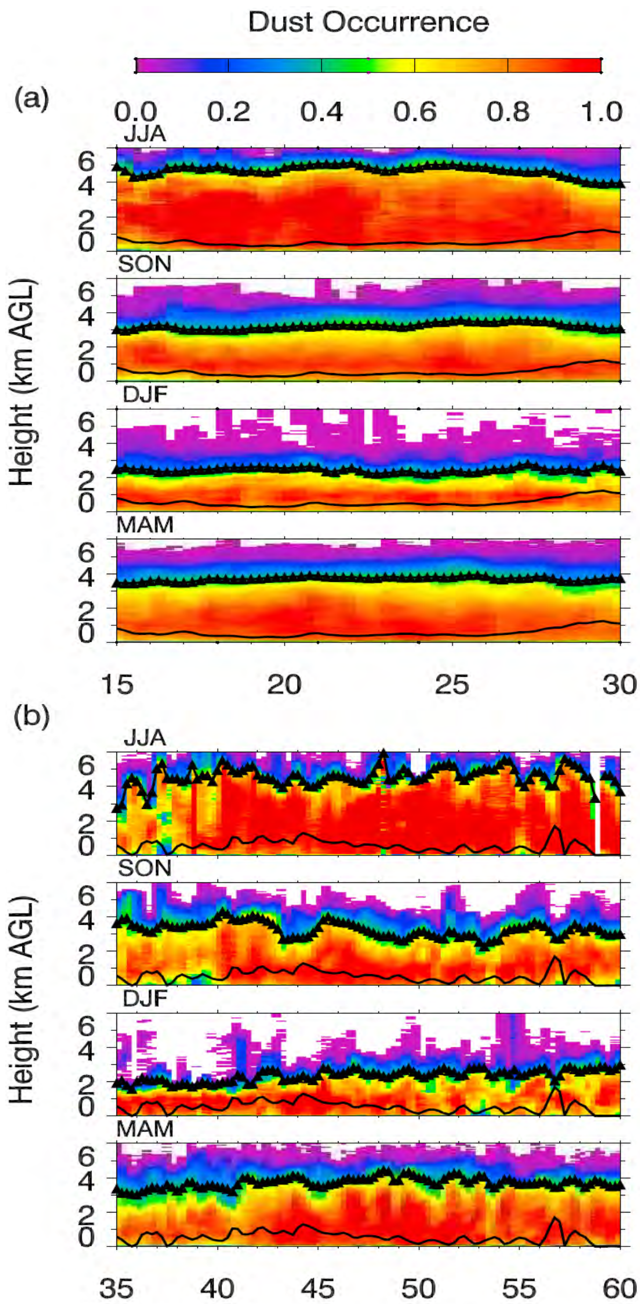


Figure 33 - The zonal (a) and meridional (b) mean vertical distributions of dust vertical occurrence, obtained by CALIPSO observations in the period June 2006–May 2007 over the Arabian Peninsula for the four seasons, respectively: the mean dust-layer top and surface altitudes are overplotted in the dust-layer occurrence as thick solid lines and thin solid lines, respectively (after *Liu et al., 2008)*

A.2.6 Dust climatology in West Asia

The previous sections have shown that there is insufficient information to obtain a full picture of atmospheric dust distribution over West Asia. It was, therefore, decided to include this section, in which a monthly climatology of atmospheric dust has been obtained from the most reliable satellite sensors, global and regional dust models and ground-based observations from AERONET. This study is not intended as a detailed analysis that would go far beyond the scope of this report, but as a first approach to identifying and understanding the distribution of atmospheric dust over the region and to confirm the potential dust sources and pathways reported in previous studies. This section will serve as a basis for identifying gaps in dust monitoring and modelling in West Asia. The information will be used later for recommending observation and modelling strategies.

A.2.6.1 Experimental approaches to identifying and understanding atmospheric dust distribution

Data from the following sensors and models were analysed:

1. The MISR instrument, on board the NASA Earth Observing System's Terra satellite (http://www-misr.jpl.nasa.gov/). The four MISR bands (blue, green, red and near-infra-red) take a global coverage every nine days with repeat coverage, depending on latitude, between two and nine days. This analysis comprises data from the period 2003–2010 (eight years).

MISR products downloaded from the NASA Giovanni (Goddard Earth Sciences Data and Information Services Center (GES DISC) interactive online visualization and analysis infrastructure) server (http://disc.sci.gsfc.nasa.gov/giovanni/overview/index.html) were:

- Daily AOD at 555 nm
- Monthly AOD at 555 nm

Data were plotted using the World Geodetic System WGS84. The four nearest pixels with a 17.6 × 17.6 km spatial resolution were used to extract MISR data over a specific station. MISR can retrieve aerosol properties over bright desert areas thanks to its unique capability of multi-wavelength observations in forward and backward directions (*Kahn el al., 2005*).

2. MODIS aboard the Terra (EOS AM) and Aqua (EOS PM) satellites (http://modis.gsfc.nasa.gov). Terra's orbit around the Earth is timed so that it passes north-south across the Equator in the morning, while Aqua passes south-north over the Equator in the afternoon. Terra MODIS and Aqua MODIS view the entire Earth's surface every one to two days, acquiring data in 36 spectral bands or groups of wavelengths. The MODIS aerosol algorithm comprises two independent algorithms, one for deriving aerosols over land and the second over ocean (*Levy et al., 2003; Remer et al., 2005*). An algorithm over land has been developed for use at low ground reflectance only (i.e. over dark vegetation). For this reason, the MODIS/Aqua-DB AOD product has been included in the analysis. It employs radiances from blue channels for which the surface reflectance is low enough that the presence of dust brightens the total reflectance and enhances the spectral contrast (*Hsu et al., 2004*). Thus, the MODIS/Aqua-DB AOD product basically provides information over arid and semi-arid areas.

The following datasets were used:

- MODIS Terra version V5.1 (daily: MOD08_D3.051/monthly: MYD08_M3.051) with 1˚ x 1˚ resolution for the period 2003–2010
- MODIS Aqua version V5.1 (daily: MOD08_D3.051/monthly: MYD08_M3.051) with 1˚ x 1˚ resolution for the period 2003–2010

The MODIS products downloaded from the NASA Giovanni server (http://disc.sci.gsfc.nasa.gov/giovanni/overview/index.html) were:

- Daily and monthly averaged AOD at 550 nm over ground with DB algorithm
- Daily and monthly averaged AOD at 550 nm over the ocean with no DB algorithm

Data were plotted using WGS 84. The four nearest pixels were used to extract MODIS data over a specific station.

3. AERONET consists of sun- and sky-scanning spectral photometers that automatically measure the intensity of sunlight and directional sky brightness from the UV (340 nm) to the near-infra-red (1 640 nm) in nine spectral band passes throughout the day. These data are relayed by satellite or FTP connection to NASA's Goddard Space Flight Centre (GSFC) or through PHOTONS (photométrie pour le traitement opérationnel de normalisation satellitaire), where they are processed in near-real-time (NRT) to retrieve AOD, particle-size distribution and complex index of refraction data available through the public access website: http://aeronet.gsfc.nasa.gov. AERONET is a federation of ground-based remote-sensing aerosol networks established by NASA and PHOTONS (University of Lille, the French National Centre for Space Studies (CNES) and the French National Centre for Scientific Research (CNRS) National Institute for Earth Sciences and Astronomy and is greatly enhanced by the participation of collaborators from national agencies, institutes, universities, individual scientists and partners.

In this study, AERONET stations operating within the West Asia geographical domain were used (see Figure 34).

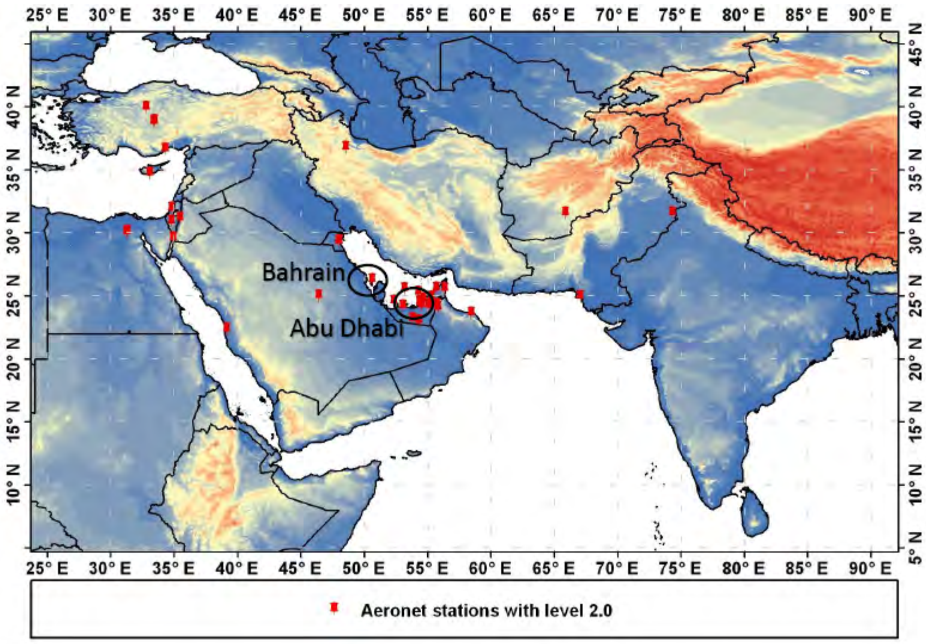


Figure 34 - Map of AERONET stations in West Asia: Bahrain and Abu Dhabi stations are circled

Only AERONET level 2.0 data were included in the analysis. The AERONET products used in this section were:

- AOD at 550 nm derived from the classical Ångström equation (AOD (λ) ~$\lambda^{-\alpha}$) (Ångström, 1929) and Ångström exponent (α) 470-865 nm
- Ångström exponent (α or AE)
- Coarse mode at 500 nm obtained with spectral deconvolution algorithm (SDA) (*O'Neill et al., 2003, 2005)*

- Fine mode at 500 nm with SDA

4. MACC-ECMWF dust model (*Benedetti et al., 2008; Morcrette et al., 2008*) from the European Centre for Medium-Range Weather Forecasts (ECMWF).

For station characterization, MACC-f93i experiment reanalysis (*Benedetti et al., 2008*) was used at 06:00, 12:00 and 18:00 UTC each day and the following variables were extracted:

- DOD at 550 nm
- AOD at 550 nm

For climatic maps, monthly mean maps were obtained from daily averages computed from MACC outputs at 06:00, 12:00 and 18:00 UTC for the period January 2003 to March 2010. The maps obtained correspond to:

- DOD at 550 nm monthly means for the period 2003–2010
- AOD at 550 nm monthly means for the period 2003–2010

5. NMMB/BSC-Dust model (*Pérez et al., 2011; Haustein et al., 2012*) from Barcelona Supercomputing Centre (BSC).

For station characterization, NMMB/BSC-Dust reanalysis was used at 06:00, 12:00 and 18:00 UTC each day and the following variables were extracted:

- DOD at 550 nm
- Dust concentration at 10 m above ground (µg/m^3)

For climatic maps, the monthly mean maps were obtained from daily averages computed from NMMB/BSC-Dust outputs at 06:00, 12:00 and 18:00 UTC for the period January 2003 to March 2010. The maps obtained correspond to:

- DOD at 550 nm monthly means for the period 2003–2010
- Dust concentration at 10 m above ground monthly means for the period 2003–2010

A detailed description of MACC-ECMWF and NMMB/BSC-Dust models can be found at http://sds-was.aemet.es/forecast-products/dust-forecasts.

Trend analysis of AOD from MISR and Enhanced Vegetation Index (EVI) from MODIS has been performed using the Giovanni online data system (*Acker and Leptoukh, 2007*).

A.2.6.2 AOD from MISR

AOD monthly mean value from MISR for July (2003–2009) is shown in Figure 35. AOD ≥ 0.5 is plotted in yellow to red.

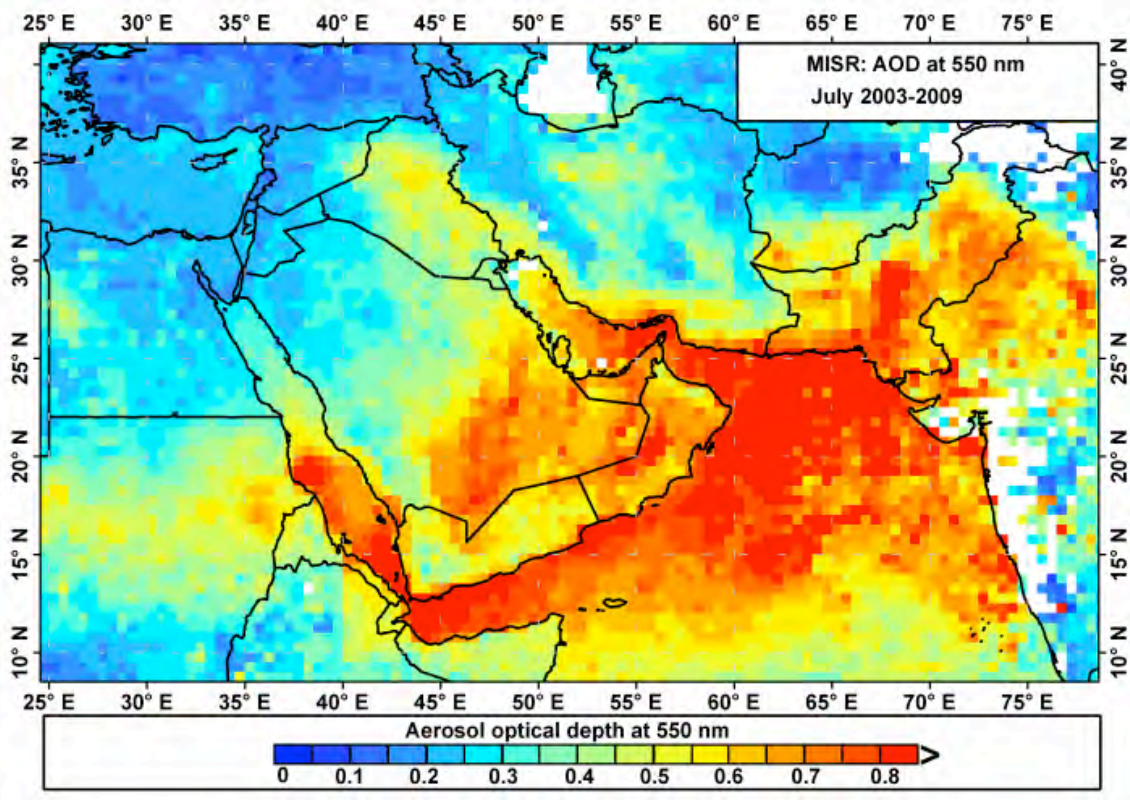


Figure 35 - Monthly mean AOD for July (2003–2009) obtained from the MISR satellite sensor

Monthly AOD averages from MISR for each month during the period 2003–2010 are depicted in Figure 36. January and February show low AOD. In March, moderate AOD ~0.5 is observed over Saudi Arabia, affecting Qatar and Bahrain and part of the Gulf Sea. AOD intensifies over Saudi Arabia and the Gulf Sea in April, with moderate AOD observed over part of Iraq, the Red Sea and central Islamic Republic of Iran. A similar pattern, but with higher and moderate AOD, is also observed over UAE and the eastern border of Islamic Republic of Iran. In June, the AOD pattern is similar to May but with increased AOD over some areas, mainly over the Arabian Sea and the southern half of the Red Sea. July is the month with the highest AOD. All the regions with moderate and high AOD observed in June show higher AOD in July. The Iranian coast of the Arabian Sea shows high values of AOD and areas with moderate levels of AOD in central Islamic Republic of Iran shift northward during this month. The southern Red Sea, the Gulf and much of the Arabian Sea have very high monthly averaged values of AOD (> 0.7).

In August, AOD values begin to decrease. This decline is significant in Saudi Arabia, Iraq and UAE, with very high values still in the northern Arabian Sea and the southern Red Sea. In September, AOD values decrease significantly in all regions, being low in October, November and December, although some low-to-moderate AOD values are observed over Saudi Arabia, the Red Sea and southern Iraq in October.

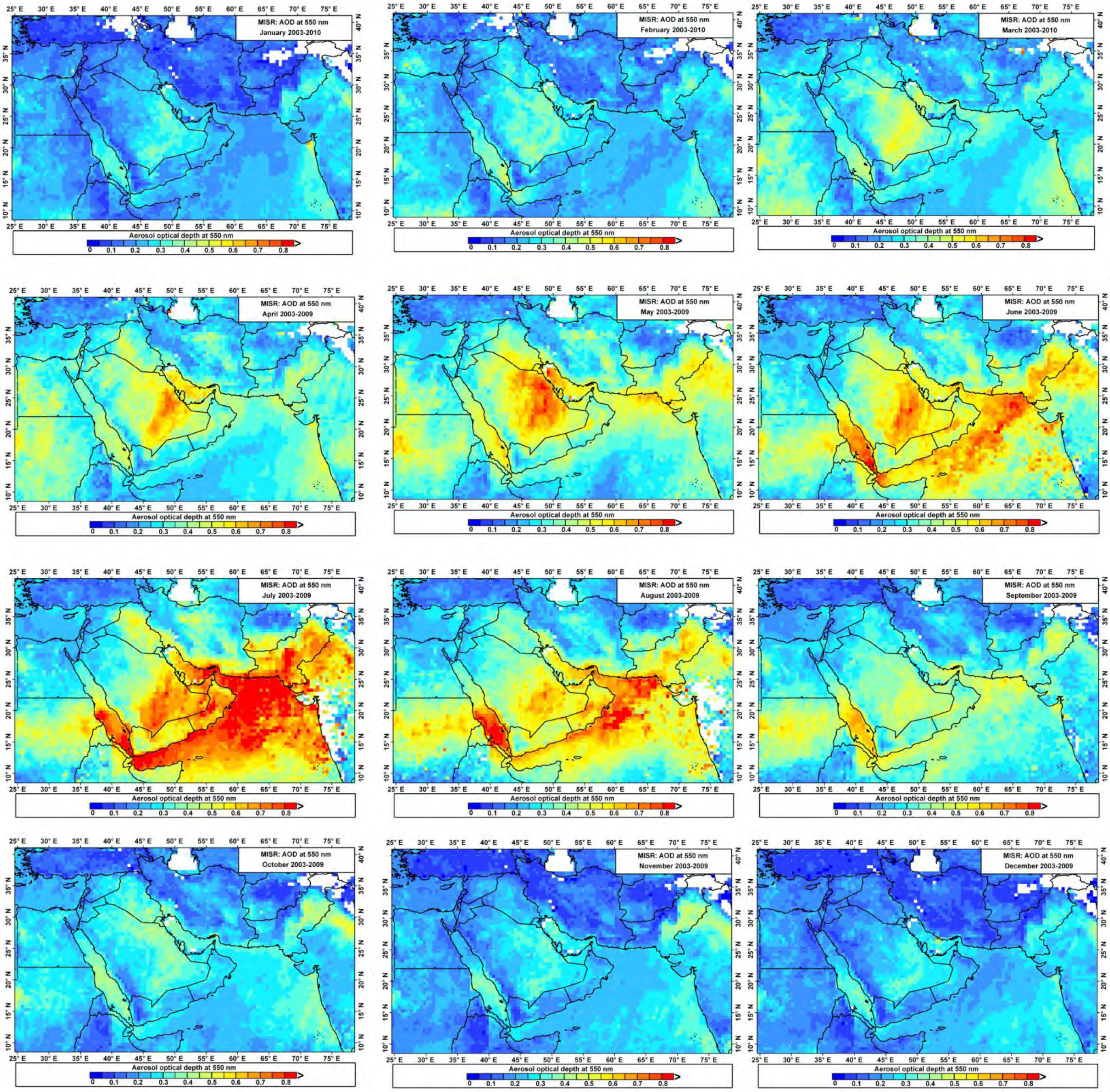


Figure 36 - Monthly mean AOD from MISR for the period 2003–2010

A.2.6.3 AOD from MODIS-Deep Blue

Monthly mean AOD from MODIS-DB (2003–2010) for July is shown in Figure 37. AOD ≥0.5 is plotted in yellow to red.

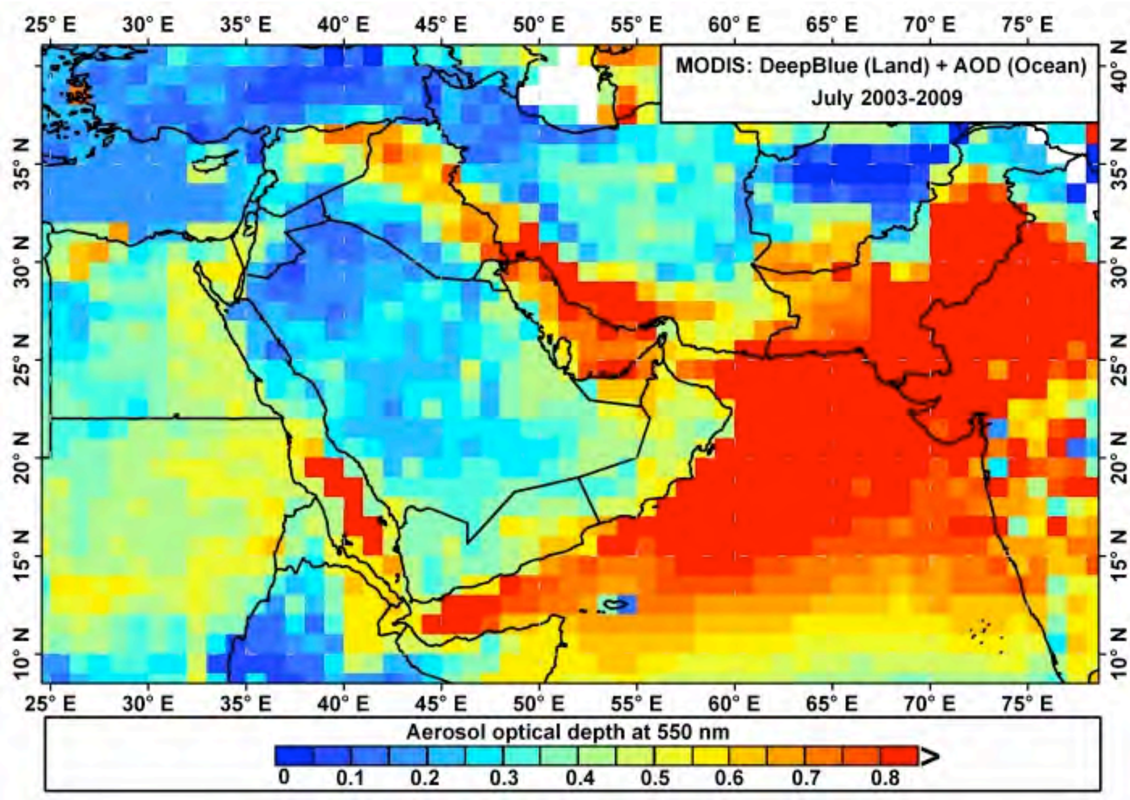


Figure 37 - Monthly mean AOD for July (2003–2009) obtained from MODIS-DB

MODIS-DB (Figure 38) and MISR show basically the same monthly AOD patterns over West Asia but there are some differences. For example, MODIS-DB highlights moderate AOD over Iraq and the Gulf in February. In March, April, May and June, the difference between MISR and MODIS-DB persists, with higher values shown by MODIS-DB in Iraq, Syrian Arab Republic and the Gulf. However, AOD over Saudi Arabia given by MODIS-DB is significantly lower than that shown by MISR. Higher AOD is also observed with MODIS-DB in the Iranian Sistan region. In July and August, the same differences between MISR and MODIS-DB are found, but AOD underestimation of the latter over Saudi Arabia, Oman and UAE is really striking. From September to December, under relatively high AOD values in the region, the most outstanding differences are found over the Arabian Peninsula (with higher AOD values from MISR) and over the Gulf (with higher AOD values from MODIS-DB). *Shi et al. (2011)* identify regions where MODIS/MISR AOD ratios were above 1.4 and below 0.7. These regions, where uncertain lower boundary conditions are likely to be a dominant factor, include portions of the Arabian Peninsula and Central Asia.

A number of reasons that might explain the differences between MISR and MODIS-DB have been investigated by several authors (*Xiao et al., 2009; Shi et al., 2011*).

Firstly, MODIS-DB retrievals normally underestimate high reflectance surfaces. This might be applied to most of the Arabian Peninsula, where MODIS-DB provides lower AOD than MISR.

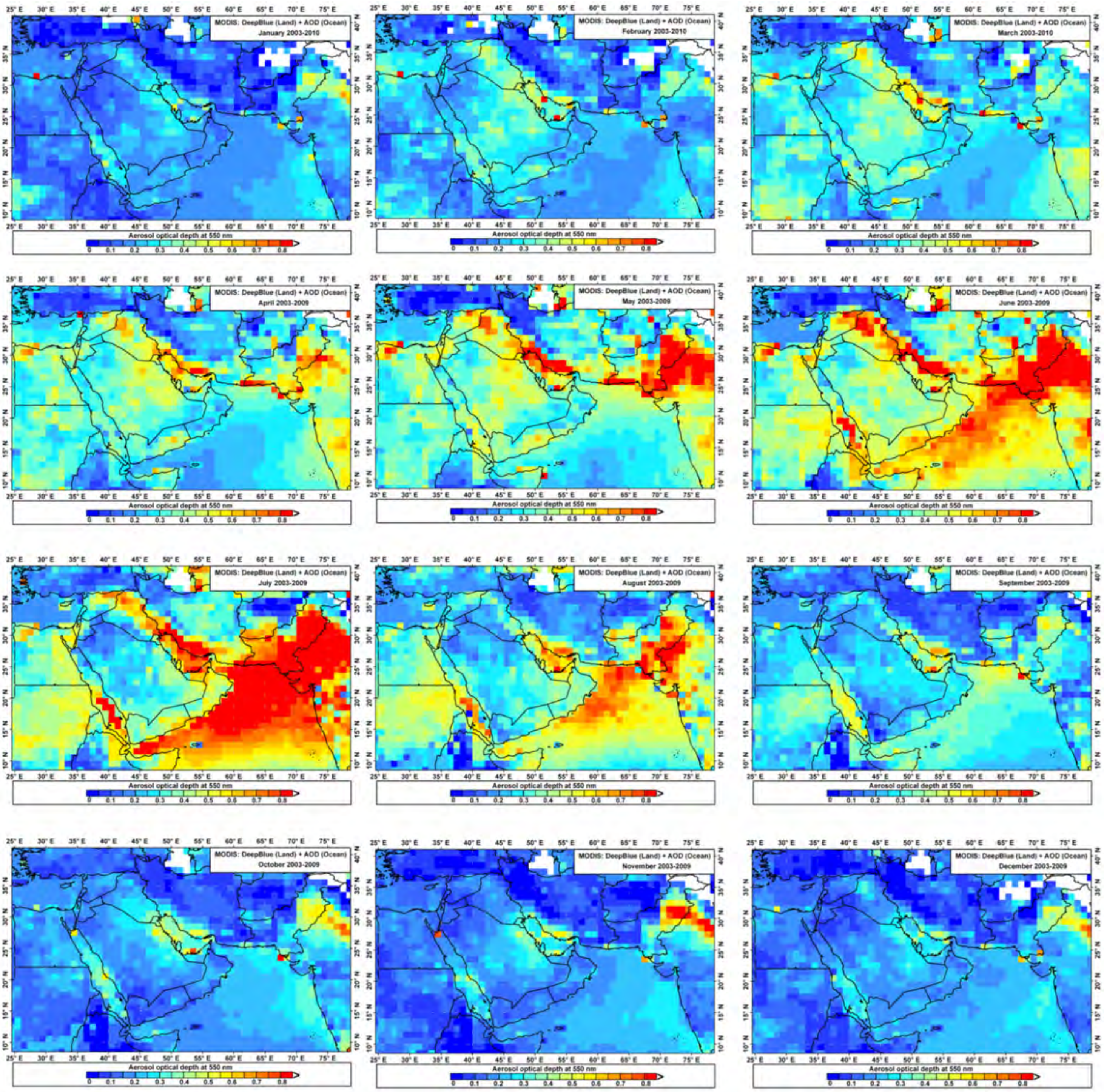


Figure 38 - Monthly means AOD from MODIS-DB for the period 2003–2010

From the comparison between MISR and MODIS-DB with an AERONET observation site at Solar Village, Saudi Arabia, performed by *Shi et al. (2011),* there is better agreement between AERONET/MISR than AERONET/MODIS-DB. Over desert regions such as North Africa and the Middle East, AOD values from the two products have differences around 0.1 to 0.3 (*Shi et al., 2011*). One of the regions of the world where MISR retrievals are much greater than those from MODIS-DB is the Arabian Peninsula (*Shi et al., 2011).*

Secondly, in the complicated aerosol content we find in regions such as the east coast of the Gulf and Islamic Republic of Iran, there is a mixture of dust and anthropogenic aerosol plumes emitted from oil- and gas-combustion industries. While this introduces an element of uncertainty, there are other inherent causes in the satellite-sensor technique and algorithm issues for one or both instruments.

Furthermore, and from a climatological point of view, we have to take into account the fact that, while MODIS-DB completes a global coverage every one or two days, MISR has a global coverage every nine days. This means that AOD climatologies correspond to a quite different number of days, during which dust episodes might vary significantly.

These differences must be analysed and understood, using ground-based measurements as carried out by AERONET. As suggested by *Shi et al. (2011),* additional AERONET sites are required for some of the regions with large MODIS/MISR ratio values, especially where it is suspected that aerosol optical property assumptions cause large uncertainties in satellite retrievals. This is the case in most of the Middle East. The NRT comparison of satellite- and ground-based measurements constitutes a good quality-assurance system, which will give a confidence level to the data provided by satellite and correct them, if necessary.

A.2.6.4 Dust climatology from AERONET stations

The mixture of aerosols found in West Asia can be derived from AERONET stations. We have included in this study a climatology of AOD: coarse-mode AOD (which corresponds mostly to mineral dust) and fine-mode AOD (which corresponds mostly to industrially derived particles). Although this study has been completed for all AERONET stations in West Asia with at least one year of Data Level 2.0 AERONET and, for sake of brevity, only Metu (Turkey), Kuwait, Bahrain, Dhabi (UAE), Mussafa (UAE) and Solar Village (Saudi Arabia) are presented in this report.

The joint analysis of monthly mean values of the total AOD and corresponding coarse and fine AOD fractions gives us an interesting picture of the seasonal variation of aerosols, including dust, in different areas of West Asia.

The box-plots in Figures 40, 41 and 42 indicate the following: the bottom and top of the box are the AOD 25th and 75th percentile; the band near the middle of the box is the 50th percentile (the median); and the red triangle expresses the AOD mean value. The ends of the whiskers represent the one standard deviation above and below the mean of the AOD data. Any data not included between the whiskers are plotted as an outlier with a dot.

There are significant differences between AERONET stations, even between those located relatively near each other. For example, when comparing the data at Bahrain and Kuwait stations, the latter presents much higher AOD values. The seasonal variation is also quite different. In Bahrain, AOD from anthropogenic aerosols (fine AOD) plays a key role annually from July to December with fine-AOD ≥ 0.2, while, in Kuwait, AOD is basically driven by dust (coarse AOD). Kuwait is also affected by fine particles, but to a much lesser extent. In Bahrain, coarse AOD outliers are observed throughout the year, but mainly in spring and summer, indicating moderate-to-severe dust storms. In Kuwait, the coarse AOD outliers are observed mainly in winter (a significant difference between the AOD mean and the AOD median). In Mussafa and Abu-Dhabi AERONET stations (both in UAE), the seasonal variation is quite different, peaking in July and August. Although the distance between them is small, there are some significant differences between them.

The influence of particles from industrial processes (fine AOD) is important at both UAE stations from July to December, where some severe pollution events in terms of fine AOD were recorded. Maximum total AOD is found in July–August at both stations. In Abu Dhabi, the maximum coarse AOD values (July and August) coincide with maximum fine AOD values. A mixture of mineral dust and anthropogenic aerosols is therefore observed in summertime. Solar Village is a key AERONET station in the heart of Saudi Arabia. It presents large total AOD values, although lower than those found in Kuwait. The incidence of fine particles is much lower than in stations located near the Gulf, with a peak of fine AOD in August (< 0.2). The seasonal variation of both total and coarse AOD is quite different from Gulf stations, peaking in May. Coarse AOD outliers occur over the year, caused by dust storms or small-scale convective dust events, and some are related to local dust re-suspension. The IMS-MET-ERDEMLI station, on the southern coast of Turkey, presents much lower total AOD and coarse AOD values than the stations in the Gulf region. However, the fine AOD values are quite large – even higher than coarse AOD levels – and much higher than monthly mean values observed at Gulf stations. Coarse AOD peaks in April (< 0.2), while a broad total AOD maximum is observed from June to August (~0.5), which is clearly driven by fine particles with a similar seasonal variation, peaking in summer (~0.3).

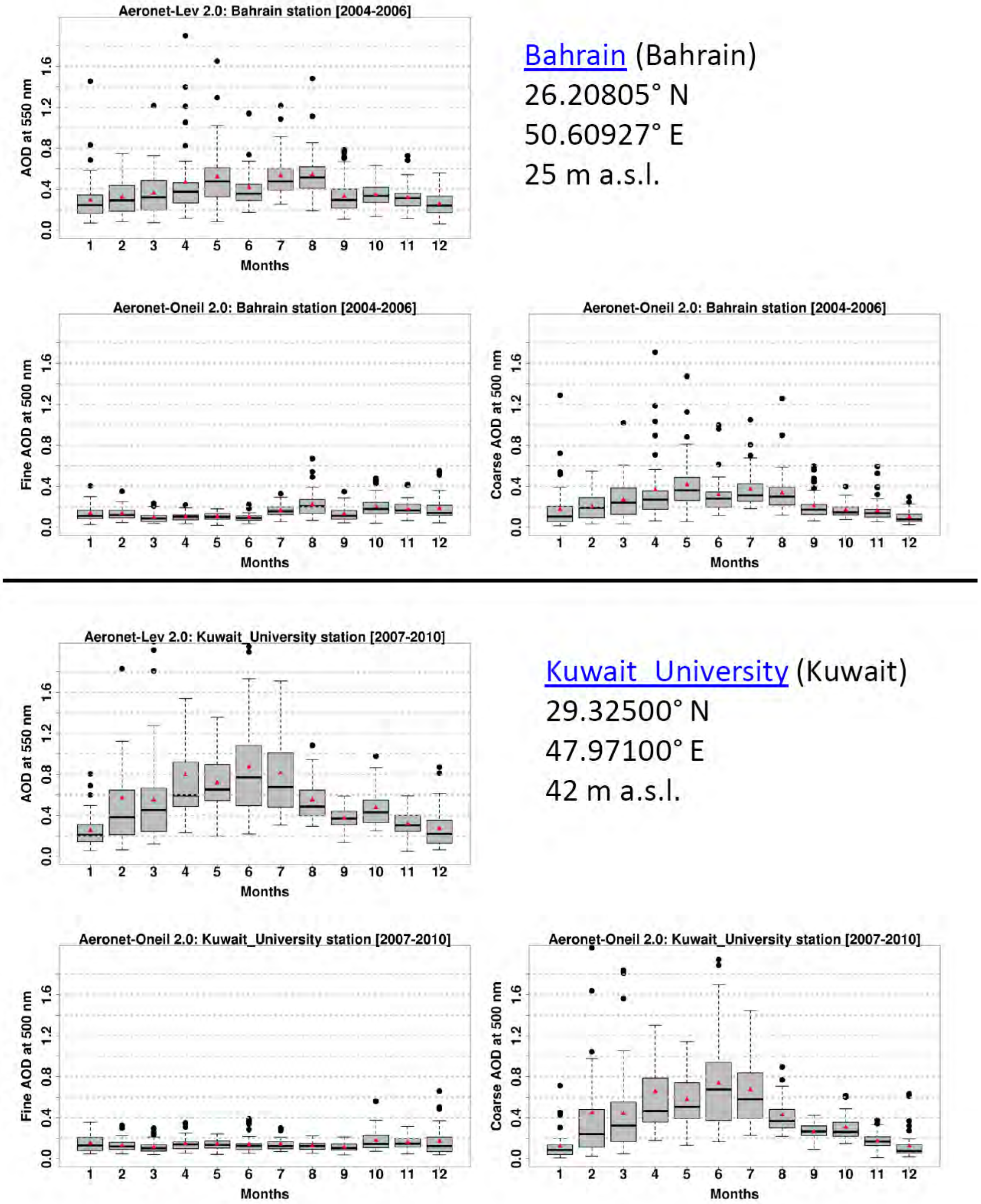


Figure 39 - Seasonal variation of aerosols at Bahrain and Kuwait AERONET stations

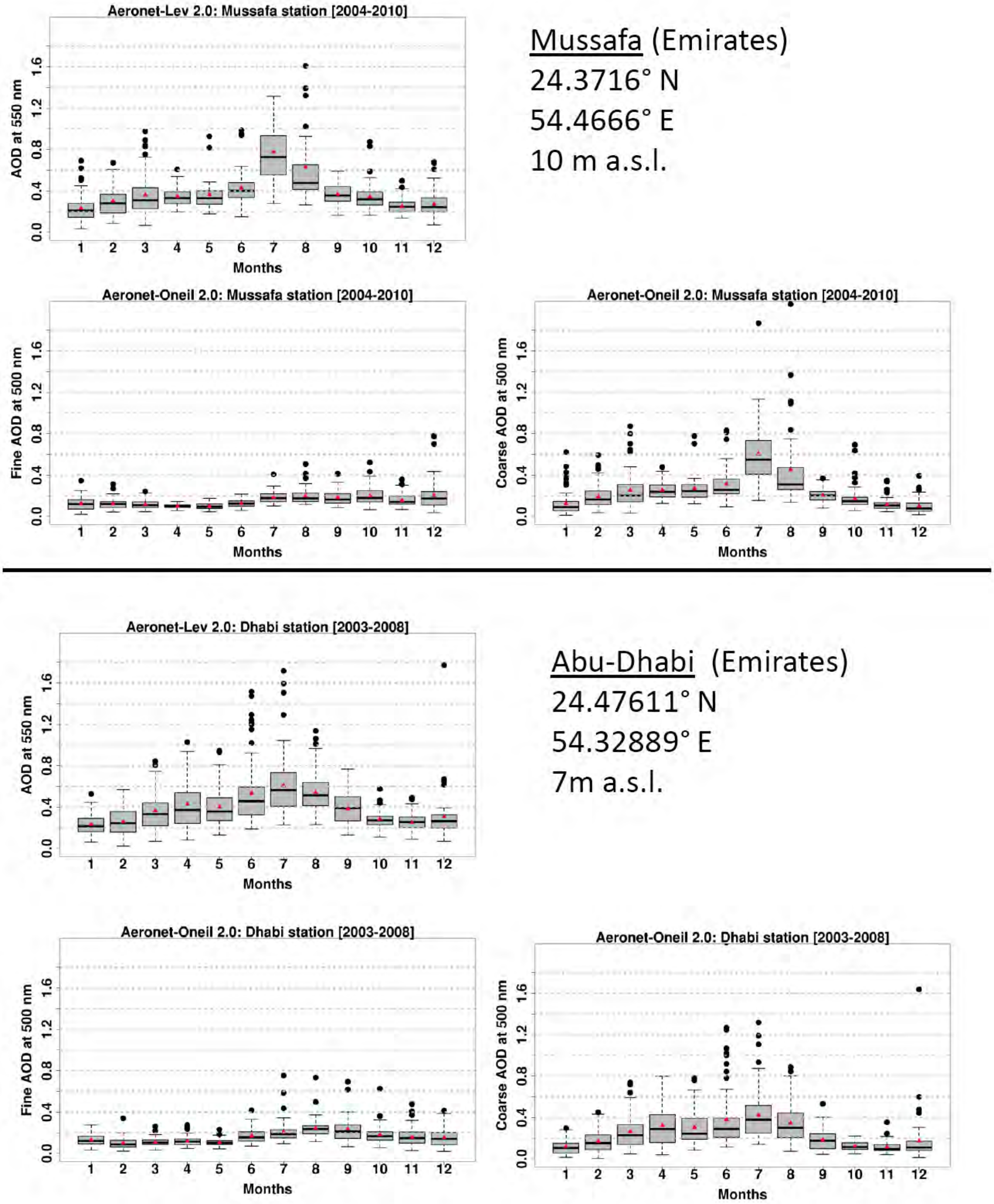
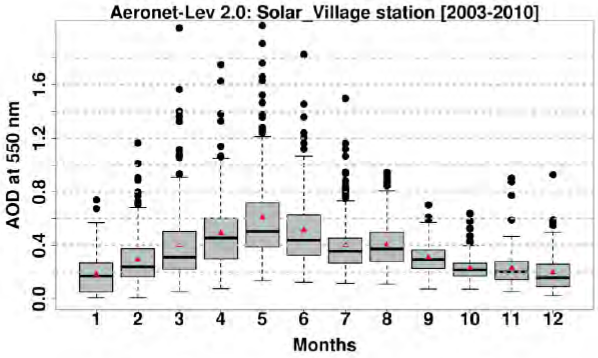
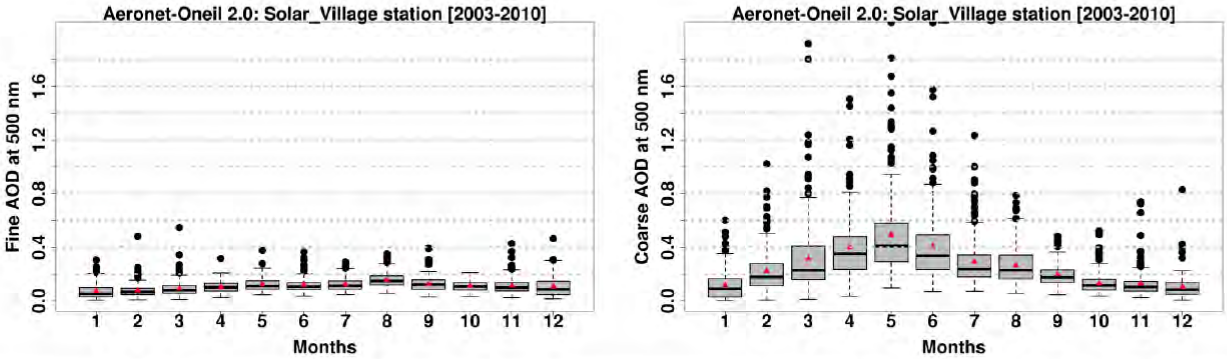
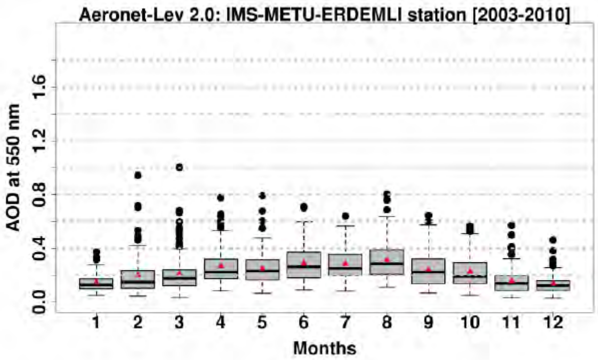


Figure 40 - Seasonal variation of aerosols at Mussafa and Abu Dhabi AERONET stations (UAE)



[Solar Village](#) (Saudi Arabia)
24.90693° N
46.39729° E
764. m a.s.l.





[IMS-METU-ERDEMLI](#) (Turkey)
36.56500° N
34.25500° E
3 m a.s.l.

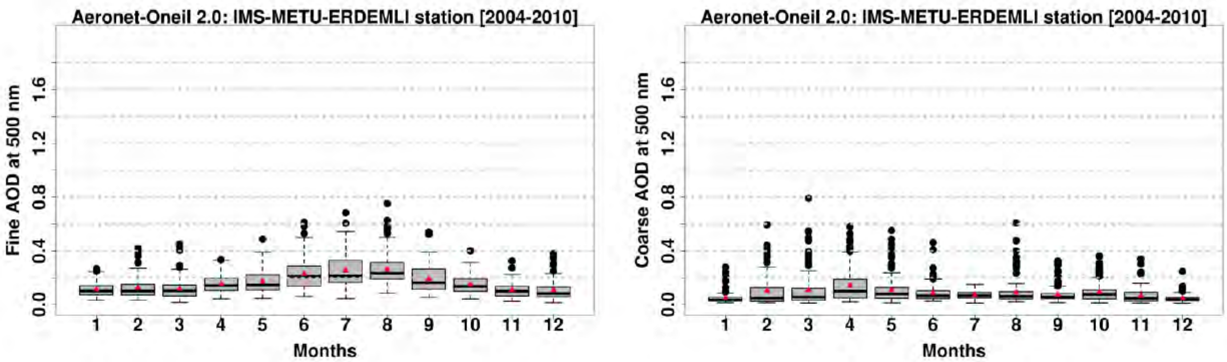


Figure 41 - Seasonal variation of aerosols at Solar Village (Saudi Arabia) and IMS-METU-ERDEMLI (Turkey) AERONET stations

A.2.6.5 Comparison of dust climatologies from AERONET and dust models

Dust climatology performed with information from a small number of AERONET stations in West Asia is limited. Although climatology of AOD from satellite-borne sensors has been previously presented, climatology from the model simulations using MACC-ECMWF and NMMB/BSC-Dust reanalysis is included in this section. A couple of examples of the behaviour of these models are presented and compared with AERONET stations. The model-validation exercise was done at each AERONET station in the region but, because of space limitations, only the results for two key stations located in the Gulf area are presented here – Bahrain and Abu Dhabi – where great complexity in the transport of dust is observed.

To validate the AOD climatologies between models (MACC-ECMWF and NMMB/BSC-Dust) and AERONET data level 2.0, statistics were obtained from monthly mean, daily averaged measurements matching between models and each AERONET station. Months with at least 15 days matching between models and AERONET were selected. The computed monthly statistics are the following:

- Mean bias (MB)
- Modified normalized mean bias
- Root mean squared error
- Correlation coefficient

For the sake of brevity, only MB has been shown.

In the comparison of dust models with AERONET stations, the average of the four nearest pixels to the station was used. Concerning the model resolution of the models, 1° for MACC-ECMF and 0.5° in the case of NMMB/BSC-Dust, small-scale processes or local dust resuspension cannot logically be captured by models. Despite these limitations, the results were generally excellent for both models, showing their ability to simulate AOD in West Asia.

NMMB/BSC-Dust is designed to simulate only dust (DOD in this case) but MACC-ECMWF can simulate total AOD and AOD contributions from different aerosols, including dust (DOD). When comparing AOD climatologies of AERONET stations and MACC-ECMWF (Figures 43 and 44(a) and (b)), there is fairly good agreement for Bahrain and Abu Dhabi stations. The month-to-month variability is well captured by MACC. Logically, there are slight quantitative differences.

Concerning DOD, both models agree quite well with the seasonal variation shown by the AERONET stations. Monthly averaged MB values of both models are normally within ± 0.15 AOD. The behaviour of the models varies depending on time of year and the subregion simulated. We cannot speak of a better behaviour of any of the models: not one model stands out as performing better than the others. Normally, each one performs best in a given area and given season/month. The best definitive option, if possible, is to use an ensemble of models for both dust forecasting and dust climatology from reanalysis.

Bahrain (26.2°N, 50.6°E, 25 m asl)

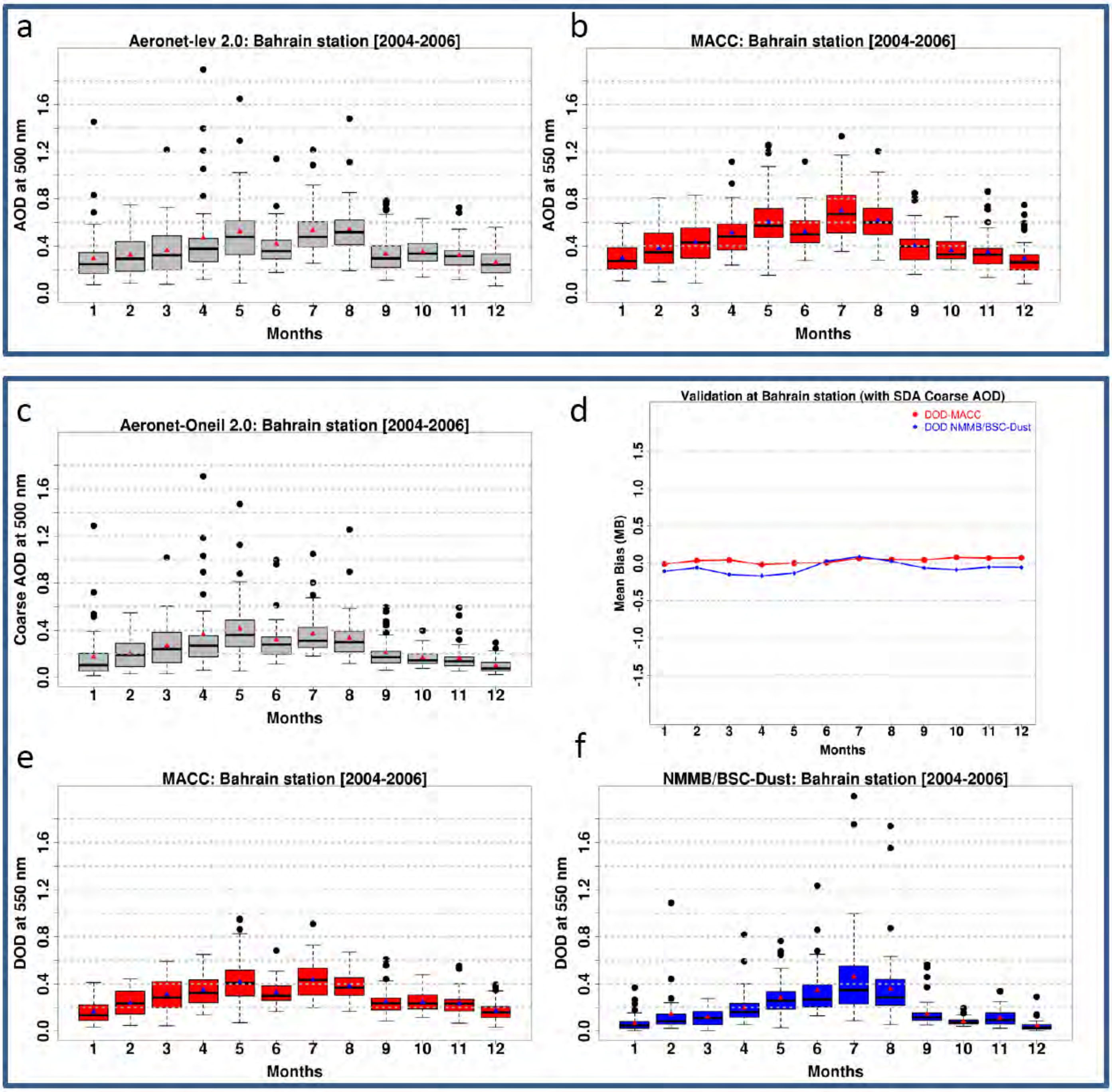


Figure 42 - (a) monthly mean values of total AOD AERONET level 2.0 at Bahrain station for the period 2004–2006; (b) monthly mean values of total AOD simulated with MACC-ECMWF using coincident days with the AERONET station; (c) coarse AOD computed with AERONET level 2.0 data at Bahrain station using SDA (*O'Neill et al., 2003; 2005*); (d) monthly averaged MB of DOD for MACC-ECMWF and NMMB/BSC-Dust simulations when compared against coarse AOD from AERONET; (e) monthly mean DOD from MACC-ECMWF for coincident days with AERONET during the period 2004–2006; (f) monthly mean DOD from NMMB/BSC-Dust for coincident days with AERONET during the period 2004–2006

Abu Dhabi (24.5°N, 54.4°E, 15 m asl)

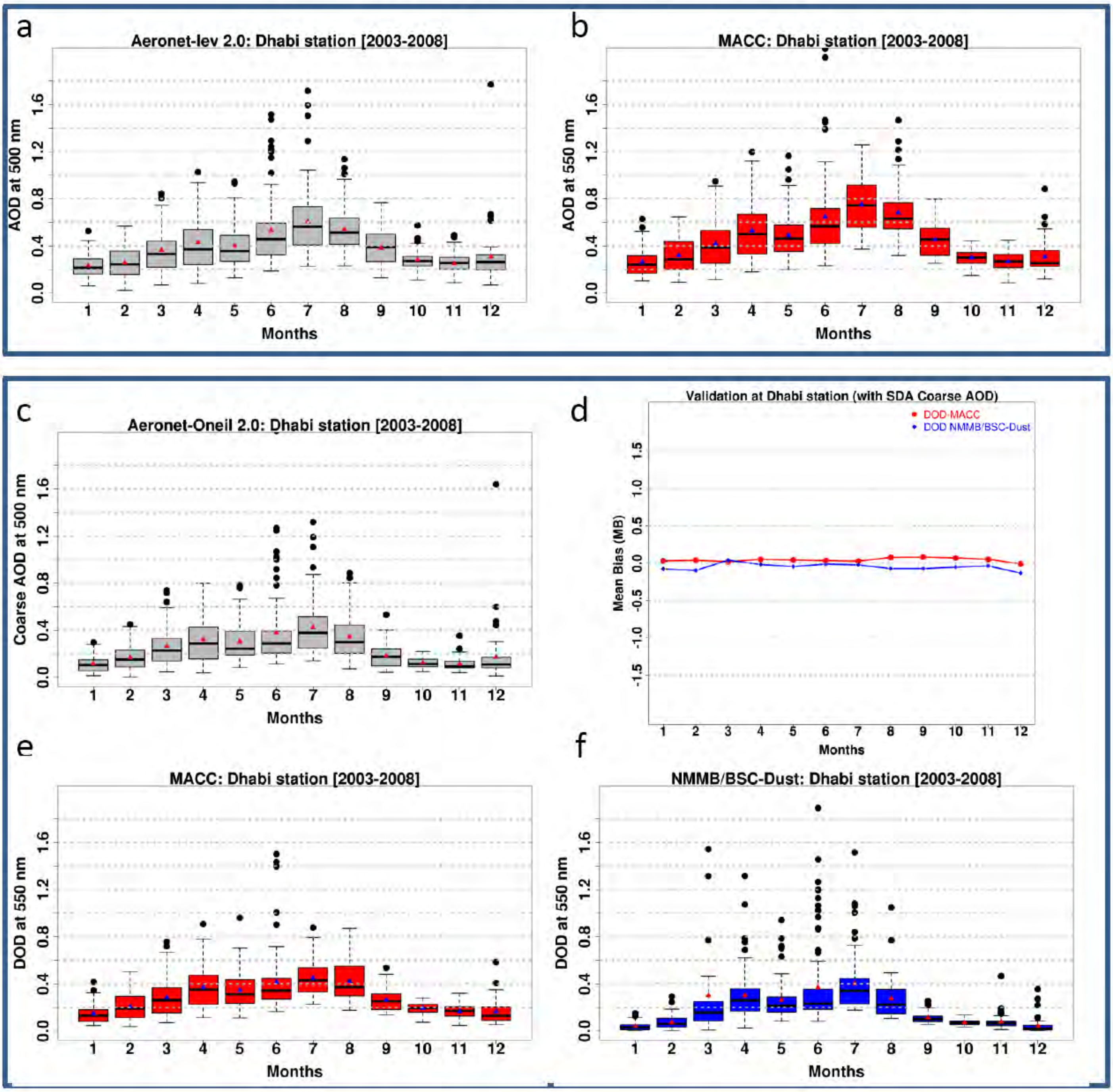


Figure 43 - (a) monthly mean values of total AOD AERONET level 2.0 at Abu Dhabi station for the period 2004–2006; (b) monthly mean values of total AOD simulated with MACC-ECMWF using coincident days with the AERONET station; (c) coarse AOD computed with AERONET level 2.0 data at Abu Dhabi station using SDA (*O'Neill et al., 2003; 2005*); (d) monthly averaged MB of DOD for MACC-ECMWF and NMMB/BSC-Dust simulations when compared with coarse AOD from AERONET; (e) monthly mean DOD from MACC-ECMWF for coincident days with AERONET during the period 2004–2006 at Abu Dhabi; (f) monthly mean DOD from NMMB/BSC-Dust for coincident days with AERONET during the period 2004–2006 at Abu Dhabi

A.2.6.6 Comparison of dust climatologies from AERONET, MACC-EMWF and satellite-based sensors

In order to show how well MACC reproduces AOD monthly climatology, it was compared with AOD climatology computed from MODIS and MISR-DB AOD for Bahrain station, by choosing those days when AOD was available from the three systems (AERONET/MACC-ECMWF/MODIS-DB and AERONET/MACC-ECMWF/MODIS-DB) (see Figure 44). A first conclusion, apart from the comparison of the systems, is that the climatology is greatly dependent on the days chosen to build it. The climatology in the left panel clearly differs from the climatology in the right panel. In general, as a monthly average, it is important to have the highest number of days with observations and/or simulations. This poses a problem in the case of AERONET and satellite sensors with clouds at some sites.

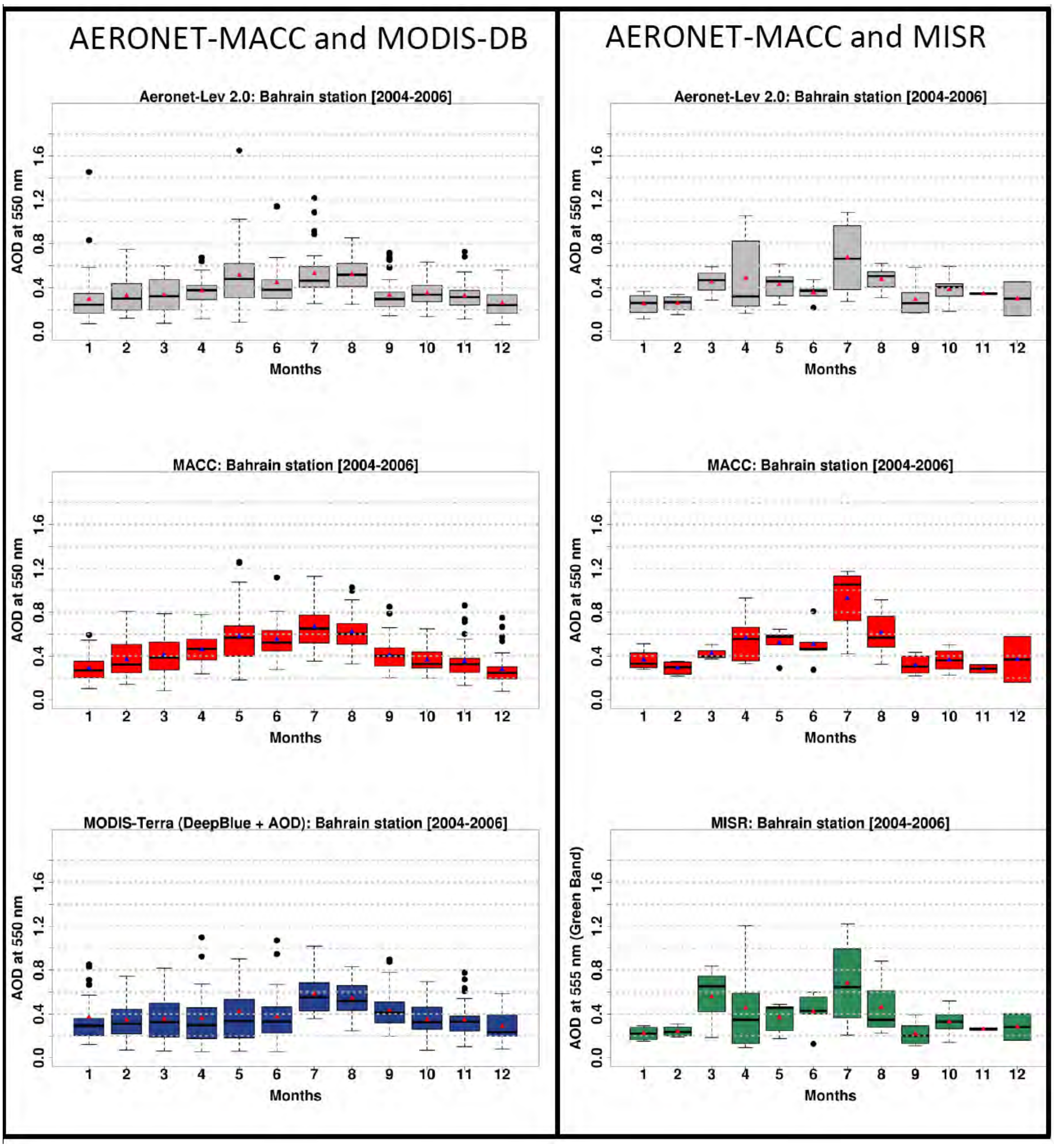


Figure 44 - Left panel: monthly mean total AOD for Bahrain AERONET station (top), monthly mean total AOD from MACC-ECMWF model interpolated for Bahrain (middle) and total AOD from MODIS-DB model interpolated for Bahrain (bottom). Note that, for the monthly climatology, only matching days in all three systems have been computed. Right panel: the same as left panel, but for AERONET, MACC and MISR. Note that both climatologies (left and right panels) do not coincide, since the days selected to produce them are very different. For example, MISR has data on the AERONET station every nine days

From Figure 44, it can be seen that MACC agrees quite well with AERONET, better than MODIS-DB and similar to MISR. In the case of inland stations well inside the desert, as, for example Solar Village, the agreement between AERONET and MACC-ECMWF is much better than the agreement found between AERONET and MODIS-DB (not shown here).

A.2.6.7 Climatology of AOD from MACC-ECMWF

Interesting conclusions can be obtained from the comparison of the monthly climatology of total AOD with the monthly climatology of the number of days with AOD higher than 0.5 (see Figure 45 as zoomed-out example corresponding to May). In Figures 47 and 48, the monthly maps of total AOD simulated with MACC-ECMWF are compared with the monthly maps of the number of days with total AOD > 0.5 from MACC-ECMWF. First monthly maps have been obtained from the daily averaged data computed from model-reanalysis outputs at 06:00, 12:00 and 18:00 UTC for the period January 2003–March 2010.

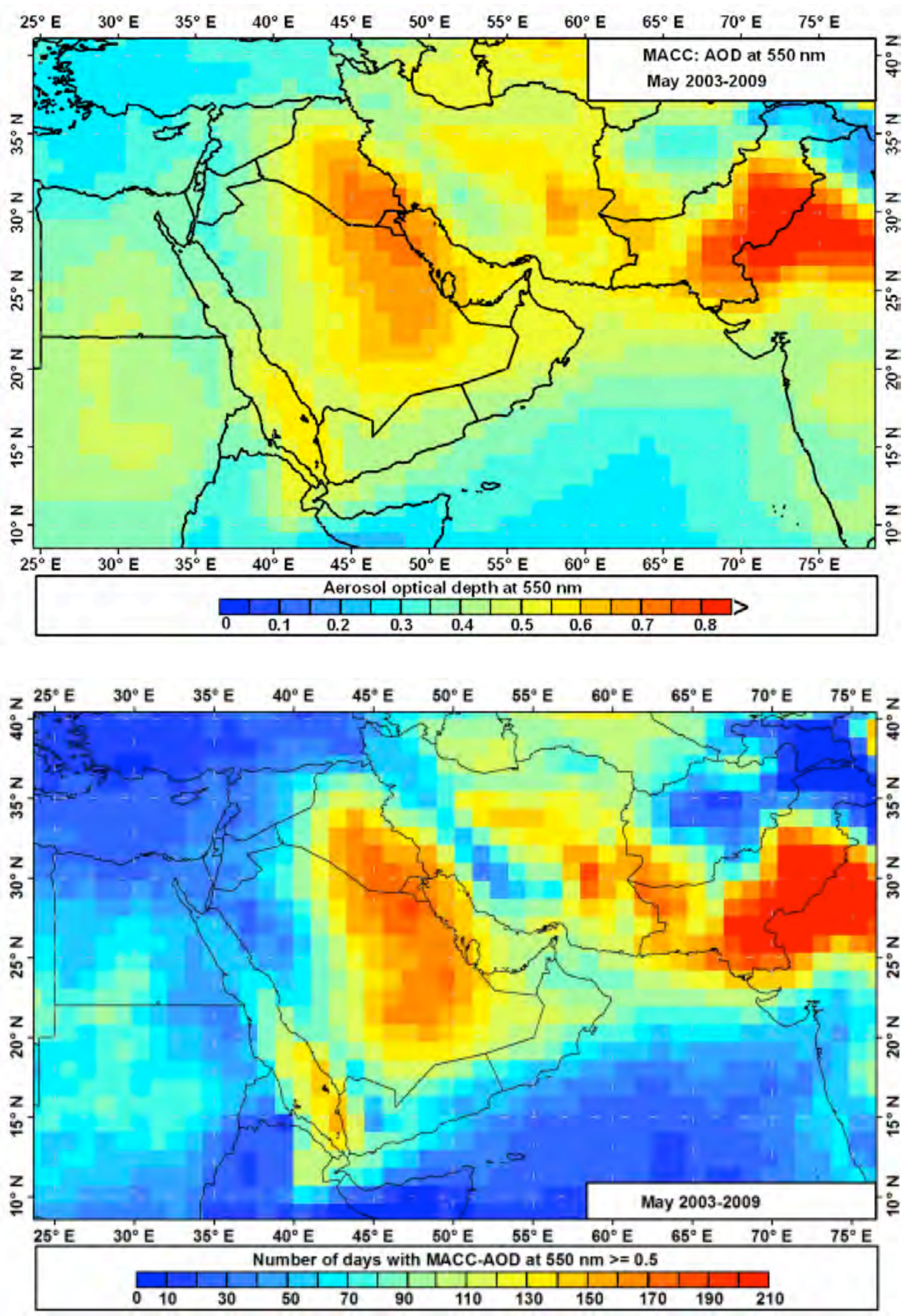


Figure 45 - Total AOD from MACC-ECMWF (top) and the number of days with AOD > 0.5 (bottom) for May during the period 2003–2010

While total AOD maps provide information about the intensity of aerosols, the number of days with AOD > 0.5 gives us information about the persistence of high AOD values. This combined information shows the regions most impacted by dust and other aerosols in West Asia (Figures 47 and 48).

In January and February, southern Saudi Arabia, the eastern part of the Arabian Peninsula and a north-west to south-east corridor covering Iraq and the Gulf Sea, as well the Iranian Sistan region, show some AOD signal in intensity and persistence that increases slightly in February.

In March, the areas are the same but with intensified AOD values and persistence.

In April, higher AOD over the aforementioned zones is observed and a new area becomes important in central Islamic Republic of Iran, following a north-west to south-east axis.

In May, the situation in the Sistan region and central Islamic Republic of Iran intensifies. The south-west coast of Saudi Arabia and southern Red Sea, which showed light-to-moderate AOD in the previous months of winter, shows significant intensification.

In June, Oman and Yemen, where low AOD persisted, compared with the moderate AOD over Saudi Arabia, the AOD signal and its persistence intensify significantly. The Tokar Gap region in north-eastern Sudan activates dust being carried into the Red Sea. AOD intensifies over southern Islamic Republic of Iran, being quite visible with a moderate-to-high north–south axis corridor. Dust sources in the south-eastern Islamic Republic of Iran/Pakistan region contribute to the high dust observed over the northern Arabian Sea.

In July, AOD maximizes in the majority of regions. The Arabian Sea presents high and persistent AOD, as well as the Gulf and the Red Sea. High AOD in central Islamic Republic of Iran is also visible. All the Gulf countries record the maximum AOD, as does Yemen.

In August, both the intensity of AOD and its persistence start to decrease in all regions, except in the southern Red Sea and the border region of UAE, Oman and Saudi Arabia. The AOD signal in the Tigris-Euphrates basin (Iraq), mainly affecting Kuwait, is also important.

In September, AOD and its persistence reduce significantly but the regions with moderate-to-high AOD observed in August still show significant AOD and persistence but at a lesser intensity.

In October, AOD becomes low in most regions and only the Sistan region and Iraq still show moderate AOD and persistence.

In November, some AOD signal is observed in Iraq.

In December, the AOD values are quite low in all parts of West Asia.

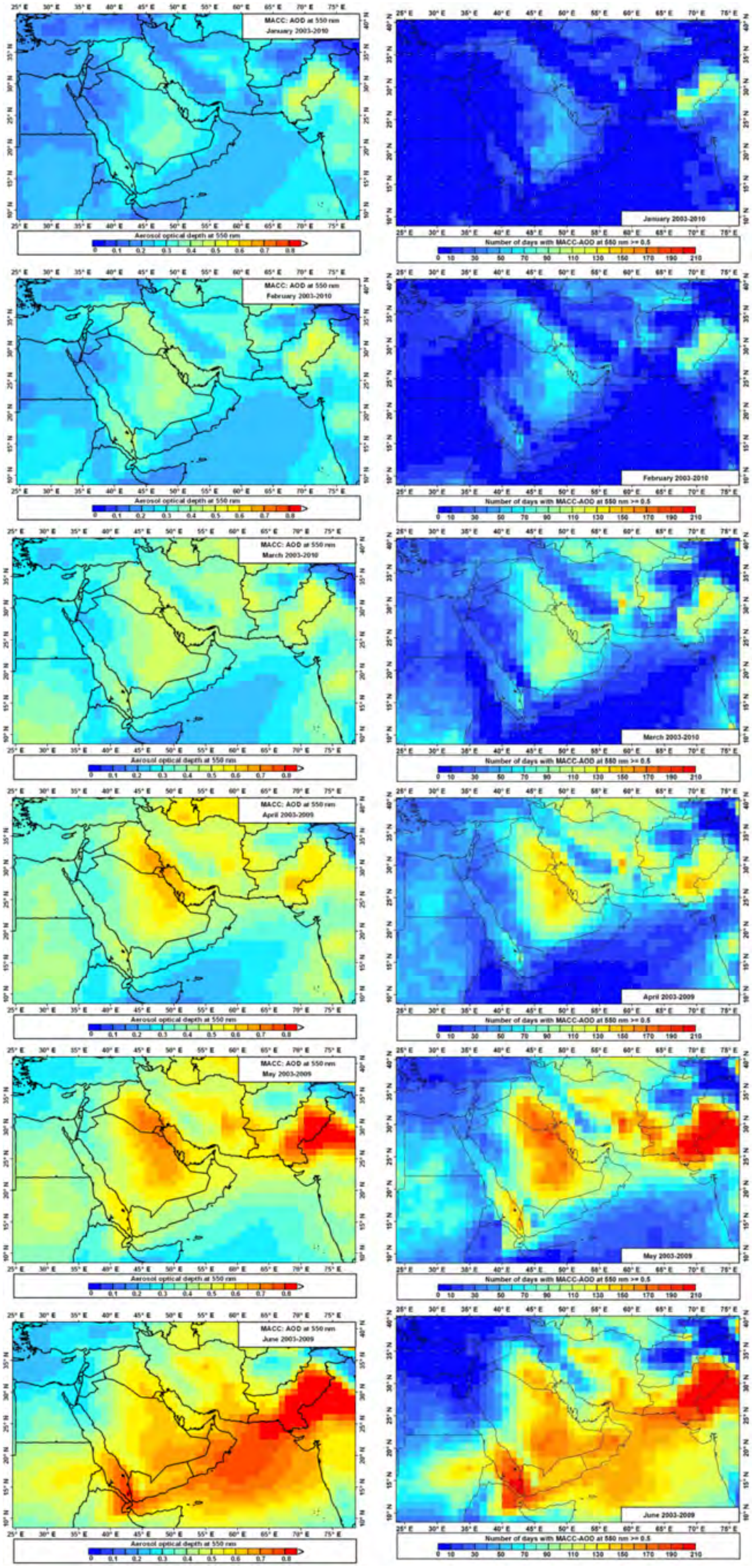


Figure 46 - Total AOD from MACC-ECMWF (left panel) and the number of days with AOD > 0.5 (right panel) from January to June during the period 2003–2010

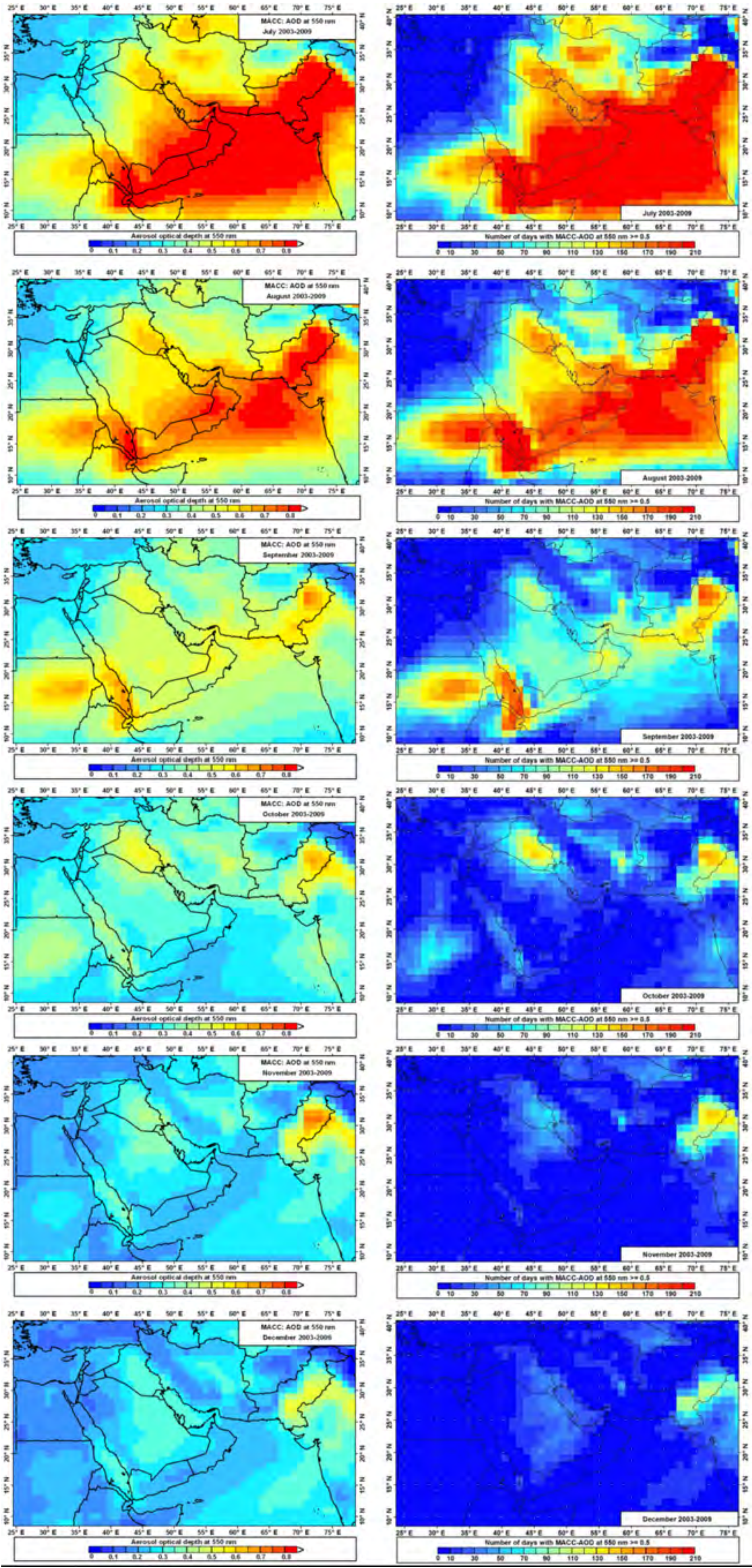


Figure 47 - Total AOD from MACC-ECMWF (left panel) and the number of days with AOD > 0.5 (right panel) from July to December during the period 2003–2010

A.2.6.8 Trend analysis at dust hotspots

This section offers a preliminary analysis of trends in AOD over those regions identified as dust hotspots. This is not a rigorous analysis but a first approach to providing useful information when making recommendations on observation networks (Part B of this report).

The following important dust hotspots and neighbouring dust pathways have been analysed:

- Tokar Gap (Sudan): 18°–21°N/35°–40°E
- Empty Quarter (Saudi Arabia): 19°–24°N/44°–51°E
- Mesopotamia (Iraq): 31°–37°N/42°–45°E
- Central Islamic Republic of Iran: 34°–36°N/50°–55°E
- Central-western Afghanistan: 30°–32°N/61°–66°E

Region 1 - Tokar Gap (Figure 48)

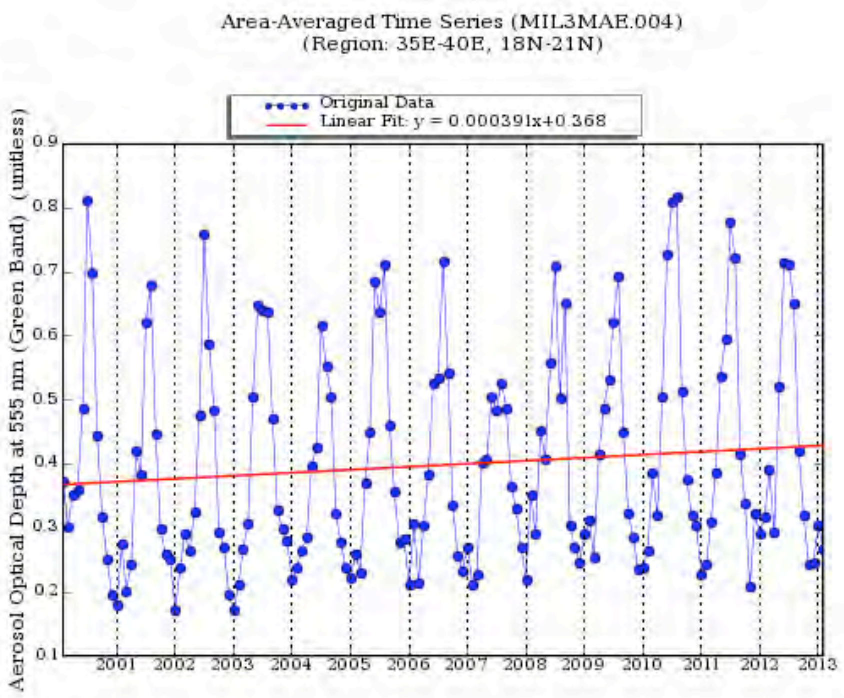


Figure 48 - Monthly mean AOD at 555 nm from MISR for Region 1 (Tokar Gap) averaged from February 2000 to February 2013

Region 2 - Empty Quarter, Saudi Arabia (Figure 49)

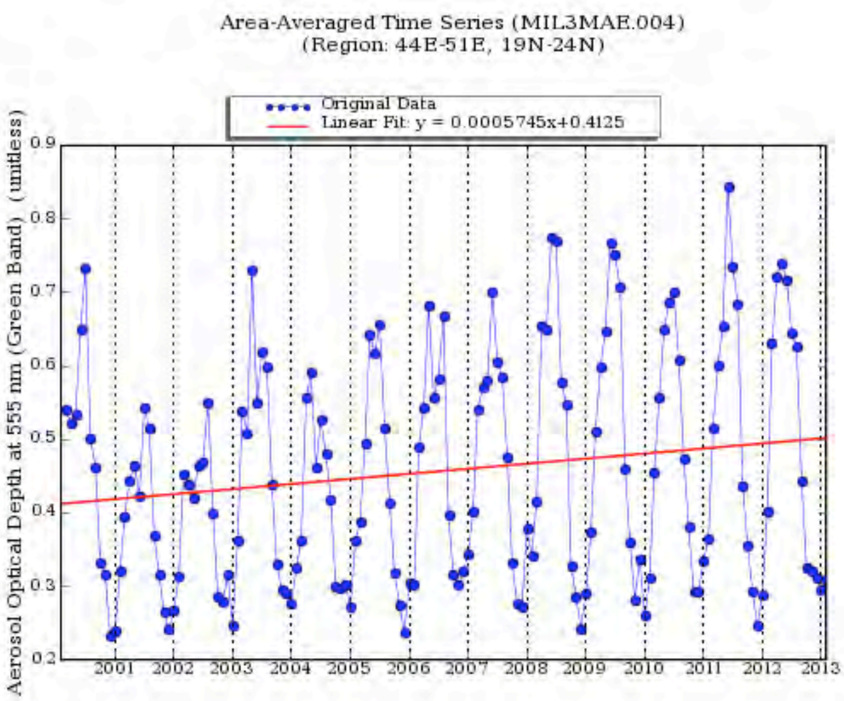


Figure 49 - Monthly mean AOD at 555 nm from MISR for Region 2 (Empty-Quarter, Saudi Arabia) averaged from February 2000 to February 2013

Region 3 - Mesopotamia, Iraq (Figure 50)

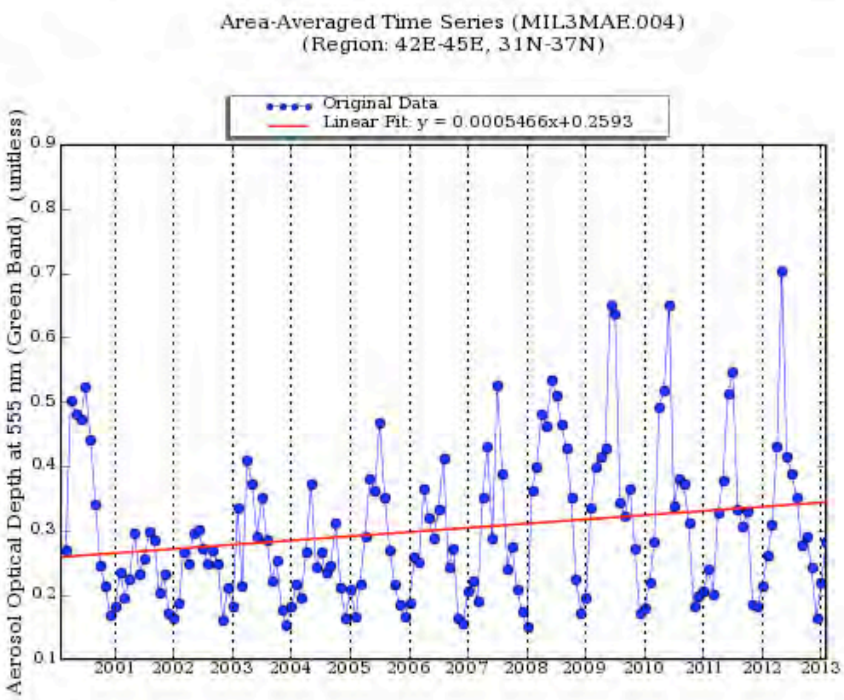


Figure 50 - Monthly mean AOD at 555 nm from MISR for Region 3 (Mesopotamia) averaged from February 2000 to February 2013

Region 4 - Central Islamic Republic of Iran (Figure 51)

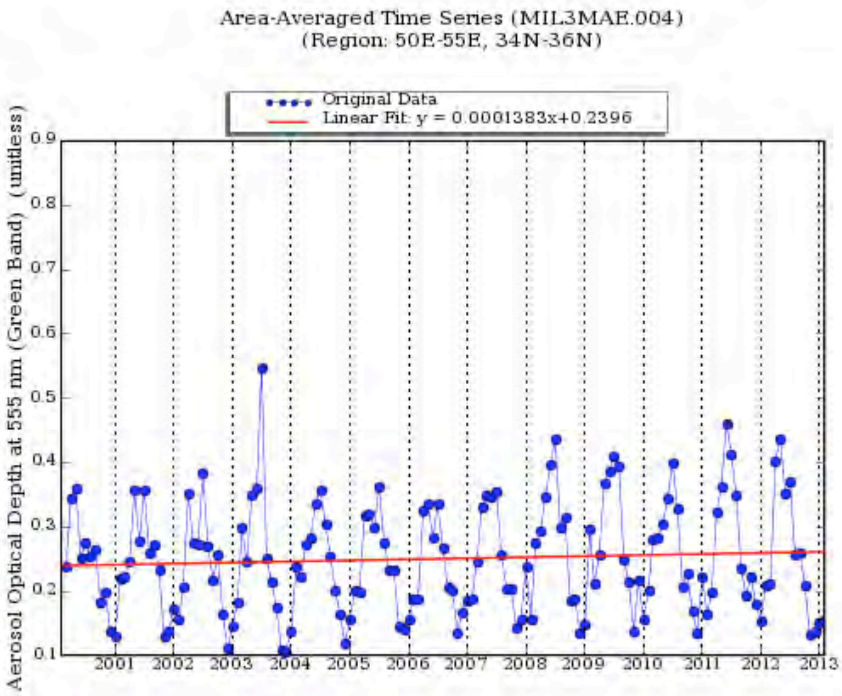


Figure 51 - Monthly mean AOD at 555 nm from MISR for Region 4 (central Islamic Republic of Iran) averaged from February 2000 to February 2013

Region 5 - Central-western Afghanistan (Figure 52)

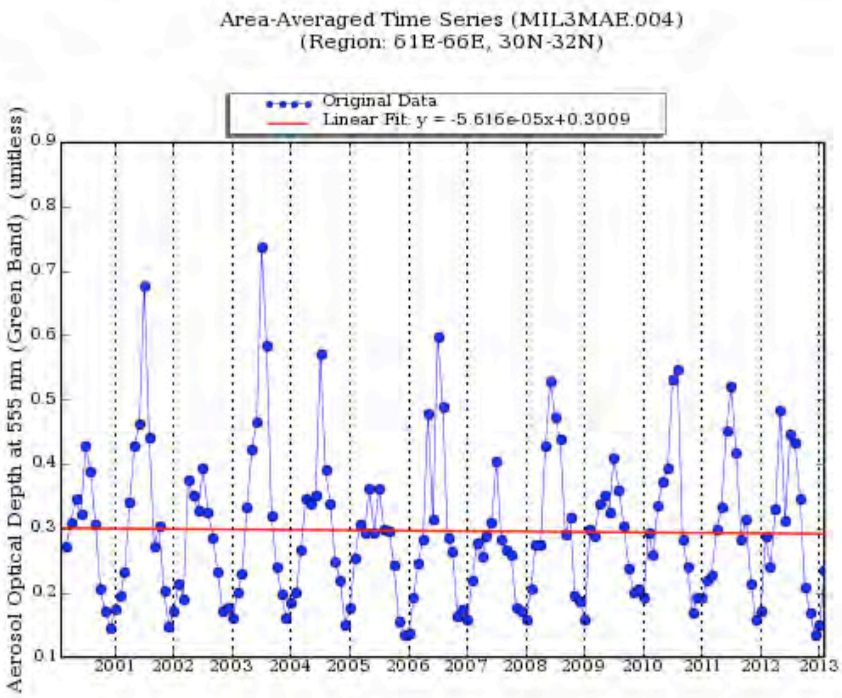


Figure 52 - Monthly mean AOD at 555 nm from MISR for Region 5 (central-western Afghanistan) averaged from February 2000 to February 2013

Although these plots constitute an initial and simple approach to dust trend, there are some interesting results. No significant trends are observed in Region 1 (Tokar Gap), Region 4 (central Islamic Republic of Iran) or Region 5 (central-western Afghanistan). Even in the latter, a non-statistically significant negative trend is observed. In Region 2 (Empty-Quarter, Saudi Arabia) and Region 3 (Mesopotamian, Iraq), however, a clear, positive AOD trend is observed from MISR. The trend seems to occur only in spring (April–June) in Region 3 while, in Region 2, the positive trend is observed in spring and summer.

The positive trend found over Iraq might be linked to the increase in the number of dust sources in the last decade found by *Keramat et al. (2011)* in the Syrian Arab Republic and Iraq. In order to check this trend, at a first approximation, EVI averaged over Region 3 was plotted (Figure 53). EVI is a measurement of the "greenness" of the Earth's land surface, with increasing greenness indicating increased ground cover by growing vegetation. A clear negative trend is observed for the available period 2002–2013 over Mesopotamia, mainly affecting spring values. The positive trend in AOD values in Region 3 might therefore be a result of land degradation, probably due to reduced water availability and land-use changes.

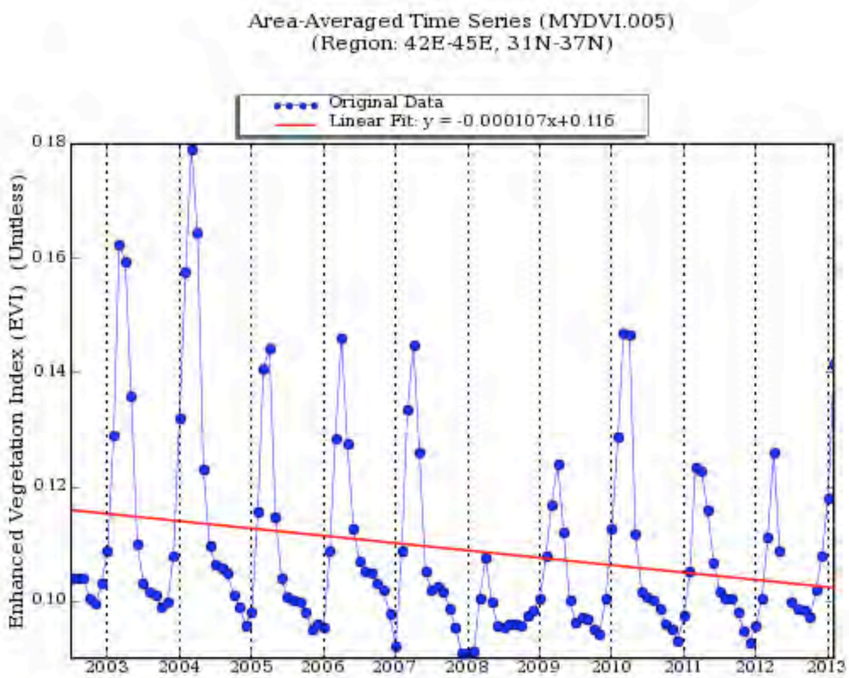


Figure 53 - Monthly mean EVI from MODIS for Region 3 (Mesopotamia, Iraq) averaged from February 2002 to February 2013

Concerning Region 2, a similar EVI plot is shown in Figure 54, where a negative trend in the EVI is again found, although values are much lower than for Mesopotamia.

Trend analysis of wind speed at 1 000 hPa (not shown here) over Region 2 for 2000–2011 between May and August does not show a trend. Further accurate trend analysis is needed to assess the observed changes (see Section B.2).

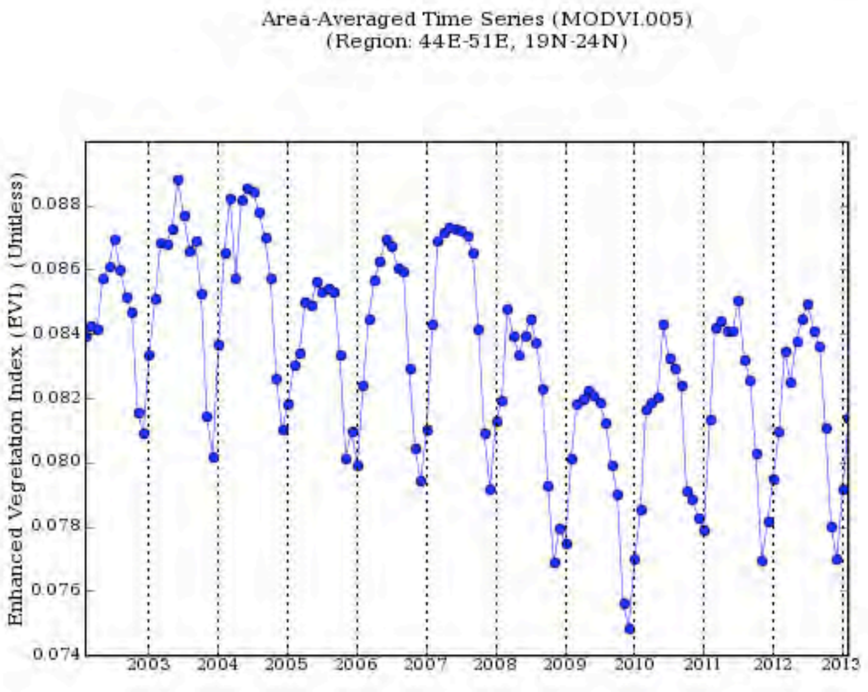


Figure 54 - Monthly EVI from MODIS for Region 2 (Empty Quarter, Saudi Arabia) averaged from February 2002 to February 2013

A.2.7 Summary of dust sources and dust storms by country

In this section, main dust sources and dust storm impacts are summarized by country, using information obtained in the literature and the dust climatology elaborated for this report (Section A.2.6).

Saudi Arabia

Saudi Arabia has many dust sources, some of which are geographically large. Dust activity is visible over most of the Arabian Peninsula throughout the year but is especially strong from March to July and low in winter.

In the north-west:

- The region lying within a southern extension of the Jordan/Syrian desert known as the high desert of An Nafud or the Great Nafud (*Bukhari, 1993*): this region provides multiple point dust sources affecting Saudi Arabia.
- The highlands north and south of Medina: after a frontal passage, dust travels to the south-east or south. Pre-frontal dust tends to blow to the north-east or east. Dust storms resulting in shear lines are normally confined to the highlands but sometimes blow west into the north-eastern Red Sea.

In the north-east:

- Tigris-Euphrates basin (Iraq) and part of the Syrian Arab Republic.

In central parts:

- The region known as the Ad-Dahna Desert, the central division of the Arabian Desert: a corridor of sandy terrain forming a bow-like shape that connects the An-Nafud Desert in the north to the Rub' al-Khali Desert in the south. Oriented north-west to south-east, it favours a continuous supply of dust south-east across the Arabian Peninsula.

In the Red Sea area:

- The Tokar Gap in north-eastern Sudan, near the Red Sea: in summer, the dust blows into the Red Sea for several days, enveloping the region from Tokar to the Gulf of Aden in a hazy/dusty atmosphere.

In the south:

- The Rub' al Khali is the largest sand desert in the world, and one of the hottest and most arid locations in Saudi Arabia, encompassing most of the southern third of the Arabian Peninsula and areas of Oman, the UAE and Yemen.
- The eastern slopes and the foot of the Sarawat Mountains of Yemen.

United Arab Emirates

- Tigris-Euphrates basin (Iraq).
- The Rub' al Khali Desert in western UAE.
- The Ad Dahna Desert (Saudi Arabia), oriented north-west to south-east, favours a continuous supply of dust south-east over the Gulf and the UAE.
- The eastern slopes and the foot of the Sarawat Mountains of Yemen.

Oman

- Tigris-Euphrates basin (Iraq).
- Intense and well-defined sources in Oman (*Prospero et al., 2002*) are active all year long, although the highest activity is in June and July and the weakest from November to February. The dust area is well delineated by the 200-m contour, mainly affecting Oman.
- The region on the southern Iranian coast of the Gulf affects the Gulf of Oman and eastern Oman (Mascate and Batina).
- The eastern slopes and the foot of the Sarawat Mountains of Yemen.

Bahrain

In general, Bahrain is affected by most dust sources in Iraq and the Arabian Peninsula and especially by:

- The Tigris-Euphrates basin (Iraq).
- The Ad Dahna Desert in the central-eastern Arabia Peninsula (Saudi Arabia) by the Gulf Sea coast favours a continuous supply of dust that is liable to affect Bahrain.
- The Rub' al-Khali Desert (Saudi Arabia).
- The region on the southern Iranian coast of the Gulf.

Qatar

In general, Qatar is affected by most dust sources over the Arabian Peninsula and specifically by:

- The Tigris-Euphrates basin (Iraq).
- The Ad Dahna Desert, in the central-eastern Arabia Peninsula (Saudi Arabia) by the Gulf Sea coast, favours a continuous supply of dust that is liable to affect Qatar.
- The Rub' al-Khali Desert (Saudi Arabia) where dust storms originate before they move over the Arabian Sea and eventually impact Qatar.
- The southern Iranian coast of the Gulf.

Kuwait

Kuwait is the country most affected by dust intrusions. It is impacted by dust sources in Saudi Arabia and to some extent southern Islamic Republic of Iran. Kuwait is much affected by a quasi-continuous dust flow from Iraq.

In general, the Mesopotamian region in the Syrian Arab Republic, Iraq, western Islamic Republic of Iran and the north-eastern Arabian Peninsula are potential sources to impact Kuwait. Dust activity in the Tigris-Euphrates basin begins around May, reaches a maximum in July and is much reduced by September–November. In spring, the region is affected by north-westerly shamal winds that transport dust down to the Gulf. In more detail, impacts from the following sources have been reported:

- The region lying east of the ruins of Babylon at Al-Hilla (Iraq), from May to October.
- The region located to the south of the Euphrates River (Iraq) in summer and autumn.

- The region to the south of Ad Diwaniyah (Iraq) from June to October.
- The region to the west of An Nasiriya (Iraq) all year.

Iraq

It is, by far, the country with the most important sources of dust affecting many countries in the region. Iraq is impacted by its own sources, located in Mesopotamia and especially in the Euphrates-Tigris basin. Iraq can also be impacted by dust sources located in the eastern Syrian Arab Republic.

Islamic Republic of Iran

The following Mesopotamian regions are potential dust sources that may impact the country:

- East of the ruins of Babylon at Al-Hilla (Iraq), from May to October.
- East of El Rashid (Iraq) to the north of the Euphrates River and south of the Abdul al Aziz Mountains.
- North of Iraq near Mosul: some dust storms moving south-east might impact Ilam province (central-western part), mainly in summer.
- South of Kut (Iraq) in the lowlands of the Tigris River: the Abadan region (south-west) might be affected, mainly in summer and autumn.
- South of Mehran, on the border with Iraq: an impact through a southward track to Khuzistan.
- South of Dezful, where southward dust storms impact the north-eastern Gulf and the south-west.
- Caspian Sea: there is notable and persistent dust activity between the Caspian and Aral Seas, from May to August, peaking in June and July.
- The Garabogazköl Aylagy (literally “land strait lake”) is a shallow, inundated depression in the north-western corner of Turkmenistan and is the most active dust source in this region.
- The Turan Depression (Turan Lowland) is a low-lying, desert-basin region stretching from southern Turkmenistan through Uzbekistan to Kazakhstan on the south and south-east end of the Aral Sea, with persistent dust activity.

In northern parts:

- A major dust-source area is located in a large intermountain basin south of the Reshteh-ye Kuhha-ye Alborz Mountains, extending from Tehran eastward to 60°E to the Dasht-e Kavir Desert, consisting largely of salt flats (*Prospero et al., 2002*).

In central parts:

- The region of several dry lakebeds to the east and south-east of Esfahan, affects central and western areas.

In the eastern-southern region:

Dust sources in the Iranian-Afghan-Pakistan borders contribute to high dust levels over the northern Arabian Sea:

- The region that lies on the eastern shores of Hamun-e Saber, to north-west Chhand, in the east.
- The intermittent salt lake of Daryācheh-ye Sīstan on the border with Afghanistan in the Sistan region.
- The region north-west of Zabol in Sistan.
- The Dasht-e Lut, known as the Lut Desert, is a large salt desert in south-eastern Kerman and is the world’s 25th largest desert.
- The Kerman Desert (along the slopes and at the foot of the Beyanae Kerman and Pir Shoran Mountains.
- The Makran coast: the region along the coast of the Gulf and the Arabian Sea on the southern flanks of the mountain chain along the coast.

The western area is affected by the east and south-eastern Arabian Peninsula and by The Rub' al Khali (Empty Quarter).

Turkey

Turkey is a special case because it has notable sources of dust but is only impacted by sporadic dust outbreaks from North Africa (the most important) and from northern Middle East (least important). Summarizing the main dust sources affecting Turkey are the following (Kubilay, 2000, 2003 and 2005):

- The North African coast in late winter and spring.
- Inland North Africa in winter and spring.
- The south-west, central-eastern Sahara in summer.
- The Middle East–Arabian peninsula, in autumn, although south-east flow from this region is infrequent: dust normally comes from the region lying within a southern extension of the Jordan/Syrian desert known as the Great Nafud, and sporadically from the highlands north and south of Medina (Saudi Arabia) and from the Upper Euphrates valley (Iraq).

A.2.8 Reported dust trends

Zhang and Reid (2010) used 10-year (2000–2009) data-assimilation quality Terra MODIS and MISR aerosol products, as well as seven years of Aqua MODIS, to study both regional and global aerosol trends over the oceans (see Figure 55). Their results about the Middle East are quite conclusive. They determined that AOD over the Arabian Sea showed increasing trends of 0.06 per decade from MODIS. This regional trend is considered as significant with a confidence level above 95%. A similar increasing trend was found from MISR, but with less relative magnitude. The authors also concluded that the trend over the Arabian Sea was partially the result of increased dust aerosol presence. Clear positive trends are observed in the Red Sea, Arabian Sea and especially in the Gulf, recording the highest positive trend of AOD in the world.

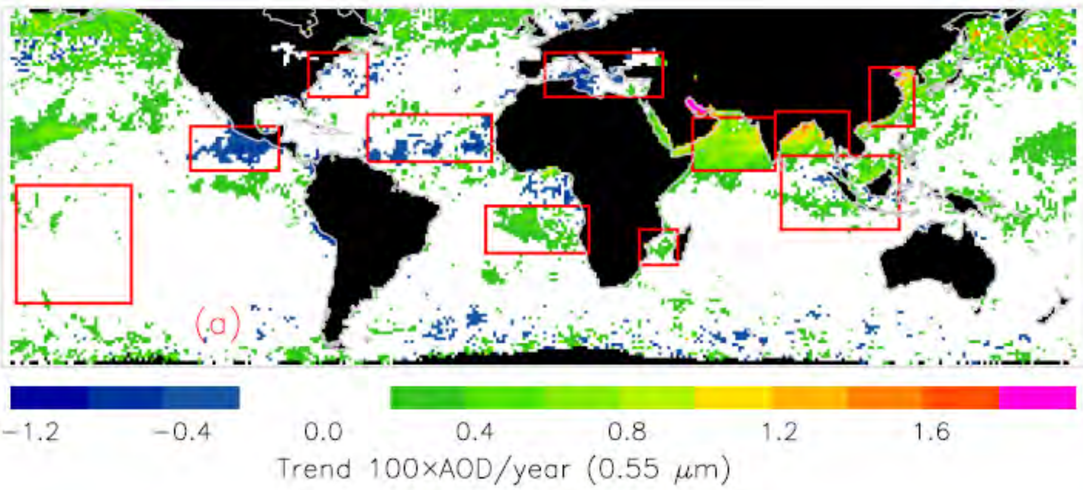


Figure 55 - Spatial distribution of 10-year AOD trends for every 1°×1° (latitude/longitude) (from *Zhang and Reid, 2010*): positive trends over the Arabian Sea, Red Sea and Gulf are well observed. Note the huge AOD increase in the Gulf (in pink), the highest positive trend on a global scale

Xia (2011) performed an analysis of changes in AOD and AE using aerosol-loading data from 79 AERONET stations with observations from more than six years. He developed a statistical method to determine whether AOD changes were due to increased background AOD values and/or an increased number of high AOD events. The analysis (Figure 56) shows that AOD at Solar Village (Saudi Arabia) showed a strong and significant increasing trend (0.17 per decade), according to time series of monthly anomalies of AOD and AE. Increased AOD was dominantly attributable to an increased occurrence of high AOD events (46%) and corresponding AOD values

(20%). AE decreased by 0.32 per decade. Increased AOD and decreased AE at Solar Village station indicate increased dust over the Arabian Peninsula.

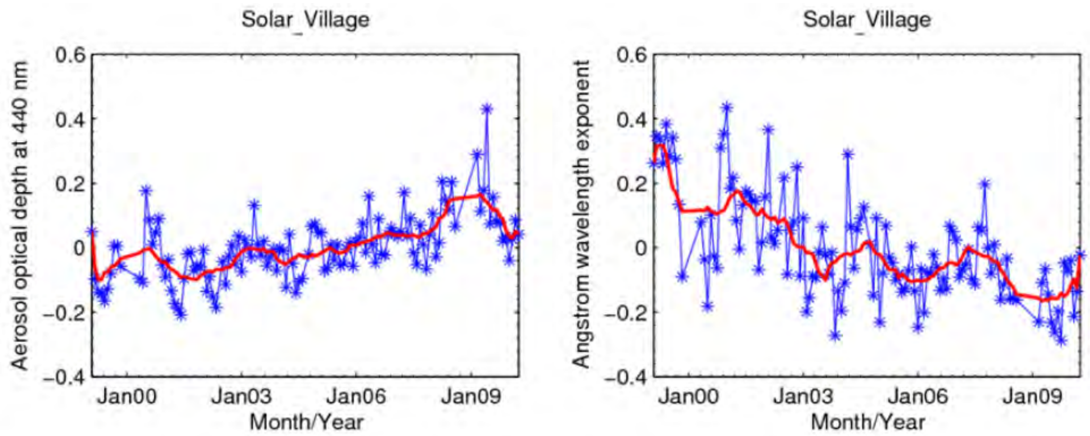


Figure 56 - Monthly anomalies of AOD (left) and AE (right) at Solar Village AERONET station (Saudi Arabia): the smoothed average is represented by the red line (from *Xia, 2011*)

Making use of a newly developed AOD retrieval algorithm for SeaWIFS measurements over land and ocean, Hsu et al. (2012) investigated the distribution of AOD and identified emerging patterns and trends in global and regional aerosol loading. They found that the Arabian Peninsula is – by far – the region with the largest AOD positive trend in the world (+ 0.0092 ± 0.0013/yr), as can be seen in Figure 57. Concerning AERONET data, they also found strong positive trends over the Arabian Peninsula, the surrounding Arabian Sea and the Gulf, especially during spring and summer (0.0116 ± 0.0015/yr and 0.0140 ± 0.0022/yr, respectively) (see Figure 58).

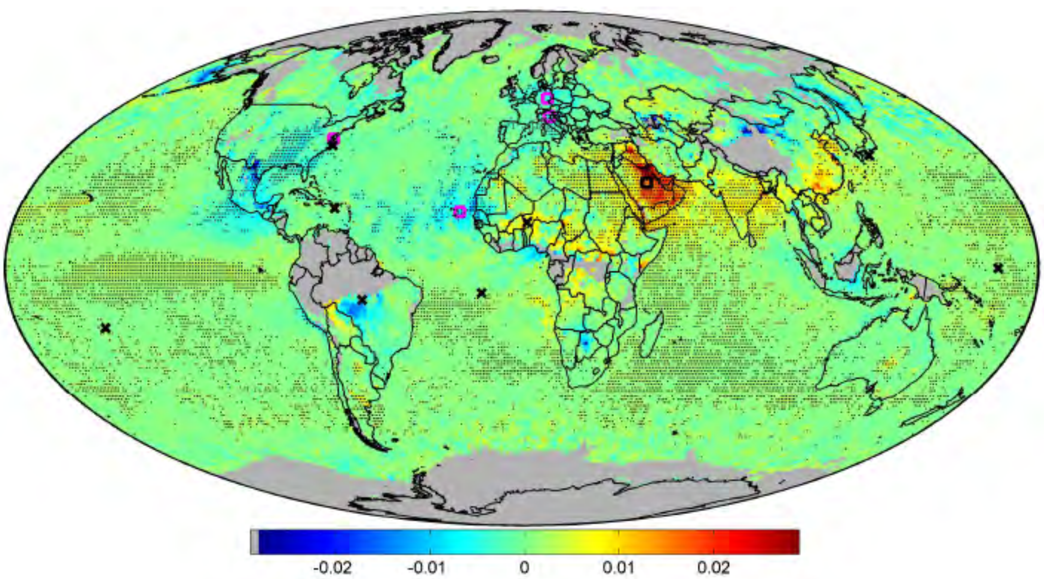


Figure 57 - Linear trend based upon deseasonalized monthly anomaly of AOD at 550 nm for the period 1998–2010 (AOD/yr): dots indicate significance at 95% confidence level (from *Hsu et al., 2012*)

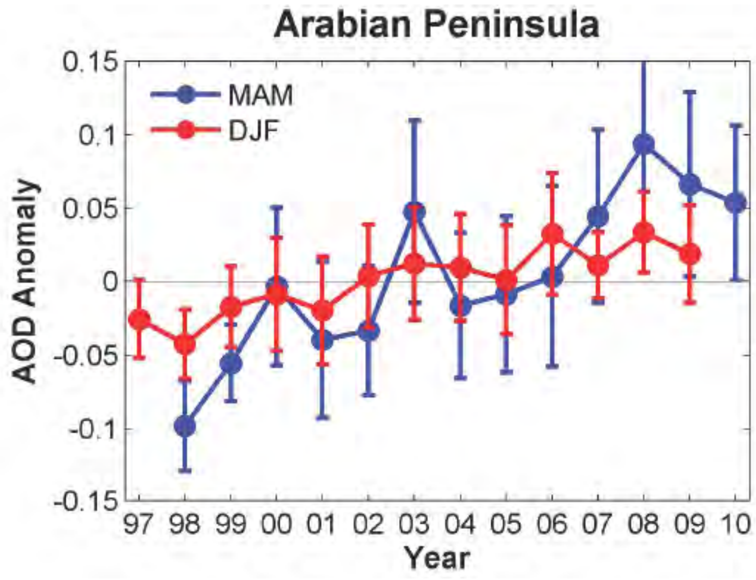


Figure 58 - SeaWiFS time series of seasonal averaged AOD anomaly over the Arabian Peninsula (10°N–35°N, 35°E–60°E). The vertical bars denote the ±1 standard deviation of seasonal averaged AOD anomaly within the specified regions (from *Hsu et al., 2012*)

Data analysis of AERONET observations at Solar Village (Saudi Arabia) shows a systematic increase in aerosol load tendency, as well as a decreasing trend in AE (440–870 nm) for the period 1999–2010 (Figure 59). AE lower than 0.75 indicates that most of the aerosol observed corresponds to the coarse fraction, i.e. mineral dust from deserts (*Basart et al., 2009*).

Figure 59 shows a systematic increasing aerosol loading signal in both SeaWIFS and AERONET data. The interannual variations of AE anomaly from AERONET data (bottom panel) also suggest a characteristic increase in coarse aerosol fraction, which corresponds to mineral dust from deserts.

According to *Goudie (2009)*, the nature of future dust activity will depend on three main factors: (a) anthropogenic modification of desert surfaces (*Mahowald and Luo, 2003*); (b) natural climatic variability (e.g. North Atlantic Oscillation); and (c) changes in climate arising from global warming.

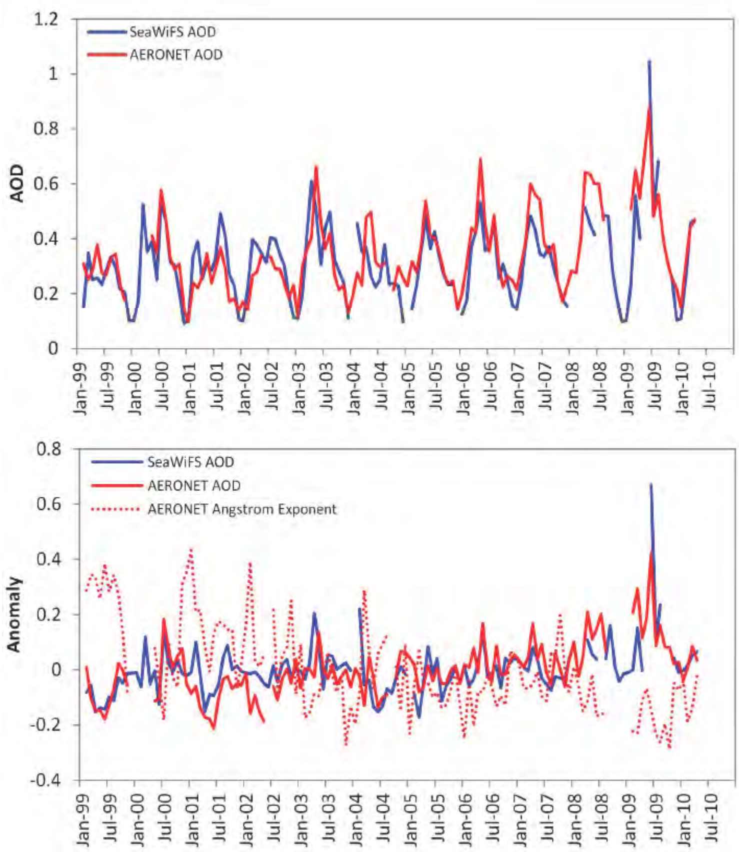


Figure 59 - Interannual variation of AOD (top panel) and AOD anomaly (bottom panel) from SeaWiFS and AERONET measurements co-located over the Solar Village site, for the period February 1999 to April 2010 (from *Hsu et al., 2012*)

Concerning anthropogenic influence, we can cite increasing human pressures, including disturbance of desert surfaces by road traffic, cutting of vegetation cover for wood supply, crop production and desiccation of lakes and soil surfaces by inter-basin water transfers and groundwater depletion (for example the Caspian Sea). *Pelletier (2006)* illustrated that water-table depths of 3–10 m represent a critical range over which small variations in water-table depth may lead to large, non-linear changes in saltation activity and dust emissions.

On the other hand, global warming has the potential to cause major changes in dust emissions. *IPCC (2007(b))* suggests that, under most scenarios, many dryland areas will suffer from lower rainfall regimes and drier terrains because of higher rates of evapotranspiration. Lower rainfall will favour the formation of shallow or extremely shallow soils that are often characterized by a high content of airborne particles and small fractions of rock-erosion elements. Under this scenario, dust storm activity could increase, though this conclusion depends on how winds change – a matter of great uncertainty. *Al-Sarmi and Washington (2011)* have provided a clear picture of climate change in the region. The general pattern of the Arabian Peninsula mean annual temperature trend indicates clear warming with 14 out of 21 stations showing statistically significant warming at the 0.05 level and most of them at the 0.001 level. The highest statistically significant mean annual warming trends are found in Oman (Sur = 1.03°C/decade) and Emirates (Dubai = 0.81°C/decade). Trends in mean annual precipitation are significant at only two stations, which show a decrease in precipitation.

In response to a proposed activity of the World Climate Research Programme's (http://www.wcrp-climate.org/) Working Group (WG) on Coupled Modelling, the Programme for Climate Model Diagnosis and Intercomparison (http://www-pcmdi.llnl.gov/) collected model output contributed by leading climate-modelling centres around the world. These archived data constitute Phase 3 of the Coupled Model Intercomparison Project (CMIP3). The CMIP3 ensemble output for temperature and precipitation for the A1B emission scenario (West Asia) is shown below.

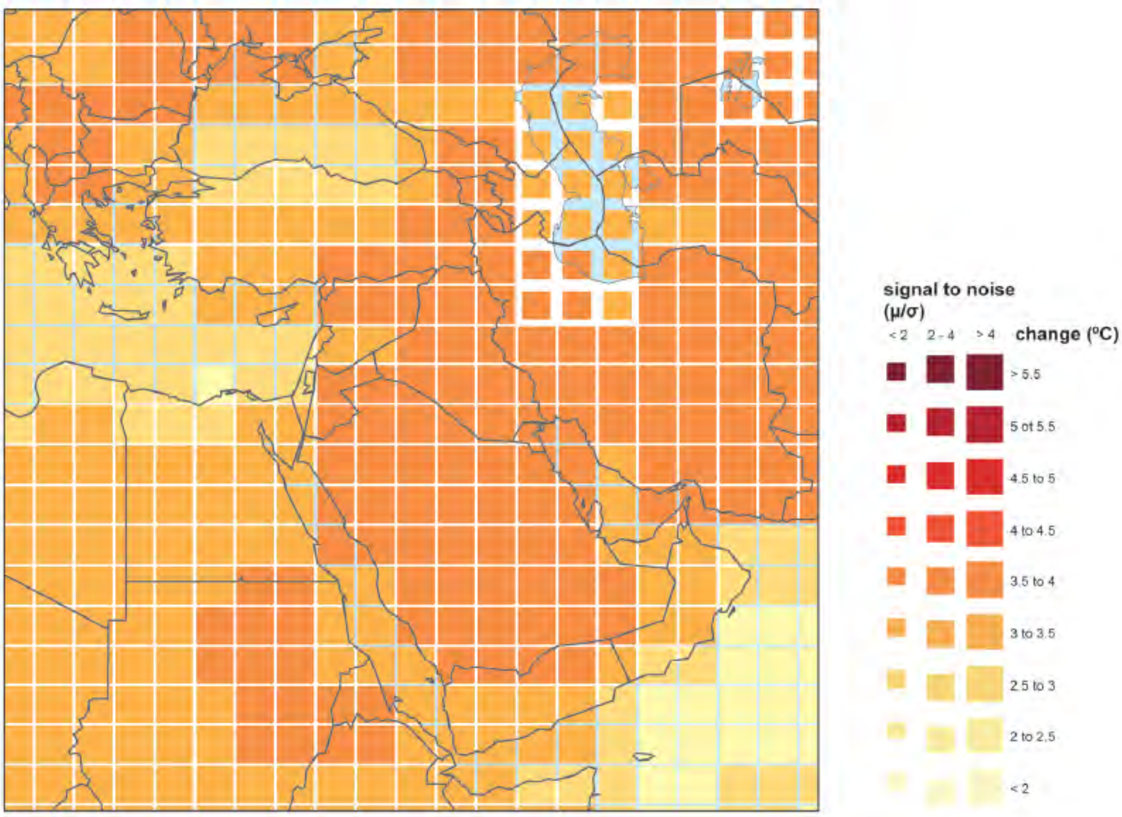


Figure 60 - Percentage change in average annual temperature by 2100 from 1960–1990 baseline climate, averaged over 21 CMIP3 models for West Asia. The size of each pixel represents the level of agreement between models (*UK Met Office, 2011*)

Figure 60 shows the percentage change in average annual temperature by 2100 from 1960–1990 baseline climate, averaged over 21 CMIP3 models for West Asia. Projected temperature increases over most of West Asia are up to 4°C. The agreement between the 21 CMIP3 models is good.

It is expected that a broad swathe of West Asia between 19°N and 41°N will experience mainly decreases in precipitation, as shown in Figure 61. Decreases of up to 20% or more are projected in north-western Saudi Arabia with strong ensemble agreement. Towards the south and east, smaller decreases are projected, and increases of up to 20% or more are projected for the far south-eastern Arabian Peninsula.

Projected higher temperatures and reduced rainfall could favour desertification processes and thus the strength of dust mobilization in West Asia.

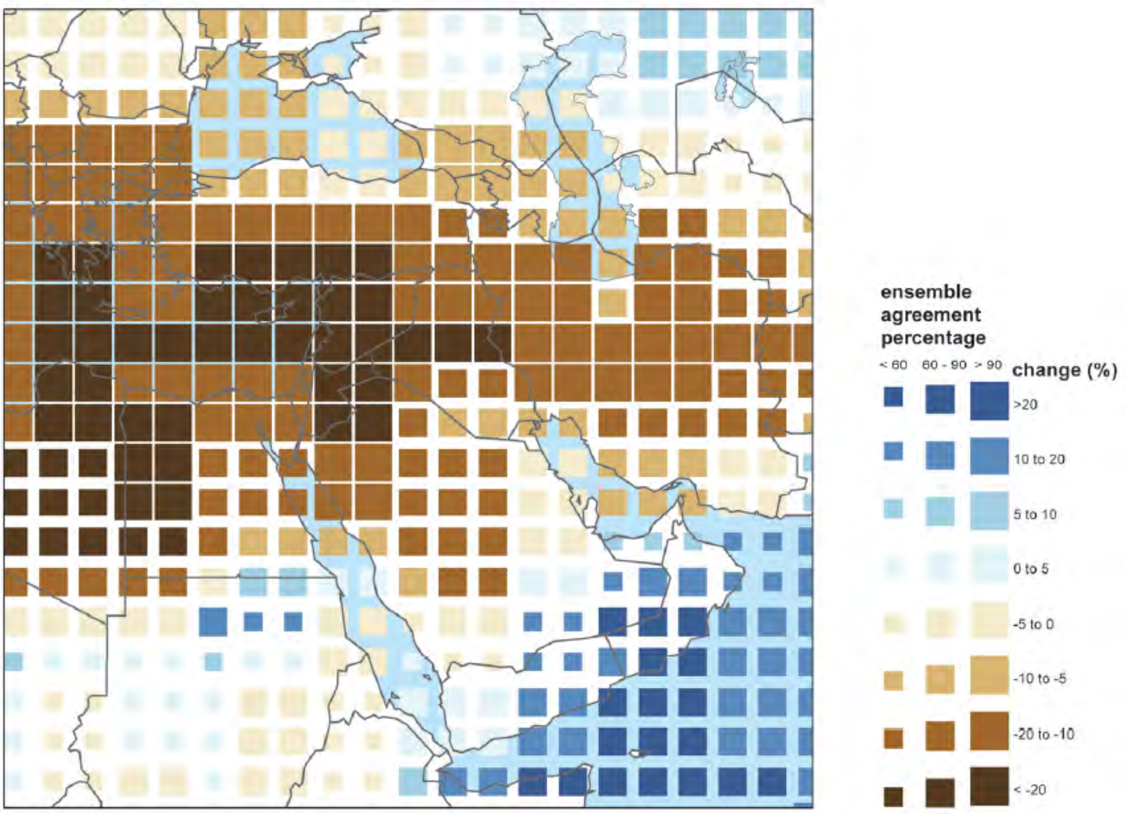


Figure 61 - Percentage change in average precipitation by 2100 from 1960–1990 baseline climate, averaged over 21 CMIP3 models for West Asia. The size of each pixel represents the level of agreement between models (*UK Met Office, 2011*)

A.3 IMPACTS OF DUST IN WEST ASIA

Atmospheric dust has significant impacts on many activity areas in much of the world. Due to the complexity of how sand- and dust storms impact various socio-economic sectors, few data regarding budgetary losses are available. The Middle East is the second largest source of global dust but, unlike North Africa, where large population centres are concentrated along the coasts of the Mediterranean and the Atlantic Ocean, relatively far away from dust sources, much of the population in West Asia lives within, or in the vicinity of, dust sources. Figure 62 shows DOD at 550 nm from NMMB/BSC-Dust for July (period 2003–2009) (left) and the Earth at night in 2012 (from Google Earth), where luminosity is roughly proportional to the number of inhabitants or to human activities. High DOD in West Asia directly impacts large population centres or industrial areas.

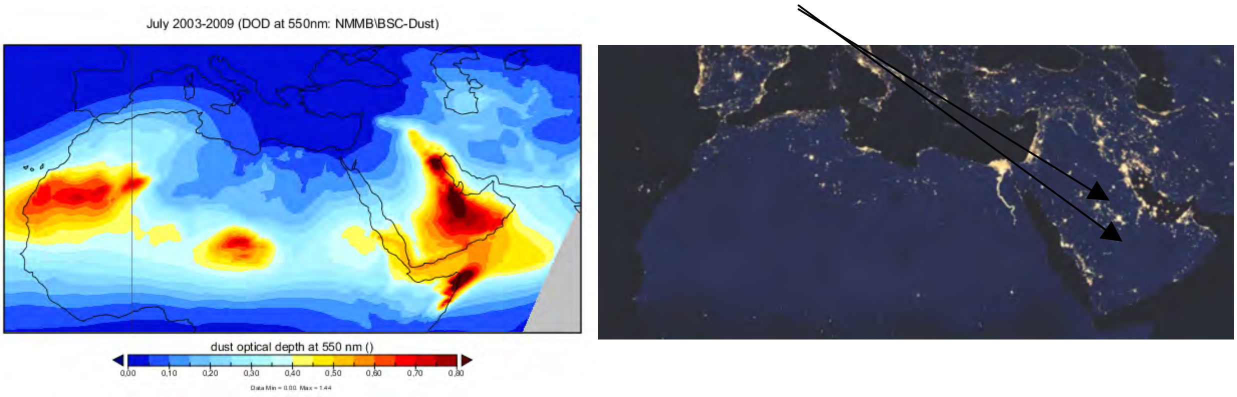


Figure 62 - DOD at 550 nm from NMMB/BSC-Dust for July (2003–2009) (left); Earth at night from Google in 2012 (https://earthbuilder.google.com) (right)

The sections below describe the main impacts of atmospheric dust in general and the impacts on countries of West Asia which have been referenced in the technical and scientific literature in particular.

A.3.1 Dust and pollution: impacts on human health

Airborne mineral dust can have numerous repercussions on human health, such as allergies, respiratory diseases and eyes infections (*WHO, 2005*). There is also evidence of a link to epidemics of lethal meningitis in the semi-arid sub-Saharan/Sahel territory, known as the meningitis belt (*Sultan et al., 2005; Thomson et al., 2006; Cuevas et al., 2011; Pérez et al., 2013*) and increased incidences of paediatric asthma in the Caribbean (*Gyan et al., 2005*).

In 1997, the US Environmental Protection Agency established the “PM2.5 standard” (EPA, 1996), which recognizes the role of aerosols that have diameters ≤2.5 µm in causing health problems. Long exposure to, or large doses of, particles below this size can cause respiratory damage, because they penetrate deep into the alveoli of the human lungs. Because a significant fraction of the mineral DSD contains particles below 2.5 µm in diameter, the welfare of humans who inhabit regions having frequent dust storms should be considered. According to Centeno (2011), the process of inhalation of mineral aerosol particles leading to deposition in the pulmonary alveoli varies with several factors, notably: (a) mineral type (composition) and inclusions; (b) dust-particle size and shape (< 10–20 µm (inhaled), <2 µm (respired)); (c) length of exposure; and (d) certain lung and immune system functions. He concluded that atmospheric dust finer than 2.5 µm is of particular importance with respect to community health, as in the PM standard and, moreover, that particles <4 µm frequently penetrate more deeply into the lungs, so prolonged exposure can lead to pneumoconiosis (including silicosis, asbestosis and other lung conditions).

Dust outbreaks may greatly increase the ambient air levels of PM recorded in air-quality monitoring networks. This impact is especially relevant in southern Europe (*Rodriguez et al., 2001; Escudero et al., 2005, 2007; Kallos et al., 2007; Mitsakou et al., 2008; Gerasopoulos et al., 2006; Koçak et al., 2007; Querol et al., 2009*), eastern Asia (*Zhang and Gao, 2007*) and in some Atlantic islands (*Prospero, 1999(a) and (b); Coudé-Gaussen et al., 1987; Chiapello et al., 1995; Arimoto et al., 1997; Viana et al., 2002*).

Some epidemiological studies indicate that long-range dust-transport events are closely associated with an increase of daily mortality in Seoul, Republic of Korea (*Kwon et al., 2002*) and Taiwan Province of China causing cardiovascular and respiratory problems (*Kwon et al., 2002*). In a study of 24 850 deaths in Barcelona (Spain), *Pérez et al. (2008),* concluded that during Saharan dust days, a daily increase of 10 µg/m^3 of PM10-2.5 increased daily mortality by 8.4% (95% confidence interval = 1.5% to 15.8%) compared with 1.4% (–0.8% to 3.4%) during non-Saharan dust days (p-value for interaction ~0.05). *Jiménez et al. (2010*) found that daily PM10 concentrations in Madrid displayed a significant statistical association with daily mortality for all causes on days with Saharan dust, while this association was not in evidence for non-Saharan dust days. Similarly, during Saharan dust intrusions, *Díaz et al. (2012)* observed effects of PM10 on mortality due to respiratory causes in the cold season and to circulatory causes in the warm one. These studies concluded that further investigation is needed to understand the role of coarse particles and the mechanism by which Saharan dust increases mortality.

Preliminary findings from *Garrison et al. (2006)* show that air samples from Mali contained a greater number of pesticides, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) and in higher concentrations than at Caribbean sites. Overall, persistent organic pollutant (POP) concentrations were similar in the US Virgin Islands and Trinidad and Tobago samples. Trace-metal concentrations were found to be similar to crustal composition with slight enrichment of lead in Mali.

Dust may be also contaminated by microorganisms, such as bacteria and fungi (Kellogg et al., 2004) or by toxic chemicals that are harmful when deposited on the skin, are swallowed or inhaled into respiratory passages. *Prospero (2004)* found that detection of bacteria and fungi on the Caribbean island of Barbados occurred only in air that contained Saharan dust. *Griffin (2007(a))* summarizes the current state of knowledge of desert-dust microbiology and the health impacts that desert dust and its microbial constituents may have in downwind environments both close to and far from their sources.

Dust may contribute to a high silicosis incidence, as occurs in China (*Derbyshire, 2001*). Trachoma is a chronic follicular conjunctivitis that has virtually disappeared from our environment but remains common in northern Africa, where it is caused mainly by hazy environments and dust storms. In the western Sahara, 83.3% of the nomadic population was affected by trachoma during the period 1884–1975 and blinding trachoma is still widespread in the region today (*Murube, 1975, 1976 and 1997*).

Specific references for West Asia

A study of the relationship of pulmonary health problems to mineral dust carried out in Turkey showed that continuous exposure to doses of mineral fibres and silica particles may be the cause of a number of benign pulmonary disorders (*Doğan, 2002*).

Dust carried by storms in Saudi Arabia has been found to contain aeroallergens and antigens which could trigger a range of respiratory ailments (*Kwaasi el al., 1998*). In Iraq, *Al-Dabbas et al. (2011)* found that the allergens commonly associated with dust storms included fungal spores, plant and grass pollens and organic detritus. *Griffin et al. (2007)* analysed air samples on top of a coastal atmospheric research tower in Erdemli, Turkey, and demonstrated that the region was routinely impacted by dust generated regionally and from North Africa and that the highest combined percent recovery of bacterial and fungal colony-forming units (CFU) and African dust deposition occurred in the month of April (93.4% of CFU recovery and 91.1% of dust deposition occurred during African dust days versus no African dust present for that month). They stated that the obvious prevalence of atmospheric desert dust, together with its associated constituents (microorganisms, organic detritus, toxins, etc.), might play a significant role in both ecosystem and human health.

Leski et al. (2011) applied highly multiplex polymerase chain reaction and a high-density resequencing microarray to screen samples of fine topsoil particles and airborne dust collected in 19 locations in Iraq and Kuwait for the presence of a broad range of human pathogens. Their results showed the presence of potential human pathogens, including Mycobacterium, Brucella, Coxiella burnetii, Clostridium perfringens and Bacillus. The presence of Coxiella burnetii, a highly infectious potential biological warfare agent had a high prevalence in the analysed samples. The detection of potentially viable pathogens in breathable dust from arid areas of Iraq and Kuwait underscores the importance of further study of these environments.

During a five-year study period, *Thalib and Al-Taiar (2012)* analysed retrospective time series of daily emergency public hospital admissions for asthma and respiratory illness in Kuwait and dust storm events. They recorded a total of 569 days with dust storm events (~34% of total days) and found a statistically significant association with an increased risk of same-day admissions for asthma and respiratory problems, which was particularly high among children.

Based on a systematic review of the literature using the Web of Knowledge database, *De Longueville et al. (2010)* found 231 articles published over the last decade on the impacts of desert dust on air quality. Of these, 48% concerned Asian dust and 39% Saharan dust, with the remaining 13% divided between the other dust source areas, which include publications of the Middle East. Considering that North Africa is the main dust-emission source area and the second biggest source is the Arabian Peninsula, Figure 63 shows an imbalance between the importance of these sources and the number of publications on the impacts on air quality and health, especially in the Middle East. It is worth mentioning that, according to *De Longueville et al. (2010),* Asia is the world's most studied region in the literature linking desert dust and air quality. Half the relevant publications are about the role of Asian dust in the degradation of air quality in countries on the same continent, mainly China and the Republic of Korea. It appears that the whole of this region is affected only by Asian dust, mainly from the Gobi Desert, although this is only the third source area in terms of quantities emitted, after North Africa and the Arabian Peninsula.

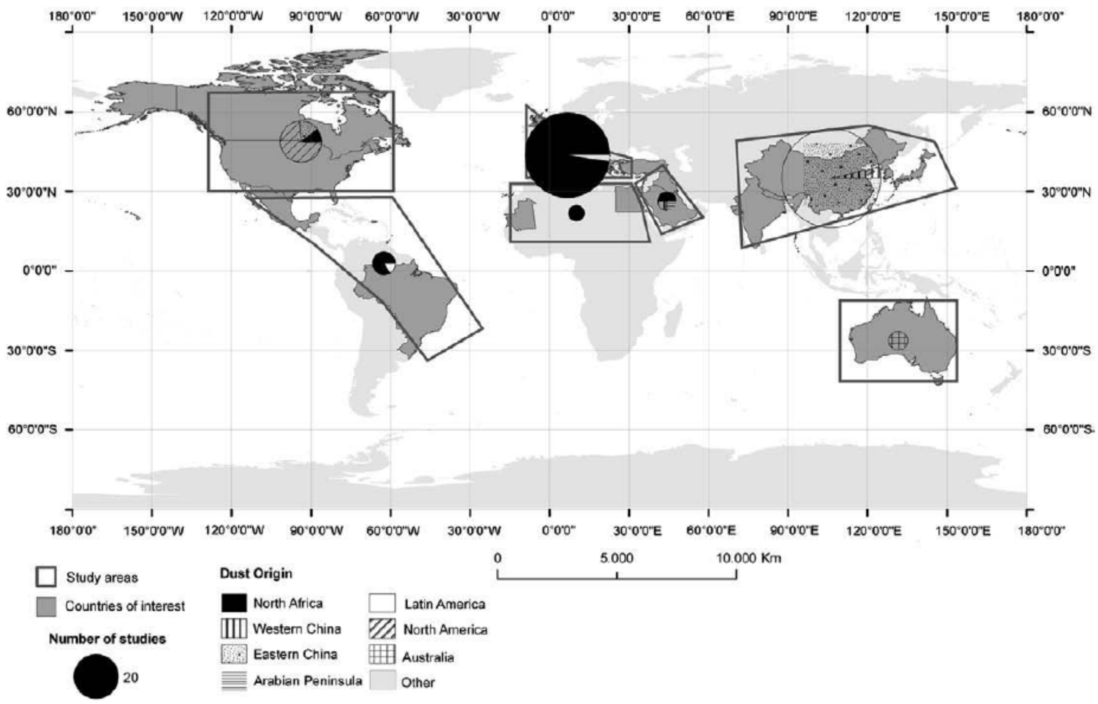


Figure 63 - Importance of the number and distribution of studies on air quality according to dust-source area (after *De Longueville et al., 2010*)

A.3.2 Ground and flight transportation problems due to visibility reduction

Suspended crustal material in a dust storm usually consists of coarse particles with mean diameters of tens of micrometres (µm) or more. Most of the particulate mass is of a diameter much greater than 2 µm. Although the light-scattering efficiency per unit mass of coarse particles is low, compared to that for fine particles, the mass of coarse particles in a severe dust storm is of the order of several thousand µg/m^3, so that total light extinction is pronounced. *Patterson et al. (1976)* found that the optically important fugitive dust particles included those up to 40 µm in diameter. For typical conditions, concentrations between 100 and 400 µg/m^3 are needed to reduce daytime visibility to 200 m (*Hagen and Skidmore, 1977*). If the background is non-sky, visibility is reduced an additional 50–75%, compared with a sky background.

Reduction of visibility might cause flight cancellations, as reported by *Shirkhani-Ardehjani (2012)* for the Khuzestan region in the Islamic Republic of Iran. In 2008, 232 flights were cancelled and 172 flights were cancelled in 2009 as a result of dust storms (Table 3). Rerouting due to poor visibility, disturbances in airport operations and massive cancelling of scheduled flights give an idea of the tremendous impact of dust intrusions on the aviation sector.

Table 3 - Economic impact of dust storms on different sectors in Khuzestan, Islamic Republic of Iran (after *Shirkhani-Ardehjani, 2012*)

Dust Economical and Social Effects(Khuzestan)

Year	Accident number (day)	Max concentration (mg/m3)	Max incidence time (hour)	Number of Flight Cancel	Schools Closing (day)	Offices Closing (day)
2001	6	2010	48	4	1	-
2002	10	2560	48	2	1	-
2003	11	3600	40	3	-	-
2004	9	3440	36	3	-	-
2005	12	2505	48	-	-	-
2006	19	2740	48	3	-	-
2007	31	8360	72	47	3	1
2008	55	9360	84	232	5	1
2009	49	6200	144	172	-	1
total	202	-	-	466	10	3

The impacts on air traffic are not only at airports and flight approach paths but also along long transects crossed by a dust storm. *Lekas et al. (2011)* reported mechanical problems in aircraft such as: erosion, corrosion, pitot-static tube blockage or engine in-flight flame-out. They summarized the following problems:

- *Erosion:* desert-dust particles, like volcanic ash, impact and bounce on cold areas of the engine (fan or propeller blades), causing surface damage and gap-size augmentation leading to gas-flow deterioration and gradual loss of performance of the engine. Damage is also caused to the external surface of the aircraft.

- *Corrosion:* if dust particles impact hot surfaces (e.g. combustor walls, turbine blades), they will form a glass deposit with a rough surface which may lead to a rapid loss of performance and, subsequently, to potential risk during take-off or landing operations. This deposit may also lead to thermal corrosion of a component of the engine or of electronic devices by blocking cooling holes.

- *Pitot-static tube damage:* desert-dust particles can lead to false flight-speed reading by blocking pitot-static tubes. This may be extremely hazardous, especially in low-level flight and during take-off or landing procedures.

- *In-flight flame-out:* the glass deposit on hot parts of the engine can significantly disturb the airflow, even leading to turbine blades stalling and in-flight flame-out.

As *Lekas et al. (2011)* stated, the ingestion of these particles has impacts on aircraft performance that have not yet been fully explored for the aerospace industry. Dust has safety and maintenance implications for aircraft operations which increase their cost in hazy/dusty environments. Flight paths and management in dusty environments must take into account quantitative predictions of dust air masses along routes and especially in low-altitude flight, as well as engine tolerance in dust-mass ingestion. By utilizing dust predictions, the geographical area affected, timing and the amount of ingested dust can be calculated along the flight path. It is curious that huge investments are being made in observation and prediction systems to monitor volcanic ash clouds after the eruption of the Eyjafjallajökull volcano in Iceland in 2010, but virtually nothing has been done to improve aviation-oriented techniques for the monitoring, forecast and early warning of dust storms, which are more frequent and more widespread than volcanic eruptions.

Recently, the International Civil Aviation Organization (ICAO) introduced some modifications to Annex 3 of the Convention on International Civil Aviation – Meteorological Service for International Air Navigation – in order to introduce criteria for distinguishing sandstorm and moderate or strong dust storm (ICAO, Annex 3, Appendix 6) as used operationally in several countries already. This requires more accurate dust-observation and monitoring systems.

Road transport is also high impacted by dust storms in northern Africa and Asia and particularly in the Middle East (Figure 64). Dozens of pages in digital newspapers in countries including Saudi Arabia, Kuwait, Qatar and the Islamic Republic of Iran, carry news about the role of dust storms in traffic accidents arising from a severe reduction in visibility (Figure 65), stacking sand and dust on roads hampering traffic, etc.

Figure 64 - Dust storms cause traffic problems on city roads (http://www.desertaquaforce.com)

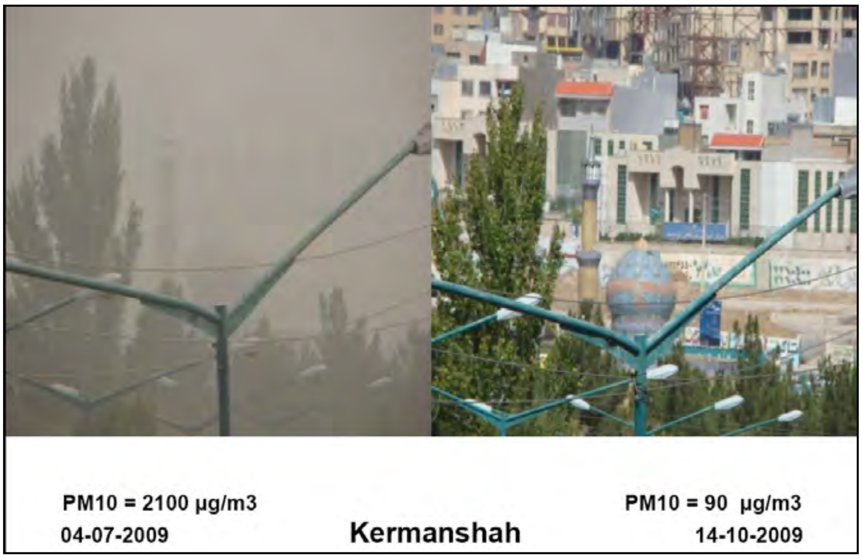


Figure 65 - Photographs taken in Kermanshah at the same point under high-surface dust-concentration conditions (left) and "low" concentration conditions (right) (after *Shirkhani-Ardehjani, 2012*)

Another issue that is acquiring importance and whose impact is beginning to be studied quantitatively is the generation of airborne dust by vehicles driving along unpaved roads and tracks. On this subject, *Greening (2011)* has made a first approach to quantifying the emission of dust in desert areas by vehicle traffic.

High-speed rail, a type of transport that operates significantly faster than traditional rail traffic, might be negatively affected by dust storms, especially sand, which could cover part of the rails, rendering the service inoperative. For example, the maintenance of Saudi Arabia's first high-speed passenger 408-km rail line, which will link the cities of Makkah and Madinah (slated for completion by January 2014) could be optimized with an NRT dust-monitoring system, consisting of ground-based sensor arrays along its path, and ad hoc, high-resolution SDS predictions.

SDS monitoring systems in Saudi Arabia will be crucial for optimum operation of new railway expansion projects currently underway, which include North-South Rail and the Land-bridge Project between Riyadh and Jeddah.

A.3.3 Dust impact on ecosystems

IPCC (2007) indicates that the problem of land degradation and desertification prevalent in West Asia will be exacerbated by climate change. The expected increase in temperature, decline in precipitation and greater intensity and frequency of droughts and dust storms will impact rangelands and rain-fed cropland and contribute to land deterioration, biodiversity loss and the spread and intensification of desertification (*UNEP, 2012*). Dust emissions reduce soil fertility through the removal of small soil particles rich in nutrients and organic matter, which contributes to desertification and reduces agricultural productivity (*Shao, 2008*).

Dust deposition has been found to affect many physiological processes of plants, including photosynthesis, stomata functioning and productivity by covering and plugging stomata, shading and removing cuticular wax (*Luis et al., 2008*). *Wijayratne et al. (2009)* experimented with plants that were dusted bimonthly at canopy-level dust concentrations, and physiology and growth were monitored until plants senesced. Average growth declined with increasing dust accumulation but seasonal net photosynthesis increased. The authors explain this pattern of greater net photosynthesis with increasing dust accumulation by higher leaf temperatures of dusted individuals. *Ibrahim and El-Gaely (2012)* investigated the effect of dust on plants in Saudi Arabia. They concluded that the exposure of plants to dust resulted in a drastic effect on some physiological parameters, such as the loss of chlorophyll-a and b contents, inhibition of net photosynthetic rate and significant decrease of stomata conductance. Their results were evidence that dust deposition decreased overall plant performance through its severe effect on photosynthesis.

Stefanski and Sivakumar (2009) summarized the impacts of sand- and dust storms on agriculture: loss of crop and livestock, loss of plant tissue as a result of sandblasting by the sand and soil particles and, therefore, reduced photosynthetic activity and reduced energy (sugars) for the plant to utilize for growth, reproduction and the development of grain, fibre or fruit.

Dust also has global impact on ecosystems far away from dust sources, however. *Garrison et al. (2003)* reported that viable microorganisms, macro- and micronutrients, trace metals and an array of organic contaminants are transported in the dust air masses and deposited in the oceans. Since hundreds of millions of tonnes of dust are transported annually from Africa and Asia to the Americas, dust deposition on oceans may be adversely affecting coral reefs and other downwind ecosystems. *Garrison et al. (2006)* worked on a multidisciplinary and international project to elucidate the role Saharan dust may play in the degradation of Caribbean ecosystems. They identified and quantified POPs, trace metals, and viable microorganisms in the atmosphere in dust-source areas of West Africa and in dust episodes at downwind sites in the eastern Atlantic (Cape Verde) and the Caribbean (US Virgins Islands and Trinidad and Tobago). Preliminary findings showed that air samples from Mali contained a greater number of pesticides, PCBs and PAHs and in higher concentrations than the Caribbean sites.

Desert-dust deposition also influences the biochemical cycles of both oceanic and terrestrial ecosystems (*Okin et al., 2004*; *Mahowald et al., 2005; Aumont et al., 2008*). The productivity of many ecosystems depends on the availability of phosphorus (*Okin et al., 2004*). The deposition of dust-borne phosphorus is therefore often critical for ecosystem productivity (i.e. primary biomass production). Soils that entrain deposited airborne particles may become enriched in nutrients that are otherwise not present in native soils. The Amazon rainforest is a good example, since its productivity is limited by dust-borne phosphorus deposition (*Swap et al., 1992*).

The impacts of mineral dust on ecosystems arise predominantly from the delivery of nutrients by dust deposition. It has been estimated that 360–500 Tg of mineral dust are deposited annually in the oceans, with ~50% of the total deposition occurring in the North Atlantic Ocean *(Prospero, 1996). Prospero (1999(a) and (b*) and *Prospero et al. (2001)* have performed interesting studies on the transoceanic transport and deposition of African dust in the south-eastern USA and islands in the Atlantic Ocean.

Wind-transported mineral dust may play a large role in supplying soluble iron to the oceans' aerosols (*Fung et al., 2000; Jickells and Spokes, 2001*), providing micronutrients to biological species, such as phytoplankton.

Nutrification of the open ocean originates mainly from deposited aerosol in which bio-available iron is likely to be an important factor (*Nickovic et al., 2013*). The relatively insoluble iron in dust from arid soils becomes more soluble after atmospheric processing and could contribute to marine primary production (*Ramos et al., 2009*). This positive impact of dust on ecosystems is schematized in Figure 66.

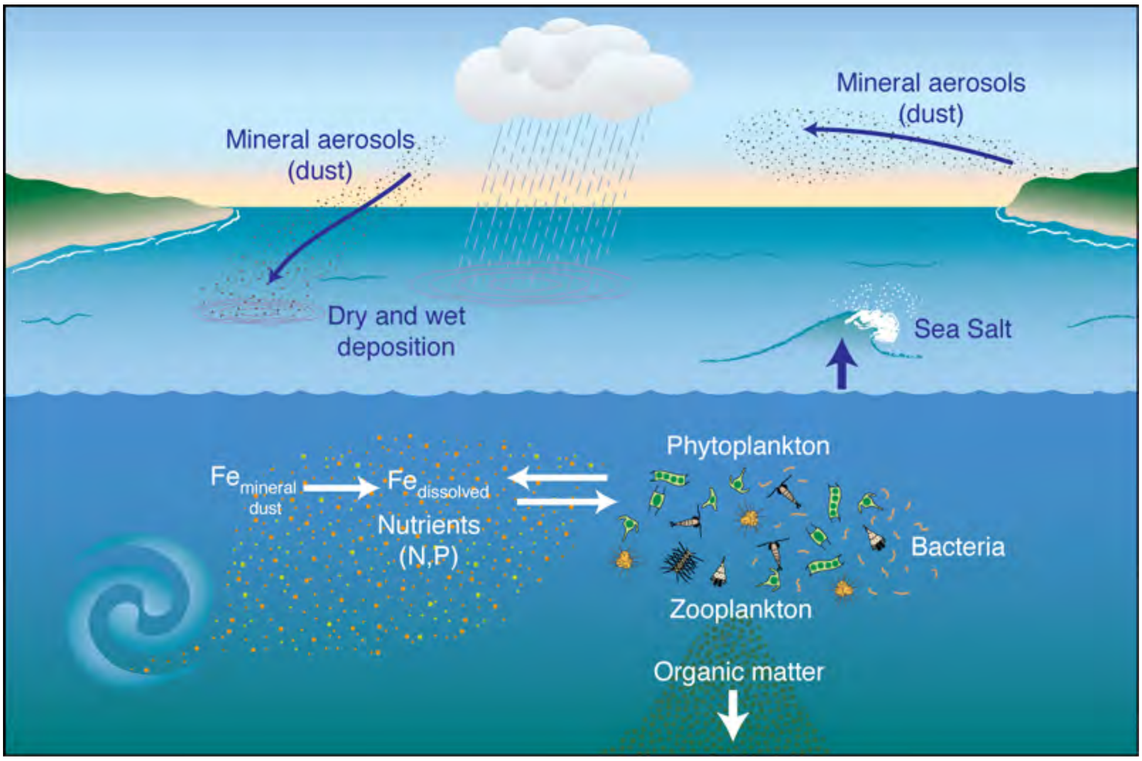


Figure 66 - Dust effect on marine ecosystem (from Woods Hole Oceanographic Institution)

Hamza et al. (2011) reported that significant quantities of dust derived from the Arabian Peninsula form part of the annual dust input into the Indian Ocean directly and indirectly through water exchange with the Gulf. This increased photosynthetic activity in the Indian Ocean due to fertilization by dust nutrients from the Gulf and its adjacent water bodies may well be important in mitigating the increase in anthropogenic CO_2 in the atmosphere.

Deposition of dust over the ocean can also produce harmful algal blooms (HABs), popularly known as red ties. An intense bloom can produce harmful impacts on marine ecosystems. When masses of algae die and decompose, they can deplete oxygen in the water and the animals either leave the area or die. Some HABs produce powerful toxins that can kill fish, shellfish, marine mammals and birds and may cause disease in humans. Two common causes of HABs are nutrient enrichment, especially phosphates and nitrogen, and warm waters. Iron and phosphates are provided by Saharan dust deposition over the North Atlantic, producing HABs (*Ramos et al., 2005).*

Nickovic et al. (2013) simulated numerically the path of iron on its atmospheric route from desert sources to sinks in the ocean. They have thus developed a regional atmospheric dust-iron model that includes parameterization of the transformation of iron to a soluble form caused by dust mineralogy, cloud processes and solar radiation.

Schulz et al. (2012) provide a review of our knowledge concerning the measurement and modelling of mineral-dust emissions to the atmosphere, its transport and deposition to the ocean, the release of iron from the dust into seawater and the possible impacts of that nutrient on marine biogeochemistry and climate. They argue that, although mineral dust is a perennial constituent of the Earth's atmosphere and its constant deposition to the ocean, there are serious limitations to modelling adequately the global dust cycle, which is one of the primary uncertainties in developing future climate scenarios. The authors say there is an urgent need for long-term measurements in the marine atmospheric boundary layer through a network of study sites spread across different oceans. In Figure 67 we can see many areas downwind from known dust sources, such as the Middle East, showing a lack of observations involving both atmospheric and marine measurements that limits the capacity to address the complex and interlinked processes and role of dust/iron fertilization in marine biogeochemistry and climate.

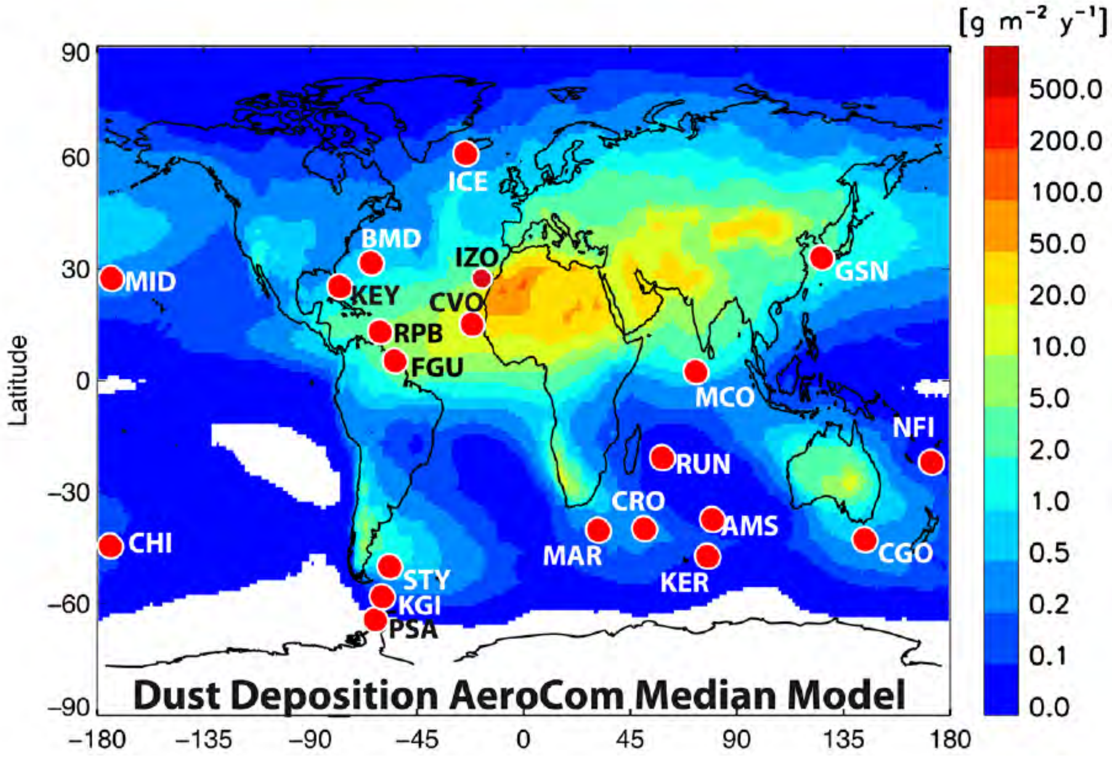


Figure 67 - Sites for a proposed long-term marine atmospheric measurement network located on multimodel median dust-deposition field from 12 AeroCom models (after *Schulz et al., 2012*)

There are few studies concerning the Arabian Sea but it is worth mentioning *Siefert et al. (1999)*, who performed a chemical characterization of atmospheric aerosols over this region and *Srinivas et al. (2011),* who assessed the impact of anthropogenic sources on iron solubility.

The deposition of dust to both land and ocean ecosystems stimulates productivity, thereby affecting also the biogeochemical cycles of carbon and nitrogen (*Mahowald et al., 2011. Mahowald et al. (2010)* hypothesized that global changes in dust deposition to ecosystems contributed to changes in CO_2 concentrations over the past century, and *Mahowald (2011)* suggested that dust-induced changes in CO_2 concentrations may also play a role in future climate changes (see also Section A.3.5).

While the only source of wind-blown dust is currently considered to be deserts, studies have shown that agricultural lands and dry playas can also be sources. *Pelletier (2006)* constructed a process-based numerical model to couple soil moisture in the unsaturated zone with saltation activity and dust emissions at the surface. He found that water-table depths of 3–10 m represented a critical range over which small variations in the water-table depth may lead to large, non-linear changes in saltation activity and dust emissions. He developed a model for determining the impact of climatic and anthropogenic changes on dust activity in playa basins.

Additionally, through the so-called semi-direct effect, dust affecting the thermal atmospheric structure can modify cloud formation (*Hansen et al., 1997*). In turn, the effect of dust on cloud formation affects the atmospheric radiative balance (*IPCC, 2007; Zeng et al., 2009*) (Figure 68). On the other hand, the deposition of dust on glaciers and snow decreases the albedo (reflectivity) of these surfaces, which produces a positive (warming) climate forcing and an earlier spring snowmelt (*Painter et al., 2010*).

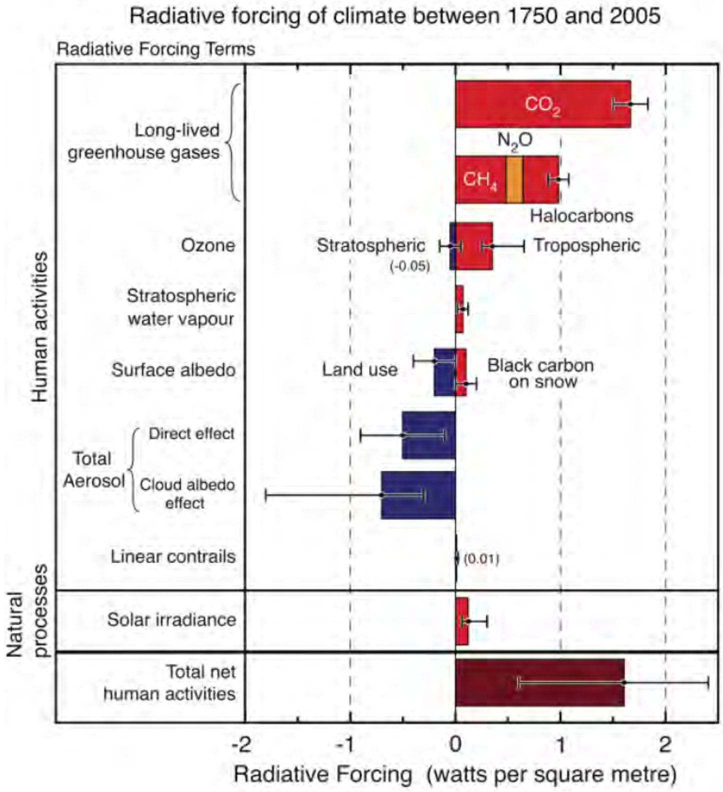


Figure 68 - Radiative forcing of climate between 1750 and 2005 (*IPCC, 2007*): the radiative forcing uncertainty from aerosols (much of the mineral dust) is significant

The radiative effects of mineral dust have been fully incorporated into an atmospheric dust model (*Pérez et al., 2006*), which represents a promising approach for further improvements in numerical weather prediction (NWP) practice and radiative impact assessment over dust-affected areas. These areas experience a strong negative feedback upon dust emission, because a smaller, outgoing, sensible turbulent heat flux reduces the turbulent momentum transfer from the atmosphere and dust emission, resulting in a high reduction of AOD over dust-covered areas.

Mineral dust may also affect air temperatures through the absorption and scattering of radiation (*Li et al., 1996; Moulin et al., 1997; Pérez et al., 2006*).

Heterogeneous chemistry occurring on atmospheric mineral dust affects the composition of the troposphere (*Cwiertny et al., 2008*). There is a long record of negative correlation between ozone (O_3) and aerosols during desert-dust outbreaks. In situ measurements show significant reduction in O_3 concentrations under high dust concentrations (*Prospero et al., 1995; de Reus et al., 2000; Bonasoni et al., 2004; Cuevas et al., 2013*). Three pathways have been proposed by de *Reus et al. (2000)* to explain observed O_3 reduction: (a) decrease in formation rates as photolysis is reduced by extra-scattering (*Dentener et al., 1996*); (b) direct uptake of O_3; and (c) nitric acid heterogeneous removal.

Dust might also inhibit hurricane formation (*Evan et al., 2006; Sun et al., 2008*) and induce coupled ocean-atmosphere variability in the tropical Atlantic (*Evan et al., 2011*).

Finally, dust can have a significant effect on sea-surface temperature (SST) retrievals from satellites. Although cloud-screening algorithms will often detect thick layers of aerosol, biases up to 3 K will remain (*Merchant et al., 2006*), depending on the SST retrieval algorithm and brightness-temperature impacts of the dust, affecting NWP. We can therefore see how dust affects weather, atmospheric composition and climate through a wide range of interactions and both positive and negative feedbacks.

Studies dealing specifically with the impact of dust on weather/climate in the Middle East are scarce. *Satheesh and Srinivasan (2002)* stated that the radiative forcing due to Arabian/Saharan aerosols (mostly natural) during April and May is comparable and often exceeds (as much as 1.5 times), the forcing due to anthropogenic aerosols during the January–March period. The presence of dust load over the Arabian Sea can influence the temperature profile and radiative balance. *Mashayekhi et al. (2010)* showed a negative radiative forcing over Tehran under the presence of mineral dust aerosols using coupled aerosol-cloud and radiation WRF-HAM modelling system simulations and measured downward radiation. *Stenchikov et al. (2011)* showed that the regional sensitivity to radiative forcing in the Middle East is very high. As shown in Figure 69, dust cools the surface and warms the column atmosphere. The aerosol (mainly dust) radiative cooling over sea is much stronger than over land.

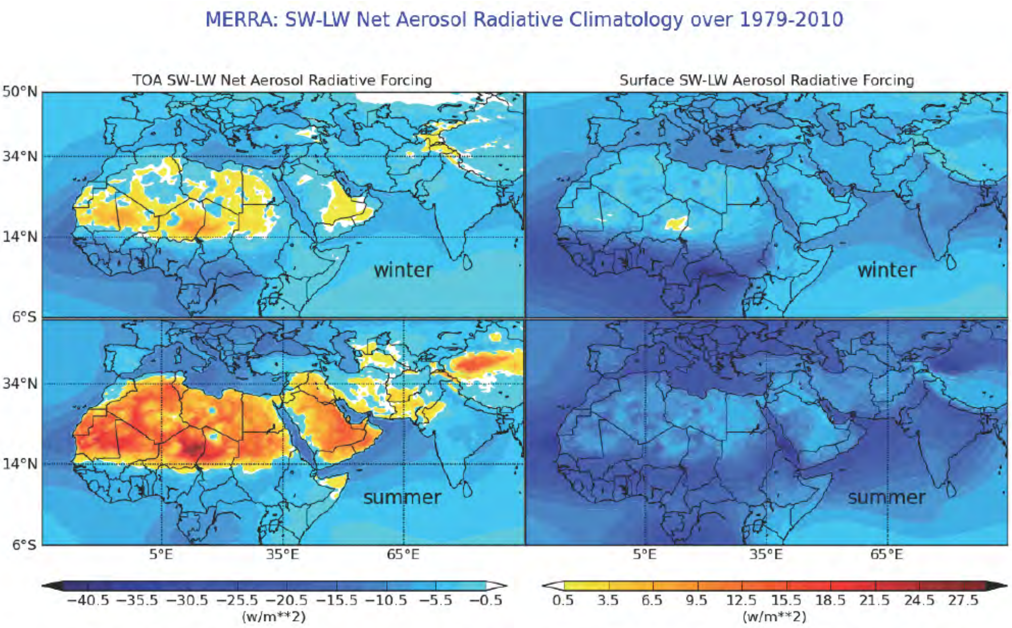


Figure 69 - Short-wave–long-wave net aerosol radiative climatology (1979–2010) (*after Stenchikov (2011)*)

A.3.4 Dust impact on energy and industry

The deserts could provide a huge amount of the power required in the world by using a variety of solar-power generation technologies, including photovoltaic (PV), concentrated photovoltaic (CPV) and concentrated solar-power systems (CSP).

Interest in electricity from solar-powered plants is reportedly increasing in the Gulf Cooperation Council countries. The targets set by individual governments for electricity production from renewable energy sources are: Abu Dhabi: 7% by 2020; Dubai: 5% by 2030; Saudi Arabia: 16-GW PV and 25-GW CSP by 2032; Kuwait: 5% by 2030; Oman: 5% by 2020 and Bahrain: 10% by 2030.

Deserts are the obvious location for solar-power plants since land is inexpensive and sunshine is plentiful. Unfortunately, dust causes solar-light extinction and dirt on the solar panels, which can greatly impair efficiency. The integration of aerosols and their radiative effects on direct normal irradiance (DNI) predictions is considered to be one of the most urgent questions to be addressed (*Gueymard, 2012*). AOD is a critical input to radiation models and determines the accuracy of modelled DNI under clear skies (*Cachorro et al., 1987*). Dust intrusions play a catalytic role on absolute levels and also DNI short-term variability. High AOD values observed in West Asia produce a significant DNI attenuation, which is a key parameter in CSPs.

Ohde and Siegel (2012) investigated the impacts of Saharan dust and clouds on solar irradiance and photosynthetically available radiation to derive a relationship between the latter and AOD. They concluded that the reduction by dust was between 3.6% and 12.3% and by clouds was between 6% and 15%. A linear relationship confirmed a decrease of nearly 1.2% in photosynthetically available radiation as per an increase of 0.1 in dust AOD.

In the case of desert sites, there is great concern that the continuous accumulation of dust on solar panels might eventually neutralize their effectiveness. Different studies show that the transmission loss of sunlight through the front glass plates of photovoltaic devices could vary from 5% to 30% per year, depending on dust deposition. Rate and characteristics of dust deposition in some of the semi-arid and desert areas of the world with a potential of large-scale solar installations and loss of transmission and reflection of sunlight in the PV, CPV and CSP systems as a function of particle size and charge distributions have been reported by *Sayyah et al., 2012.*

El-Shobokshy and Hussein (1993) analysed the effect of accumulation of dust and particulate matter on the surface of PV cells in Saudi Arabia, concluding that fine particulates significantly degrade their performance – more so than coarser particles. *El-Nashar (2003)* studied the influence of dust deposition on the evacuated tube collector field on the operating performance of the solar desalination plant at Abu Dhabi, UAE. He measured the reduction in transmittance due to dust deposition on the amount of heat collected and its influence on distillate production.

Elminir et al. (2006) showed that the reduction in normal glass transmittance depends strongly on dust-deposition density in conjunction with tilt angle. They showed that, for dust deposition density ranging from ~5 to ~16 g/m^2, the transmittance diminishes by ~13% and 53%, respectively. For moderately dusty places, therefore, they recommend weekly cleaning of the glass covers as part of the maintenance routine and cleaning of the equipment immediately after a dust storm to retain its nominal operating efficiency. *Sulaiman et al. (2011)* reported that dust had an important effect on the performance of solar PV panels, being the reduction in the peak power generated of up to 18%. They also showed that, under high irradiance, the effect of dust is slightly reduced but not negligible.

Apart from a dramatic deterioration in performance of solar panels, dust also causes additional costs for cleaning and maintenance (*Boykiw, 2011*).

Charabi and Gastli (2012) performed a climatology of AOD from MISR over Oman, concluding that high dust-deposition rates in areas near dust sources disable these areas for the production of energy from PV and CPV plants, since they require more frequent cleaning and, hence, large amounts of water. They recommended including the annual average AOD as a variable to be taken into account when planning solar-energy systems and gave the example of Oman, where 64% of the territory is severely affected by dust and is not recommended for solar power plants. *Charabi and Gastli (2013)* demonstrated that only 9% of the total area of Oman, mainly concentrated in the proximity of the southern east coast, is suitable for the implementation of large PV power plants because of the low DOD and moderate temperatures due to the wind regime.

Mani and Pillai (2010) published a comprehensive review of the current state of research into the impact of dust deposition on the performance of solar systems, particularly PV, and identified challenges to further research in this area. Particularly interesting are the new methodologies of self-dusting solar panels that are cleaned by an electric charge provided by the solar panels themselves. The self-dusting solar panels are based on technology developed for missions on Mars. The technology consists of placing a transparent, electrically sensitive material deposited on glass or a transparent plastic sheet covering the panels. Sensors monitor dust levels on the surface of the panel and energize the material when dust concentration reaches a critical level. The electric charge sends a dust-repelling wave cascading over the surface of the material, removing the dust and transporting it off the screen's edges.

The Abu-Dhabi-based Research Centre for Renewable Energy Mapping and Assessment (the Masdar Institute) created, developed and validated a satellite-based solar mapping tool for producing 15-minute solar irradiance maps, together with monthly and yearly solar irradiation maps for the UAE's Solar Atlas. Hosni Ghedira, Director of the Institute, explained the need for a regional model thus: "While, in theory, the UAE receives the same if not far more solar energy than Europe or North America, in reality the dusty atmosphere cuts out as much as 90% of the Sun's energy during a heavy dust storm" (http://www.satelliteprome.com/tech-features/satellite-imagery-for-solar-maps/). Dust monitoring and climatology must therefore be incorporated into the irradiance atlas of the region.

On the other hand, the microwave signal attenuation caused by dust is one of the major problems in utilizing microwave bands for terrestrial and space communication, especially in desert and semi-desert areas (*Elabdin et al., 2009*).

Tribology is the science and engineering of interacting surfaces in relative motion. It includes the study and application of the principles of friction, lubrication and wear. Dust has such an important impact on industrial processes, mechanics, etc., that *Diao (2009)* identified specific tribology problems (and solutions) deriving from dusty environments and has developed equipment to study industrial tribology problems in natural sand and dust environments.

US Army (2009) describes the sand and dust tests performed on vehicles, engines and other military equipment, using an outdoor facility. These highly protocolized tests are performed in order to know the effect of sand and dust on different pieces of equipment and their performance under high sand and dust concentrations.

The presence of dust has a significant impact on the reliability of printed circuit board assemblies (PCBAs). *Song et al. (2012)* found negligible change in the impedance spectra of control samples at different relative humidities, while there were orders of magnitude changes observed in the samples in the presence of indoor or outdoor dust. They demonstrated that at the same dust-deposition density, test samples with indoor dust are more likely to induce moisture-related failures. These failure mechanisms include loss of surface-insulation resistance between electrodes, electrochemical migration and corrosion. The impact of dust on the reliability of PCBAs is ever growing, driven by the miniaturization of technology and the increasing uncontrolled operating conditions with more dust exposure in telecommunication and information industries. This could have special impacts in countries with hazy environments, such as those in West Asia.

Finally, dust storms affect the oil industry. It is not unusual to read in the newspapers that dust storms halt oil exportation when commercial port activities are suspended due to low visibility (e.g.http://www.upi.com/Top_News/World-News/2011/04/13/Dust-storm-halts-Kuwait-oil-traffic/UPI-63241302703251/).

A.3.5 Dust, weather and climate

Mineral dust is one of the major contributors to Earth's radiative balance in view of its radiation backscattering (*Tegen et al. 1996; Mahowald et al., 2006, 2010*). Dust also impacts long-wave terrestrial irradiance, especially at dust sources because of the relatively large size of the dust particles, which interact efficiently with terrestrial radiation. Mineral dust thus modifies the transfer of solar radiation (spectral range: 0.3 µm–3 µm wavelength) through the atmosphere by scattering and absorption processes. Depending on the size distribution, chemical composition and shape of the dust particles (which determine their optical properties: extinction coefficients, SSA and phase functions) and depending on the vertical position/extent of the dust layer and the local surface albedo, the mineral dust particles may have positive (heating of climate system) or negative (cooling) radiative forcing (e.g. *Sokolik and Toon, 1996; Tanré et al., 2003*). In a global annual balance, dust net radiative forcing at the top of the atmosphere (TOA) is most likely negative (cooling) for desert dust (*Kaufman et al., 2001; Dubovik et al., 2002; Balkanski et al., 2007; García et al., 2012*) but regionally positive values (warming) may occur over bright surfaces such as snow-covered or desert areas (*Tegen et al., 1996; Hansen et al., 1997*). This is because dust normally causes increased reflection of sunlight over dark surfaces (e.g. the ocean) and decreased reflection of sunlight over bright surfaces (e.g. snow, ice, clouds or desert). *Spyrou et al. (2013)* showed strong interaction of dust particles and solar and terrestrial radiation, with several implications for the energy budget of the atmosphere. A profound effect is the increased absorption (in the short and long wave) in the lower troposphere and the induced modification of the atmospheric temperature profile.

IPCC (2007) reported that the dust radiative effect due to mineral aerosols lies in the range of –0.56 to +0.1 W/m^2. Case studies of instantaneous dust net radiative forcing during individual dust events show negative TOA values higher than −6 W/m^2 (*Christopher and Jones, 2007; Zhu et al., 2007*) or negative values larger than −400 W/m^2 at the surface (*Costa et al., 2006*).

Dust impacts climate, and changes in climate have driven the global dust cycle. *Rea (1994) and Kohfeld* and *Harrison (2001)* reported a larger global dust-deposition rate during glacial maxima than during interglacials. The radiative forcing resulting from such large changes in the global dust cycle is thought to have played an important role in amplifying past climate changes (*Jansen et al., 2007; Abbot and Halevy, 2010*).

Dust also affects the hydrological cycle. Firstly, when dust cools, the surface inhibits both evaporation and precipitation (*Miller et al., 2004; Zhao et al., 2011*). Secondly, dust modifies the size distribution and the phase of cloud particles by acting as CCN and ice nuclei (*DeMott et al., 2003),* modifying the development of precipitation (*Levin and Cotton, 2008*) or either enhancing or suppressing precipitation (*Ramanathan et al., 2001; Toon, 2003*). Mineral dust generates large concentrations of CCN (*Rosenfeld et al., 2001*), mostly in the small-size range that can lead to cloud formation dominated by small droplets. As a result, this could lead to droplet coalescence reduction and suppressed precipitation (*Teller and Levin, 2006*). Mineral dust coated with sulphate and other soluble materials such as nitrates can, however, generate large CCN (*Levin et al., 1996; Li and Shao, 2009*) and, consequently, large drops, which accelerate precipitation development through droplet growth by collection.

A.3.6 Role of SDS activities in the new climate services

Climate variability and change are posing significant challenges to societies worldwide. Timely communication of climate information helps prevent the economic setbacks and humanitarian disasters that can result from climate extremes and long-term climate change (WMO, http://www.wmo.int/pages/themes/climate/climate_services.php). Climate information also plays a crucial role in national development planning, for managing development opportunities and risks and for mitigation and adaptation strategies. Efficient application of climate services requires the integration of climate information into policies in various sectors.

West Asia countries have a hazy environment, as SDS occur throughout the year, impacting crucial social and economic activities (*Akbari, 2011*). Dust-related parameters and variables, such as horizontal visibility, PM concentration, AOD, etc., must be incorporated as added values in databases of future national climate services. Long-term dust-related observations and model reanalysis may help health and energy communities and other economic sectors understand, assess and plan respective activities. SDS are closely linked to droughts and soil deterioration, so they can be used as early warning indicators of climate variability and change. Comprehensive, long-term dust databases might help to understand and prevent health problems through epidemiological studies. Dust climatologies might contribute to planning and performing feasibility studies of future solar-power facilities.

Dust-related products are fundamental in customer-oriented climate services in West Asia countries.

B.1 ANALYSIS OF SDS ACTIVITIES IN WEST ASIA COUNTRIES

This section contains a summary of capabilities in West Asia countries concerning SDS observation and modelling, capacity-building and data exchange.

The survey took account of information from:

- International observation and monitoring networks related to SDS activities.
- Institutions running dust models.
- Completed questionnaires received from the WMO permanent representative of each country and from groups carrying out SDS activities at air-quality agencies, research centres and universities of the region.
- Direct contacts made during the mission to Marrakech, during the Arab Permanent Committee of Meteorology (Session 29), 8–10 April 2013.

This section has been structured as in the questionnaire:

B.1.1 In situ observations
B.1.1.1 Visibility and sky conditions
B.1.1.2 In situ PM10/PM2.5
B.1.1.3 Ground-based remote-sensing observations
B.1.2 Satellite observations
B.1.3 Modelling
B.1.4 Data exchange
B.1.5 Application of SDS products and services
B.1.6 Capacity-building

B.1.1 In situ observations

B.1.1.1 Visibility and sky conditions

The most comprehensive network of observations related to SDS activities is undoubtedly the synoptic observation network (Figure 70) providing visibility and present-weather data.

In general, there is a good distribution of SYNOP stations, except in the Empty Quarter in Saudi Arabia and adjacent areas of Oman and Yemen, where the gap is significant (Figure 70). Certain lowland areas (blue) in the Islamic Republic of Iran have a low density of stations. Most countries have operational automatic devices for visibility range such as meteorological optical range (MOR) and runway visual range (RVR) at airports, which is important, since one of the activities most affected by dust is air traffic.

Visibility reduced by atmospheric dust from SYNOP observations could be an interesting product, at least for dust nowcasting. Some value-added activity should be implemented in NRT, however, as a filter for including relative humidity and present-weather data, to avoid including reduced visibility arising from fog or heavy rain.

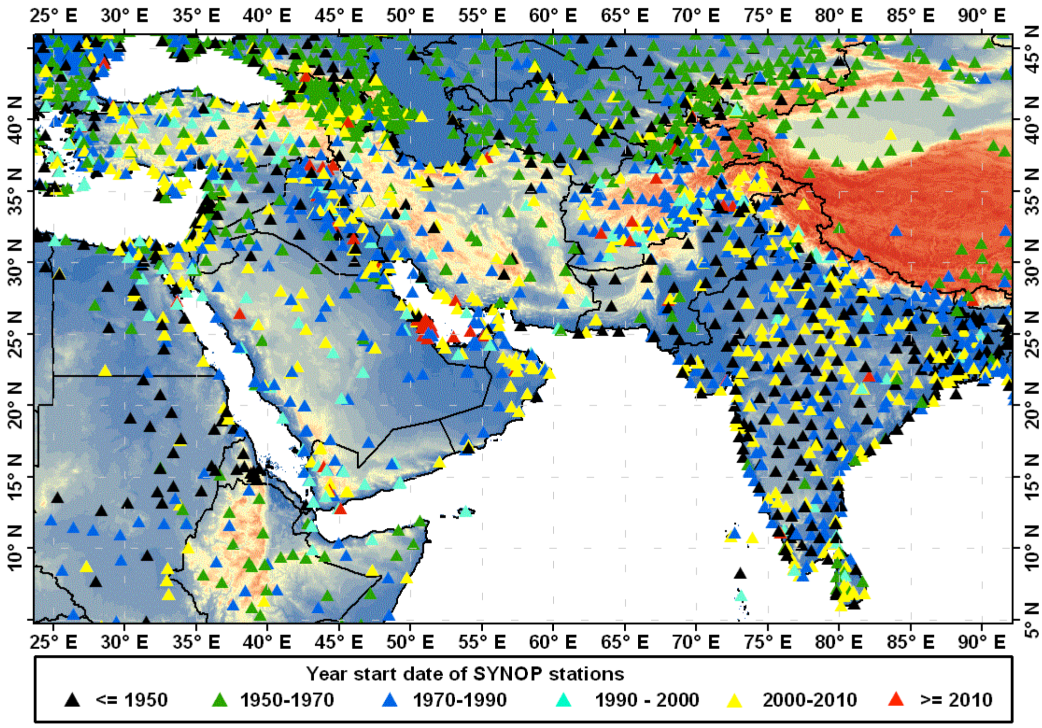


Figure 70 - SYNOP stations in West Asia: a specific colour indicates the decade when observations started at each station

Figure 71 gives the monthly climatology (box plots) of horizontal visibility at the Bahrain station. The main problem of this information is that reduced visibility is traditionally reported only when it is lower than 10 km but haze and dust are normally present with much higher horizontal visibilities. Hence, this parameter is really useful only to report moderate-to-strong dust storms. The monthly visibility trend at Bahrain shows a flat behaviour (quite similar through the year), which has nothing to do with the annual variation of AOD in this station shown in Section A.3.5 (Dust, weather and climate).

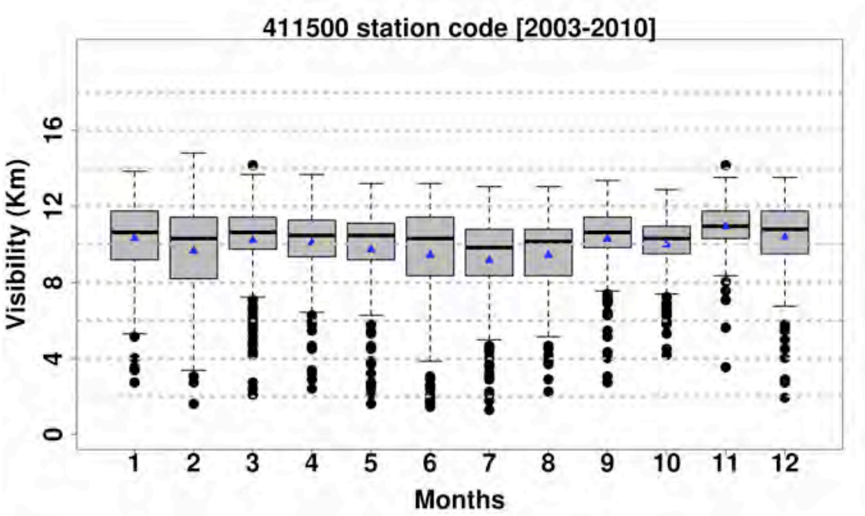


Figure 71 - Monthly climatology of horizontal visibility at Bahrain (20032010)

See Section B.2.1.1. (Visibility) for corresponding recommendations.

Concerning complementary visual information provided by total-sky cameras or web cameras, no institution has reported their use in the questionnaires.

During the UAE[2] experiment, however, total-sky cameras were used to provide visual information of dust intrusions, demonstrating their usefulness for high-temporal resolution tracking of dust storms (see Figure 72).

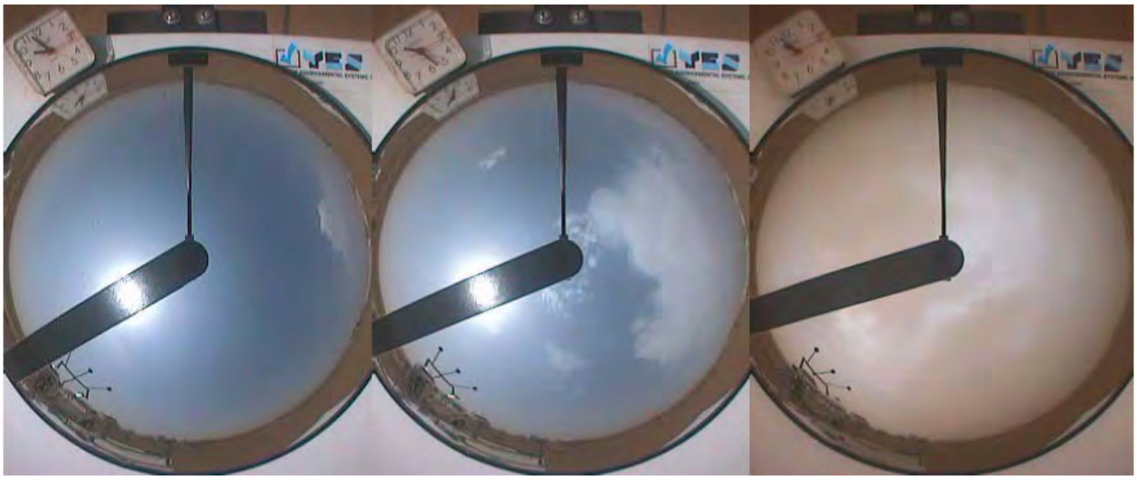


Figure 72 - Selected sky images for 3 September 2004 during the UAE[2] campaign. At about 10:00 UTC, the dust front was looming on the horizon in the east. Half an hour later, part of the sky was blocked. The sky turned brownish during the dust storm (after *Reid et al., 2005*)

B.1.1.2 In situ PM10/PM2.5

PM10 and PM2.5 are interesting atmospheric parameters normally monitored within air-quality network programmes.

The number of PM10/PM2.5 stations in the countries reporting this information is reasonable and proportional to their population (Table 4) and geographical extension.

Table 4 - Number of PM10/PM2.5 stations per country

Country	Gravimetric method	NRT (Beta** or TEOM***)	Chemical analysis
United Arab Emirates		~40	
Islamic Republic of Iran	5	118	
Kuwait	3	11 (2 NRT)	
Oman*		4 (with a mobile unit)	
Saudi Arabia		5	
Turkey	45 (cities)	More than 100 (cities)	45 (cities)

* *The Ministry of Environment and Climate affairs of Oman has been running a mobile network for monitoring PM2.5 and 10 in Muscat, Sohar, Sur and Salalah since 2002.*
** *Betabeta-attenuation analysers*
*** *Tapered element oscillating microbalance*

It seems that the majority of stations – if not all – are in cities as part of air-quality networks.

PM10/PM2.5 networks for dust characterization and for understanding its impact on the population are of great importance to the countries of the region. On the other hand, in situ PM10 measurements are crucial to validate surface-dust concentration from models. Some efforts should be made in the design and strategy of part of the measurement programme in order to obtain optimal performance in the characterization of aerosol/dust background, which is explained in Section B.2.1.2. (In situ particulate matter). In situ PM measurements are important, since they tell us about aerosols/dust inhaled by people and, therefore, how dust storms directly affect people and ecosystems. We have to bear in mind that most of the information provided by satellites corresponds to the total content of aerosol/dust in the atmospheric column and this does not necessarily have a direct correspondence with surface-dust concentration. Furthermore, the chemical composition of surface aerosol/dust is another important aspect of impacts on health and other applications and cannot be provided by remote techniques, only by in situ PM sampling. From the point of view of SDS monitoring, the major deficiencies identified are the following:

- An insufficient number of stations to monitor mineral dust (mainly PM10) are located in rural background conditions, which would provide information about its impact on air quality in cities. PM10 and PM2.5 measurements in urban air-quality networks represent a mix of anthropogenic pollution (vehicles, gas flares, industries, ships) and natural contributions. It is difficult to separate the contribution of each source if there are no background stations unaffected by anthropogenic contributions.

- There are no standards of air quality – especially for PM10 – common to all countries of the region.

- A regional centre for common and homogenized quality assurance is lacking.

B.1.1.3 Ground-based remote-sensing observations

AERONET (http://aeronet.gsfc.nasa.gov) is a federation of regional networks based on photometric instruments located at ground stations (currently, more than 400 stations worldwide) for monitoring atmospheric aerosols, including atmospheric mineral dust. It requires the standardization of instruments, calibration, data processing and distribution. AERONET seeks to provide continuous time series of aerosol measurements, such as microphysical and radiative properties in the atmospheric column, that are easily accessible and is dedicated mainly to the characterization of aerosols and the validation of satellite data and aerosol models, as well as synergies with other databases. AERONET was established by NASA and the Atmospheric Optics Laboratory (Laboratoire d'optique atmosphérique (LOA) of the University of Lille (France)). PHOTONS (http://loaphotons.univ-lille1.fr/) and the Iberian network for aerosol measurements (Red ibérica de medida fotométrica de aerosoles (RIMA), http://www.rima.uva.es/) have joined as federated AERONET networks, following the same standards and requirements.

The world AERONET map (Figure 73) shows a high density of stations over Europe, the Americas and East Asia but the two most important dust sources in the world (northern Africa – Sahara – and West Asia) have very few photometers. Focusing on West Asia, Figure 74 shows poor, unevenly distributed, network coverage. AERONET does not cover dust hotspots or large cities affected by sand- and dust storms.

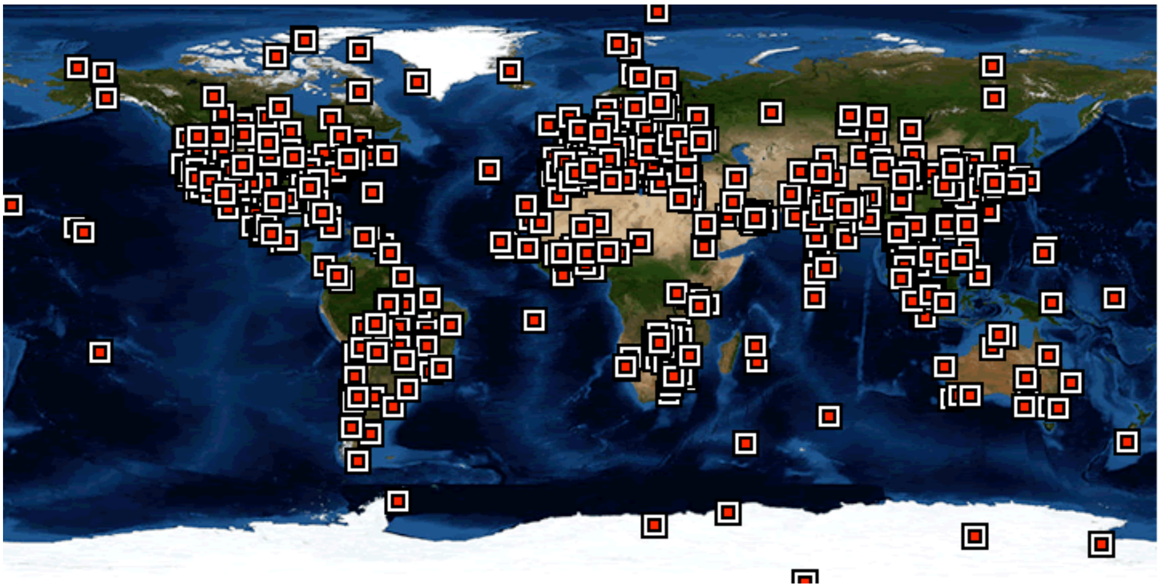


Figure 73 - Map of AERONET stations (http://aeronet.gsfc.nasa.gov)

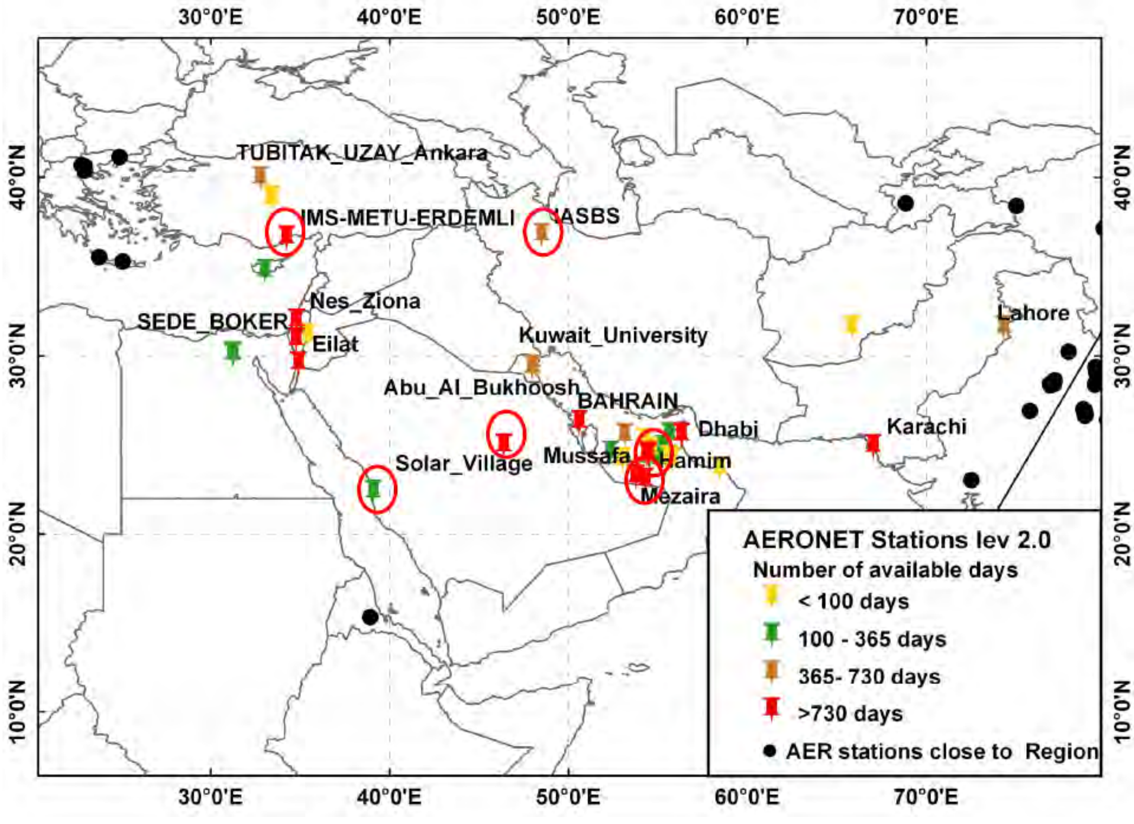


Figure 74 - Location of AERONET stations in West Asia. Stations circled in red correspond to present operationally active stations

The present active AERONET stations are the following:

Table 5 - List of current operational AERONET stations in West Asia

Country	AERONET station	Site, institution
Saudi Arabia	KAUST campus	Thuwai, King Abdullah University of Science and Technology (KAUST)
Saudi Arabia	Hada El-Sham	Jeddah, King Abdulaziz University and the Finnish Meteorological Institute (temporary)
Saudi Arabia	Solar Village	Naif Al-Abbadi, Energy Research Institute King Abdulaziz City for Science and Technology (KACST)
United Arab Emirates	Masdar Institute	Masdar city, Masdar Institute of Science and Technology
United Arab Emirates	Mezaira	Mezaira, National Centre for Meteorology and Seismology
Islamic Republic of Iran	IASBS	Zanjan, Department of Physics, Institute for Advanced Studies in Basic Sciences
Turkey	IMS-METU-ERDEMLI	Erdemli Mers'n, Marine Sciences-Middle East Technical University

Only seven AERONET stations are operational at present in West Asia and one of them is for the temporary field campaign, Hada-El-Sham (Saudi Arabia), next to a permanent station (Table 5).

Recognizing that AERONET is the largest and most important network in the world for aerosol monitoring and validation of both satellites and aerosol models, and that there is no evidence of the existence of other photometer networks in the region, the situation is decidedly worrying. The surface of West Asia is greater than that of western Europe, where there are nearly 100 active and operational AERONET stations, and where problems derived from aerosols/dust are not as pressing as they are in West Asia.

According to the station map, sites are lacking in southern Saudi Arabia (Empty Quarter), in the large corridor leading from eastern Syrian Arab Republic and Mesopotamia (Iraq) to north-east Oman, passing over the Gulf.

Observation capacity with sunphotometers must be urgently addressed for the reasons discussed above. See Section B.2.1.3 (Aerosol optical depth with sunphotometers (recommendations)).

Concerning lidars and ceilometers, the capacity is quite low.

Worth noting, however, is the long-established expertise (nine years) in lidar techniques of the Optics Laboratories of the Institute for Advanced Studies in Basic Sciences (IASBS) at Zanjan (Islamic Republic of Iran), led by Hamid Khalesifard. The monitoring of atmospheric aerosols, including dust and urban pollution, is the main goal of this group. The remote-sensing laboratory of IASBS is equipped with:

- A four-channel Raman lidar (2 x 532 nm, 1 064 nm and 607 nm, N_2 Raman-channel); and
- A transportable scanning (p-plane and almucantar), two-channel elastic backscatter depolarization lidar (532 nm).

Both lidars have been designed and constructed in the IASBS Optics Laboratories.

In August–September 2004, the intensive UAE[2] field campaign was conducted in the UAE and over the adjacent Gulf and Gulf of Oman. Two MPLNET lidars were deployed, co-located with AERONET Cimel sunphotometers. The synergy of the AERONET and MPLNET instruments was used to separate dust from cloud and retrieve dust vertical profiles during daytime conditions.

Figure 75 shows the available lidar sites in the northern hemisphere from different lidar networks constituting the WMO Global Atmosphere Watch (GAW) Aerosol Lidar Observation Network (GALION). There are two large lidar-observation gaps in desert-dust sources in northern Africa and the Middle East. East Asia is reasonably well monitored by lidar techniques.

The lidar at Zanjan has not been included in the graphical lidar and ceilometer database (http://www.dwd.de/ceilomap) developed by Werner Thomas (*Thomas, 2012*) and maintained by the German Weather Service (DWD). According to this map of lidar and ceilometer sites (Figure 76), West Asia shows sparse data coverage, well below tht of North Africa and Europe. The two lidars marked on the map correspond to those deployed in the UAE during UAE[2] in summer 2004 but are not now in operation.

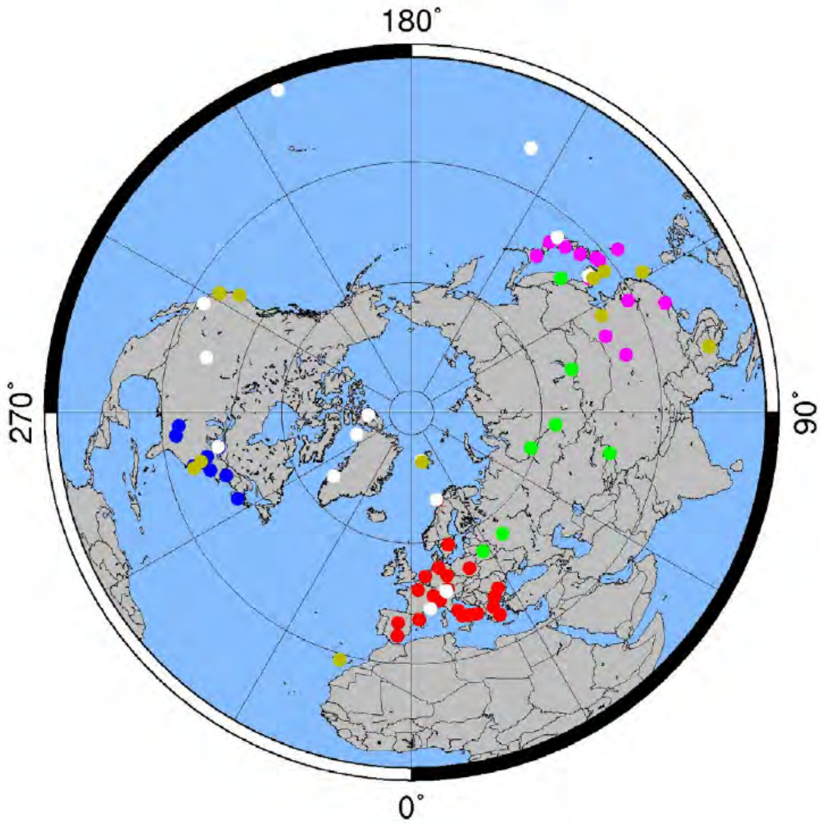


Figure 75 - Distribution of stations available through cooperation between existing networks: the different networks are indicated by the colour of the dots: AD-NET violet, ALINE yellow, CISLiNet green, EARLINET red, MPLNET brown, NDACC white, REALM blue (after the GALION report, *WMO, 2007*)

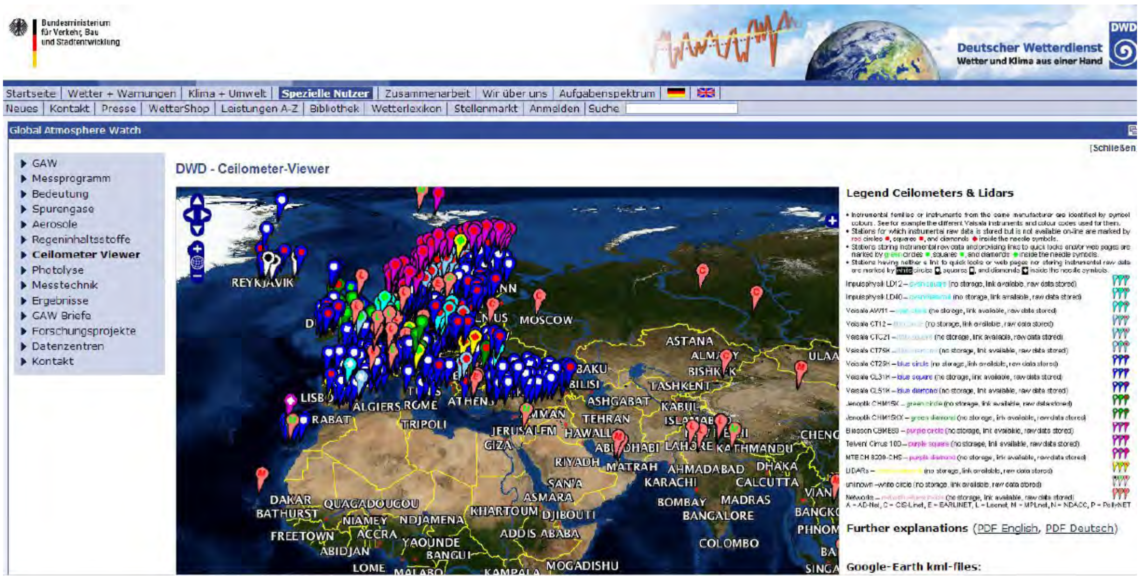


Figure 76 - Map of lidars and ceilometers developed by *Thomas (2012)* available at http://www.dwd.de/ceilomap

Figure 77 - Map of lidars and ceilometers in West Asia (http://www.dwd.de/ceilomap)

A CT25K ceilometer is run at Kuwait airport but this model cannot retrieve vertical aerosol backscatter and does not appear in the ceilomap. Concerning ceilometers, there is a significant contrast between Turkey, with a dense network of Vaisala CL31 ceilometers, and the West Asia countries, as can be seen in Figure 77.

B.1.2 Satellite observations

Most of the countries in West Asia use the SEVIRI-MSG sensor for monitoring dust storms. In some countries, MODIS Aqua/Terra (both images and quantitative AOD) are used but to a lesser extent, mainly for case analysis or for short-term studies of a few years (e.g. *Amanollahi et al. (2011)* in the Islamic Republic of Iran). NOAA-nn is used mainly for meteorological analysis. In Oman, *Charabi and Gastli (2012)* have used MISR to obtain a quantitative climatology of AOD oriented to feasibility of solar-power plant projects. The degree of utilization of aerosols/dust data from satellites is actually very low. In most cases, satellite information has an immediate use for weather forecasting. Satellite images of dust storms are used for illustrating analysed events in some scientific articles. Table 6 shows all the current satellite sensors providing aerosol and dust information.

Table 6 - Satellite-borne aerosol and dust sensors and products

Sensor	Platform	Spatial Resolution	Data period	Features
SEVIRI/MSG	Meteosat (MSG)	From (HRV) to	Aug'02-	High spatial resolution, very high temporal resolution Qualitative information
MODIS	Terra Aqua	10x10 km	Jan'00- Jul'02-	High spatial coverage AOD
MISR	Terra	17.6x17.6 km	Jan'00-	Multiple viewing angles AOD
OMI	Aura	13.7x23.7 km	Oct'04-	Absorption, SSA AOD
POLDER	ADEOS ADEOS-2 PARASOL	19x19 km	Oct'96-Jun'97 Apr'03-Oct'03 Mar'05-	Polarization
CALIOP	CALIPSO	5x0 km	Jun'06-	Vertical profiles
SeaWiFS	SeaStar	13.5x13.5 km	Jan'98-Dec'10	The longest time span, precise calibration AOD

B.1.3 Modelling

According to the information obtained from the questionnaires and other sources concerning the use of dust models, the situation in each country is the following:

Bahrain

The global NAPPS model (*Westphal et al., 2004*) is the only model used for both forecasting and case analysis. Only graphical outputs are used.
http://www.nrlmry.navy.mil/aerosol/#currentaerosolmodeling

United Arab Emirates

The COSMO_ART aerosol model has been running at the National Centre of Meteorology and Seismology since November 2010. Main features: 0.0625° horizontal resolution, 41 vertical levels, 3 bins (1.5, 6.7 and 14.2 μm), 12 soil types and GRAALS radiation scheme. COSMO_ART is run in cooperation with DWD and the Karslruhe Institute of Technology (Germany) but seems not to incorporate a specific mineral-dust module: aerosol modelling consists only of secondary aerosols resulting from gaseous pollutant reactions.

Islamic Republic of Iran

The DREAM8 Eta model has been run at the Islamic Republic of Iran Meteorological Organization (IRIMO) since 2012. Main features: 0.25° horizontal resolution, 28 vertical levels, 4 bins. This implementation is a result of cooperation with the South East European Virtual Climate Change Centre (SEEVCCC), hosted by the Republic Hydrometeorological Service of Serbia.

The WRF/CHEM model is run by the Atmospheric Science and Meteorological Research Centre (ASMERC) in Tehran. Main features: 0.10° horizontal resolution, 28 vertical levels, four bins of aerosol particles.

The Geoinformatics Research Institute at the University of Tehran is developing the DuSNIFF model for dust forecasting based on remote-sensing information and air-mass trajectories.

Some analyses of dust storms in the Sistan region, using 25-year observations at Zabol meteorological station and artificial neural networks, have been performed in order to implement a statistical dust storm prediction system (*Jamalizadeh et al., 2008*).

Kuwait

The HYSPLIT model has been used since early 2007. A PM10 emission algorithm was incorporated into a Lagrangian transport and dispersion model, described by *Draxler and Gillette, 2001.*

Oman

The global NAPPS model (*Westphal et al., 2004*) is the only model used for both forecasting and case analysis. Only graphical outputs are used.
http://www.nrlmry.navy.mil/aerosol/#currentaerosolmodeling

Forward trajectories from the 14-km resolution Oman Regional Model (Oman Meteorological Department) combined with RGB images from SEVIRI-MSG have been used for case analysis (*Al-Yahyai and Charabi, 2012*).

Forward trajectory calculation was used by *Al-Yahyai and Charabi (2012*) for dust storm forecast in some case analyses.

Saudi Arabia

The Presidency of Meteorology and Environment has used the NAAPS global model, the BSC-DREAM8b regional model and multimode products from the SDS WAS NAMEE Regional Node for both forecasting and case analysis. DREAM-NMME-MACC has been used for case analysis.

Some dust storm events were studied with the CARMA-dust model and MM5 weather data (*Barnum et al., 2003*). WRF-Chem, coupled with an aerosol chemistry component, was used by *Kalenderski et al. (2013)* to simulate various aspects of dust phenomena over the Arabian Peninsula and Red Sea during a dust event in January 2009.

Turkey

The BSC-DREAM8b model has been run at the Turkish State Meteorological Service (TSMS) since July 2010 in cooperation with BSC, Spain. Main features: 1/3° horizontal resolution, 24 vertical levels, 8 bins (0.1–10 µm).

Qatar

No information.

In summary, only two countries (Islamic Republic of Iran and Turkey) run appropriate regional dust models. In the case of ASMERC (Islamic Republic of Iran), the use of WRF-CHEM as a dust model for operational purposes does not seem to be the appropriate solution. The CHEM module associated with WRF has not been conceived and developed for dust but for chemical processes in air-quality issues, as is also the case in the UAE with the COSMO_ART aerosol model. Considering this circumstance and the fact that, WMO SDS-WAS NAMEE has recently made a set of dust-model outputs available to West Asia countries, there are other solutions that are more interesting and effective for predicting dust storms. These are described in Section B.2.3 (Recommendations on SDS activities in West Asia).

B.1.4 Data exchange

Atmospheric dust-data exchange between institutions within the same country is usually limited to short-term activities or case studies. The exchange of information between countries is practically non-existent, at least in an organized and systematic way, leading to the need to establish a monitoring system for dust storm early warning.

B.1.5 Application of SDS products and services

There are no specific user-oriented products and services for sand- and dust storms. Most National Meteorological or Hydrometeorological Services (NMSs) run classical NWP models.

B.1.6 Capacity-building and training

Most countries are interested in general topics related to sand- and dust storms.

The Islamic Republic of Iran organized five courses/conferences on SDS in the period 2010–2012:

- Regional Seminar on SDS Management, University of Medicine Sciences and Health, Kermanshah (four days), 2012.
- National Conference on SDS Management, Khorram Abad (four days), 2012.
- Training Course on Sand and Dust Storms, IRIMO, Tehran, 10–13 October 2011. Topics were observation, monitoring, modelling and forecasting of SDS. The instructors were from WMO, Spain, Croatia and the host country. The participants were from the host country, Turkey, Iraq and some international organizations, as well as water-resources management and environmental departments and university students.
- SDS International Conference, Ramin University, Ahwaz (four days), 2011.
- Training Course to Combat Desertification and SDS Management for Iraq’s Experts, Ahwaz (15 days), 2010.

Turkey has held three international workshops and training courses on SDS in the period 2011–2012:

- Training on Sand and Dust Storm (SDS), Erosion Preventing Techniques and Controlling Methods and Meteorological Services, SDS Forecast and Early Warning System, 22–26 February 2011, Istanbul; organized by TSMS, General Directorate of Combating Desertification and Erosion (CEM) and General Directorate of Forestry (OGM). Participating countries/institutions: Egypt, Iran (Islamic Republic of), Iraq, Jordan, Mauritania, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, BSC (Spain), Spanish Meteorological Service (AEMET), EUMETSAT, University of Murcia (Spain).

- Second Training Course on WMO SDS-WAS (Satellite and Ground Observation and Modelling of Atmospheric Dust), 21–25 November 2011, Antalya, Turkey, organized by: WMO, EUMETSAT, BSC, AEMET and TSMS. Participating countries/institutions: Algeria, Burkina Faso, Cape Verde, Chad, Egypt, Ethiopia, Iraq, Jordan, Kuwait, Morocco, Oman, Saudi Arabia, Senegal, Sudan, Turkey, Yemen, CSIC-Spain, University of Leeds (United Kingdom), METU-Erdemli (Turkey), ITU-Eurasia Institute of Earth Sciences (Turkey), SEEVCCC (Serbia), Directorate General of Meteorology and Air Navigation (DGMAN, Oman), BSC, Izaña Atmospheric Research Centre (Spain), AEMET, EUMETSAT, WMO.

- Workshop on Meteorology, Sand and Dust Storm (SDS), Combating Desertification and Erosion, 26–28 November 2012, Ankara, Turkey; organized by: TSMS, CEM and OGM. Participating countries/institutions: Azerbaijan, Bahrain, Cyprus, Egypt, Iran (Islamic Republic of), Iraq, Kyrgyzstan, Kuwait, Libya, Morocco, Palestinian Meteorological Office, Saudi Arabia, Spain, Sudan, Tajikistan, Tunisia, Turkey, Uzbekistan.

The Centre of Excellence (CoE) for training in Satellite Meteorology in Muscat (Oman) has been in operation since 2006. It trains scientists from Middle East countries in the understanding and use of satellite data. Since its inception, it has trained more than 180 weather forecasters and experts in marine and water-resources management. Humaid Al-Badi, Chief of Remote Sensing, leads the work of the centre, on behalf of the Oman Department of Meteorology.

The CoE forms part of the WMO Coordination Group for Meteorological Satellites (CGMS) Virtual Laboratory for Education and Training in Satellite Meteorology (VLab), a global network set up by WMO for the use of data and products from meteorological and environmental satellites. Each centre is sponsored by one or more satellite-operating agencies. EUMETSAT sponsors the CoE in Muscat through various initiatives, including joint training events and training for locally based trainers.

Training at the CoE in Muscat takes place in cooperation with the Sultan Qaboos University and the main goals are to:

- Address training needs in-remote sensing applications for Middle East countries, especially in satellite meteorology.
- Establish and promote the concept of a VLab for training in meteorological remote-sensing applications by organizing training sessions and using VLab online training tools.
- Establish a regional focus group that meets online to carry out weather briefings, seminars and related meetings on a regular basis.

More information about the CoE for Training in Satellite Meteorology can be found at http://www.met.gov.om:8888/coe/.

Some countries have shown interest in organizing SDS courses and meetings to enhance regional cooperation. There is also considerable interest in SDS monitoring and early warning in subjects ranging from observations (ground-based monitoring networks, satellite data access and analysis) to forecasting and modelling techniques (implementation of dust numerical models, modelling methodologies, data assimilation), as well as consultation meetings with potential users to develop effective and helpful products. Other countries are interested in specific problems such as the prediction of haboobs.

B.2 RECOMMENDATIONS FOR SDS ACTIVITIES IN WEST ASIA

In this section, a number of general and specific recommendations addressing all aspects that should be covered by an SDS-WAS Regional Node are presented. The recommendations have been made after careful analysis of information obtained about capabilities of observation, modelling, data exchange and capacity-building. The information available may be limited in some respects, so it would have to be taken into account when assessing these recommendations.

This section has been structured as follows:

B.2.1 In situ observation systems
B.2.1.1 Visibility
B.2.1.2 In situ particulate matter
B.2.1.3 Aerosol optical depth with sunphotometers
B.2.1.4 Lidars and ceilometers
B.2.1.5 New or complementary developments
B.2.2 Satellite observations
B.2.3 Multi-scale/downscaling dust forecasting
B.2.4 Dust-forecast validation
B.2.5 Model reanalysis
B.2.6 Regional collaboration mechanisms
B.2.7 Data-exchange policy
B.2.8 SDS products and services
B.2.9 Training and capacity-building

B.2.1 In situ observation systems

B.2.1.1 Visibility

Visibility and present-weather information from SYNOP and METAR reports from countries of the region and neighbouring countries should be stored in a historical database. This database should be updated NRT in order to achieve the following goals:

1. Produce NRT visibility data maps. Visibility from 3-hour reports or 30-minute METAR reports can be plotted in on a map with coloured markers (Figure 78) for dust nowcasting and early warning, as done by the SDS WAS-NAMEE Regional Centre (http://sds-was.aemet.es/forecast-products/dust-observations/visibility). This might help forecasters who may know at a glance when and where there is reduced visibility owing to dust. Some filters using present weather and other meteorological parameters as relative humidity and precipitation must be used to disregard reduction of visibility from fog or heavy rain.

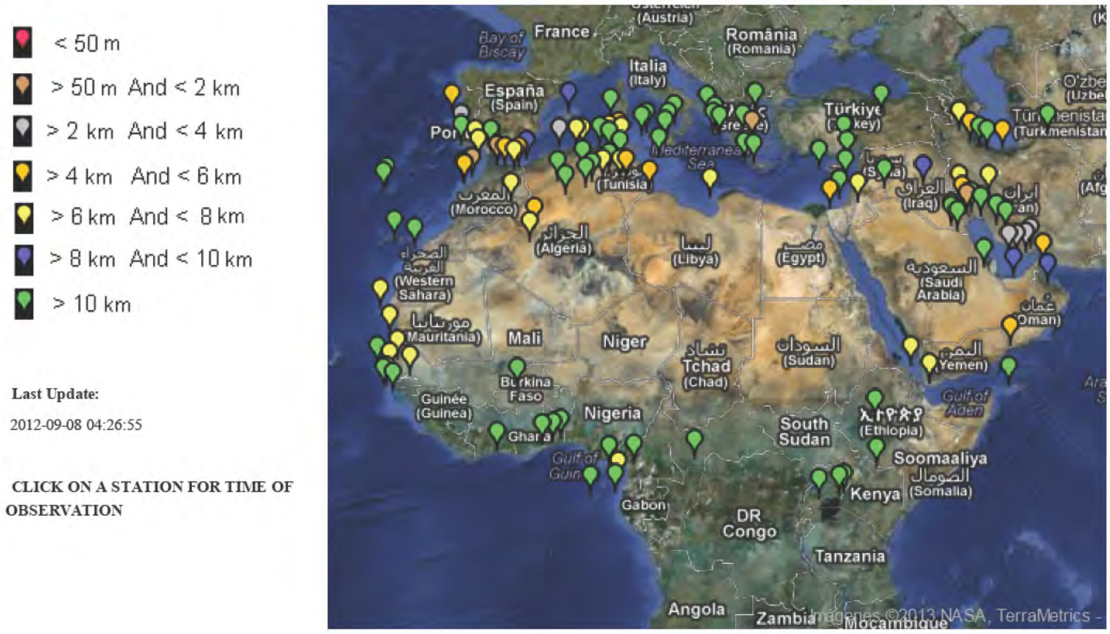


Figure 78 - NRT visibility indicated by coloured markers at the SDS-WAS NAMEE Regional Centre (http://sds-was.aemet.es/forecast-products/dust-observations/visibility)

2. NRT visibility data can be used for model validation. Some authors have found an empirical relationship between visibility and PM10 or TSP (*D'Almeida, 1986; Ben Mohamed et al., 1992)* (see Figure 79). *Camino et al. (2012)* proposed a new relationship based on simultaneous visibility/PM10 observations in the Canary Islands and the Sahel.

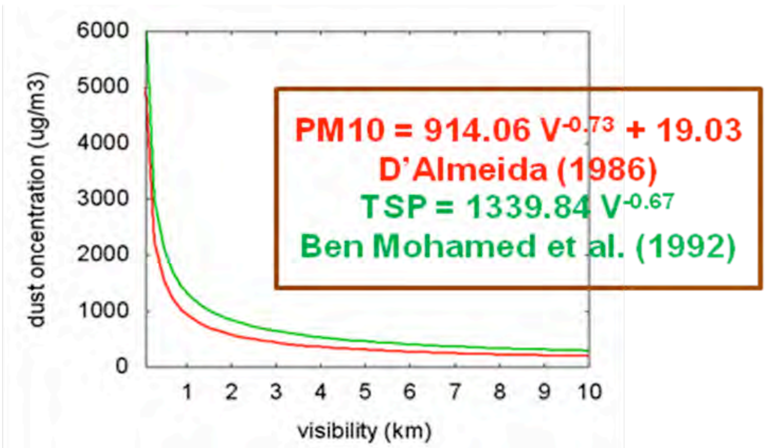


Figure 79 - Experimental relationship between visibility and PM10 (*D'Almeida, 1986*) and TSP (*Ben Mohamed et al., 1992*)

Extinction at surface level from dust models could be compared with horizontal visibility from SYNOP and METAR. The experience shows that useful METAR visibility information for model verification is constrained to days with severe reductions of visibility (below 10 km), since most SYNOP and METAR stations do not report reduced visibility when it is beyond 10 km. Few SYNOP stations report accurate visibility conditions using distant references. Investigations are currently being conducted at the SDS-WAS NAMEE Regional Centre to implement NRT validation of modelled surface-dust concentration, using visibility data and some visibility-dust concentration empirical relationship (contact person: Enric Terradellas, eterradellasj@aemet.es). As an example of this application, see the following validation case analysis made for the purpose of this study using visibility at two stations in Kuwait and Oman (Figure 80).

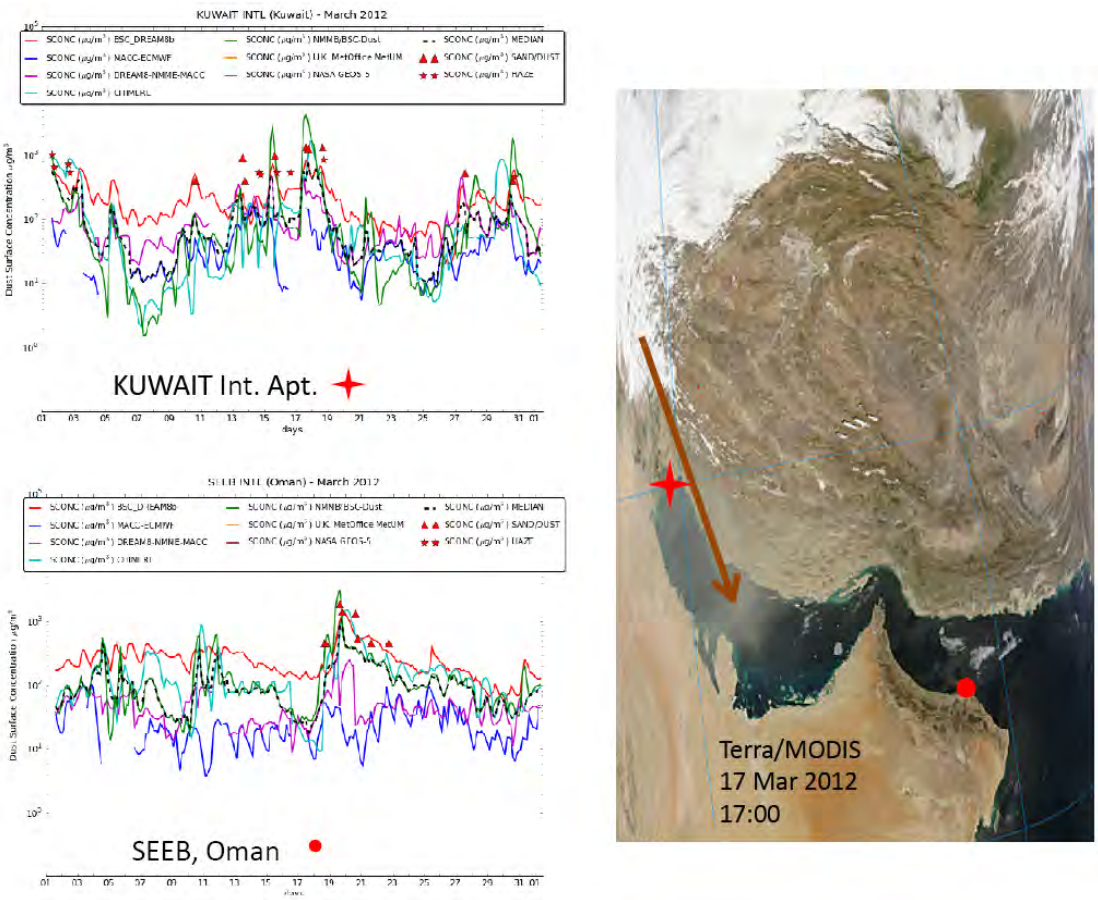


Figure 80 - Comparison of dust concentrations from seven different dust models with estimated PM10 from visibility observations at Kuwait International Airport and Seeb station in Oman during a dust intrusion from Mesopotamia captured by MODIS on 17 March 2002 at 17:00 UTC (contact person: Enric Terradellas, eterradellasj@aemet.es)

3. Long-term monitoring of visibility reduction at SYNOP-station level or grouping the SYNOP stations regionally in areas with common soil-type or climatological characteristics may be an interesting activity. A first analysis would consist in obtaining an updated climatology of visibility similar to that obtained by *Kutiel and Furman (2003),* but expanded to the whole of West Asia on monthly and seasonal scales. Many stations started operations in the 1970s, so long-term analysis of more than 30 years can be performed. The number of days per month/year with visibility range below a threshold value (with some filter parameters to avoid reduction of visibility caused by atmospheric parameters other than dust, such as fog and heavy rain) would be an interesting first approach to indirectly determine dust trends. This information would constitute a simple but unique picture of long-term dust trends.

Global, daily averaged visibility data (averaged with a minimum of four daily SYNOP observations) can be obtained from the National Climatic Data Center (NCDC) Global Surface Summary of Day (http://www.ncdc.noaa.gov/).
Please read ftp://ftp.ncdc.noaa.gov/pub/data/globalsod/readme.txt.

Visibility data can be downloaded from the Integrated Surface Database (ISD) at NCDC (http://www.ncdc.noaa.gov/land-based-station-data/integrated-surface-database-isd).
This database consists of global hourly and synoptic observations. ISD integrates data from more than 100 original data sources and comprises more than 20 000 stations worldwide. Currently, more than 11 000 "active" stations are updated on a daily basis.

B.2.1.2 In situ particulate matter

As a preliminary approach to dust storm monitoring, *dust-deposition gauges* are highly recommended. This method measures dust-deposition rate and involves the passive deposition and capture of dust within a funnel-and-bottle arrangement. Data are usually collected over monthly periods and results are expressed in g/m^2/month (i.e. the mass of dust deposited per square metre per month). This method enables determination of the relative "dustiness" of sampling locations. It does not provide data on dust concentrations or enable determination of dust levels from a particular event or source. Data from relatively dense networks of simple dust-deposition gauges might provide a temporal and spatial climatology of breathable dust at surface level. It is necessary to install a regional network of dust-deposition gauges in each country, using standardized sampling and evaluation methodologies and a network topology that meets objective criteria, taking into account dust sources and pathways, and filling observation gaps.

High-volume samplers determine average dust concentrations. They comprise the collection of dust by drawing a constant flow rate of ambient air through a filter. Data are usually collected over a 24-hour period and results are expressed in $\mu g/m^3$/24 h. A selective inlet may be fitted to a high-volume sampler to restrict the particle size being sampled (for example, to ensure only PM10 particles are sampled).

A few PM10 stations must be set up at rural sites, far away from direct impacts of anthropogenic sources in populated cities and industrial centres, in order to obtain aerosol background measurements which would be affected, basically, by mineral dust from local resuspension or transported from other regions.

Due to the complexity and vastness of West Asia, it is not possible in this report to give recommendations on specific geographic locations for rural background stations. On a national level, the most interesting areas covering every current and potential dust storm pathway should be explored. As a rough estimate, about 10% of PM10 stations must be located in rural background conditions.

The rural background PM10 stations network will provide useful information regarding the spatial and temporal variability of surface mineral-dust concentration and, at the same time, will help to distinguish and understand the different sources of particulate matter pollution measured by the air-quality networks of each country. More specifically, this network will permit:

- Climatology of surface-dust concentration in hotspots at country level, thus climatology of surface-dust background (inhaled by population)

- Improvement of knowledge about the origin of the daily exceedances of PM10 thresholds established by air-quality regulations in each country (e.g. 50 $\mu g/m^3$ as a daily limit value of the European Union air-quality directive) by using back-trajectory analysis, available PM model outputs, satellite data and meteorological maps, is a mandatory activity of air-quality managers. This will allow the detection of high PM episodes caused by natural sources on a regional scale and the study of their seasonal and geographical variability (*Escudero et al., 2007*). From the point of view of air-quality managers, this information is important, since it permits quantifying the contribution of natural sources (mineral dust) in the exceedance of legal limits for PM10, apart from anthropogenic sources. Xavier Querol (xavier.querol@idaea.csic.es) is an international expert in this matter (*Querol et al., 2008*).

In order to implement a quality-assurance system, periodical (at least once a year) manual calibrations with gravimetric PM10 high-volume samplers should be performed by co-located continuous PM10 analysers (such as PM10 tapered element oscillating microbalance and PM10 Betabeta-attenuation analysers), as recommended by *Rodríguez et al. (2012).* A regional quality-assurance centre providing homogenized and standardized methodologies and quality-control/quality-assurance protocols should be implemented. For detailed advice on this subject, please contact Sergio Rodriguez (srodriguezg@aemet.es).

Receptor modelling techniques based on principal component analysis and subsequent multilinear regression analysis must be applied to databases for source-apportionment analysis at each sampling site, following the methodology proposed by *Thurston and Spengler (1985).* Xavier Querol (xavier.querol@idaea.csic.es) and Andrés Alastuey (andres.alastuey@idaea.csic.es), among other experts, have wide experience in this technique applied to surface aerosol measurements (*Querol et al., 2008*).

Long-term surface-dust concentration (e.g. PM10) in rural sites could be used in offline model validation. Figure 81 is an example of PM10 validation of the NMMB/BSC-Dust model performed using daily data from in situ African Monsoon Multidisciplinary Analysis (AMMA) stations in the Sahel for the period 2006–2008 (*Cuevas et al., 2012*). This validation permits knowledge of model performance throughout the year. Similar analyses should be performed for current and future dust models.

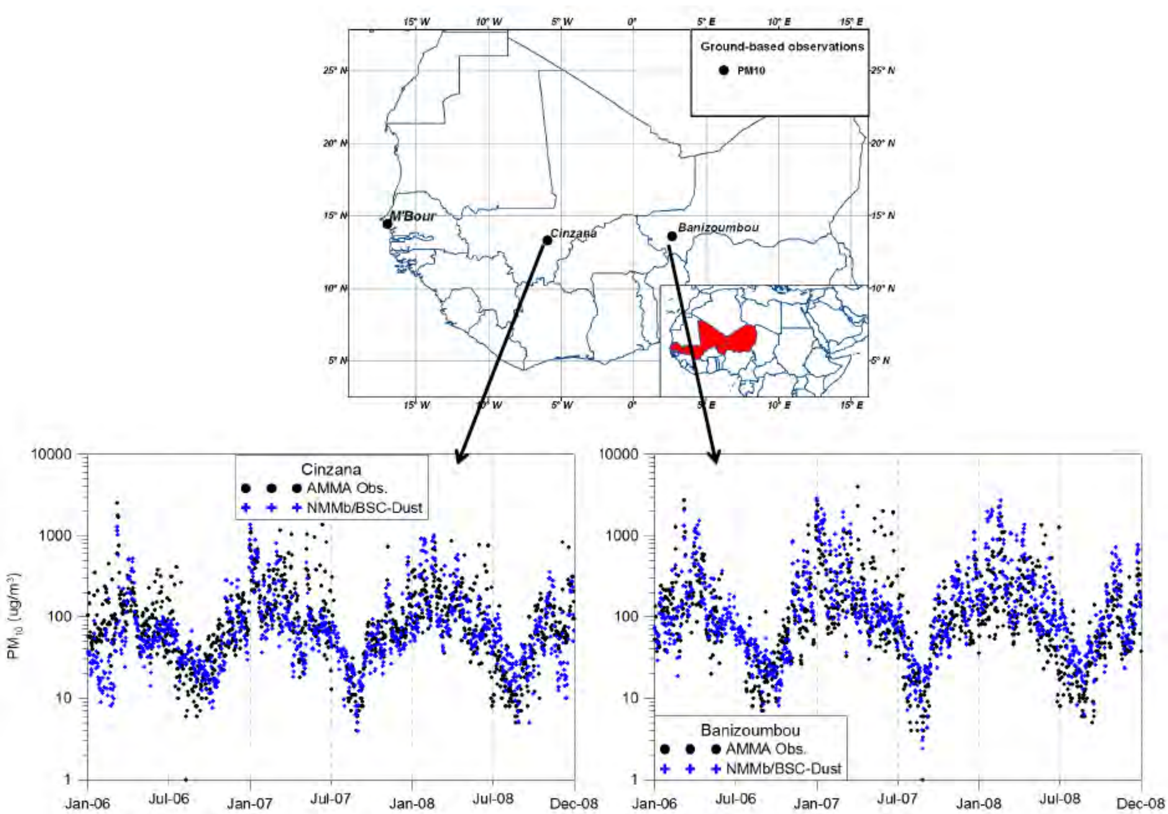


Figure 81 - Daily comparison between simulated PM10 with NMMB/BSC-Dust model and in situ PM10 data at AMMA Cinzana and Banizoumbou stations in the Sahel for the period 2006–2008 (after *Cuevas et al., 2012*)

Regarding in situ PM observations, a specific recommendation is made for the implementation of a marine boundary layer observatory in the Gulf region for the analysis and long-term monitoring of dust deposition impacts over the sea. As shown in Figure 67 (Section A.3), there is a clear lack of marine observations in the Gulf and Arabian Sea. A marine observatory is of great importance for marine biochemistry and climate issues. The marine observatory might be implemented under the auspices of the Regional Organization for the Protection of the Marine Environment (ROPME).

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B.2.1.3 Aerosol optical depth with sunphotometers

There are clear gaps concerning sunphotometers with regard to dust hotspots and pathways as analysed in Sections A.2.1 and A.2.6. Figure 82 shows locations of desirable new AERONET stations in a first phase of sunphotometer deployment.

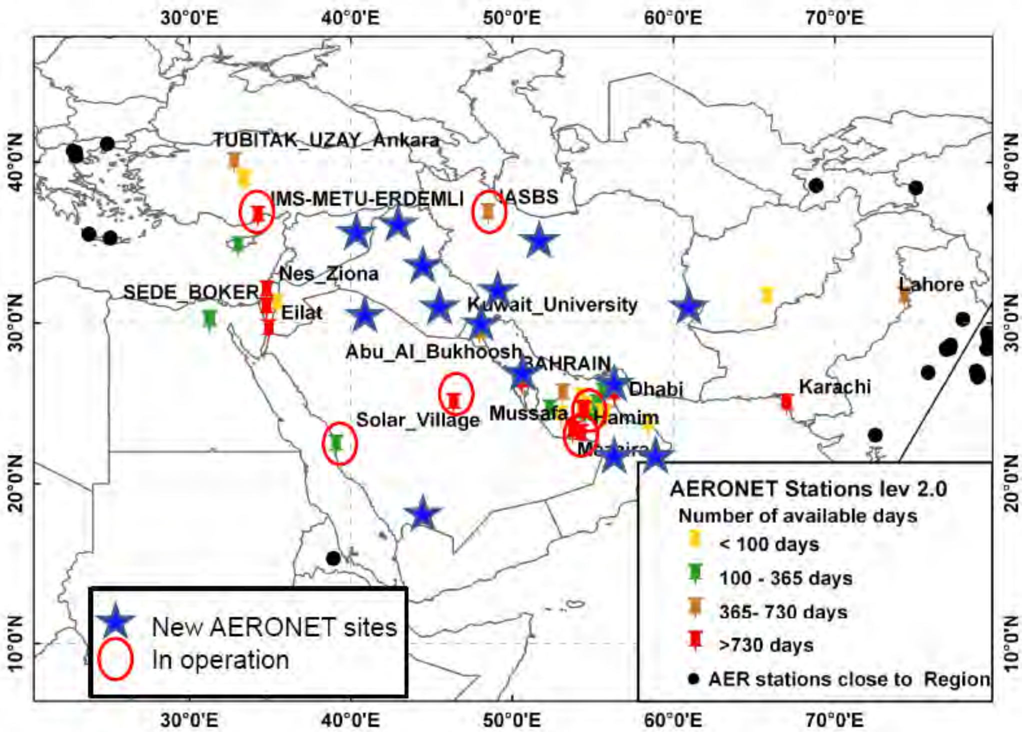

Figure 82 - Map of active AERONET stations (red circles) and proposed new AERONET stations (some of the former AERONET stations) (blue stars)

A preliminary recommendation of new AERONET sites, which will need the consensus of experts, is the following (Figure 82):

- Re-start operations at the following former AERONET sites:
  - Kuwait University, Khalidiyah campus
  - Bahrain (re-start operations in the most convenient free-horizon site)
  - Dhadnah (UAE)

- Possible new AERONET sites chosen for the geographical location of dust storm pathways and considering the topology of the regional network:

  - Arar (northern Saudi Arabia)
  - Najran (south-western Saudi Arabia)
  - Somewhere in Empty Quarter (Saudi Arabia): not indicated on the map
  - Dayr az Zawr (eastern Syrian Arab Republic)
  - Mosul (northern Iraq)
  - Baghdad (central Iraq)
  - As Smawah (southern Iraq)
  - Faud, Dhahirah (Oman)
  - Bani Bu Hassan (Oman)
  - Ahvaz, Khuzestan (south-western Islamic Republic of Iran)
  - Zabol (preferable) or Zahedan (Sistan basin, eastern/south-eastern Islamic Republic of Iran)
  - Tehran (Islamic Republic of Iran)

The proposed AERONET network topology will assure continuous monitoring of dust hotspots and impacted areas with a minimum number of stations. Special interest has been paid to the north-west to south-east dust corridor from eastern Syrian Arab Republic/northern Iraq to north-eastern Oman passing over Kuwait, Bahrain, Qatar, UAE, eastern Oman and the Gulf Sea. Dust transport from Saudi Arabia and southern Islamic Republic of Iran is also monitored. As a complementary goal, this network might also be used to monitor aerosols from gas flares, refineries and industrial combustion.

The establishment of this network will not be easy and will need to be taken step by step. The first important issue is that AERONET photometers need to be calibrated every 12 months and data processing is performed centrally at the AERONET headquarters at GSFC (http://aeronet.gsfc.nasa.gov).

The AERONET calibration structure is complex and costly because it involves several procedures:

- Annual photometric calibration of field instruments (AERONET requirement). Full calibration of a station photometer takes at least two months by intercomparison with a master instrument. Master instruments are managed by AERONET or by associated calibration centres.

- Radiance calibration with integrating sphere in a darkroom.

- The master instrument calibration is performed every three months at a high mountain station with pristine skies, using the Langley method.

- Integrating spheres are calibrated against a standard reference sphere from NASA, using a strict protocol.

Since station instruments must be calibrated on an annual basis and the calibration takes a minimum of two–three months, plus shipment time and, in some countries, considerable additional time for customs clearance (export and import), the actual operation of an instrument is really limited to seven–eight months per year. To avoid this limitation, it is recommended to have an exchange instrument for every two or three station instruments. Using instrument rotation, the continuity of each station (almost 100%) throughout the year can be assured. This is why a regional AERONET network is proposed. In this case, a couple of additional instruments could be used as masters, which could be calibrated in AERONET qualified calibration centres, and then perform one or two intercomparisons per year (in autumn or winter) of station instruments to transfer the calibration. It seems unrealistic to send a large number of instruments individually every year to an AERONET calibration centre in Europe or the USA. On the other hand, the creation of a regional AERONET network will require expert and instrument operator training with courses related to the installation, operation, maintenance, and data evaluation of Cimel photometers. The degree of knowledge in different technical subjects will much depend on the degree of technical responsibility the regional network will acquire. The estimated price of a full Cimel sun photometer (the only instrument accepted by AERONET) is about US$ 40 000.

International experts in AERONET calibration and regional AERONET networks are the following:

- AERONET: GSFC, USA (http://aeronet.gsfc.nasa.gov/). Contact person: Brent Holben (Brent.N.Holben@nasa.gov)

- PHOTONS: CNRS-University of Lille, France (http://loaphotons.univ-lille1.fr/), network associated with AERONET. Contact person: Philippe Goloub (philippe.goloub@univ-lille1.fr)

- RIMA: University of Valladolid, Spain (http://www.rima.uva.es/), network associated with AERONET. Contact person: Angel de Frutos (angel@goa.uva.es)

- PHOTONS and RIMA use the Izaña Atmospheric Observatory (AEMET, Spain, http://aemet.izana.es) as absolute sun calibration centre for AERONET masters. Contact person: Emilio Cuevas (ecuevasa@aemet.es). The experience of PHOTONS and RIMA as regional networks would be interesting in this proposal.

Experts in the region operating instruments:

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The experience of regional experts could help technicians and operators of new AERONET stations.

There are other alternatives for monitoring AOD, although none of them achieves the degree of optimization of AERONET for NRT monitoring and the determination of aerosol optical properties with inversion techniques. For long-term, high-accuracy AOD measurements (also providing NRT data), we would recommend the WMO GAW precision filter radiometer (http://www.pmodwrc.ch/worcc/). Contact person: Christoph Wehrli (Christoph.Wehrli@pmodwrc.ch).

B.2.1.4 Lidars and ceilometers

Lidars provide quantitative physical parameters of aerosol and dust vertical distribution. Various aerosol lidar techniques have been developed during the past 40 years or so. A comprehensive description of the currently available methods is presented in Annex A of The WMO GAW/GALION programme report (*WMO, 2007*). The most important lidar techniques are: backscatter lidar, Raman lidar, depolarization lidar and high spectral resolution lidar. These methods can be applied at either one or multiple wavelengths (multiwavelength backscatter lidar, multiwavelength Raman lidar). Height-time displays of the range-corrected signal are sufficient to provide an overview of the measurement situation in terms of the evolution of the planetary boundary layer (PBL), lofted aerosol layers and cloud distributions, which have operational applications (aviation, weather forecast) and research applications. As stated by *Mona et al. (2012),* lidars permit analysis of the intrusion of desert dust into the PBL and mixing processes of dust with other aerosol types, as well as the transport of dust to upper levels. Lidar measurements in combination with other techniques, such as sunphotometry, are ideal for investigating certain aspects of atmospheric composition, transport, deposition of dust and dust–cloud interaction, including cloud-formation processes.

Lidars are advanced, expensive instruments (>US$ 100 000) that require specially trained staff to operate them, as well as dedicated personnel to retrieve vertical profiles with data-inversion algorithms. Maintenance costs are also high. Compared with sunphotometers, the lidar technique is one order of magnitude more expensive and requires much more experienced specialists for both operation and data processing.

According to existing capabilities and sites of AERONET stations, a proposal for a lidar network is given in Figure 83. This is a first approach, which needs further and more detailed discussions with interested institutions to ensure the necessary resources for implementing a lidar programme.

A lidar network similar to that proposed for sunphotometers would be the ideal scenario and should be the goal in the coming years. Given the enormous complexity of the lidar technique, its high cost and the level of development of this technology in the region, however, caution is necessary when proposing lidar sites. For this reason, a first recommendation is to strengthen what has already been achieved. Support to the IASBS group that has designed, developed and operated two lidars in Zanjan (Islamic Republic of Iran) is therefore highly recommended. It is a unique lidar facility in the region and must achieve and ensure future continuous operation. Aside from the importance of the measurements taken from these lidar sites, the expertise provided by the IASBS group is also highly valued.

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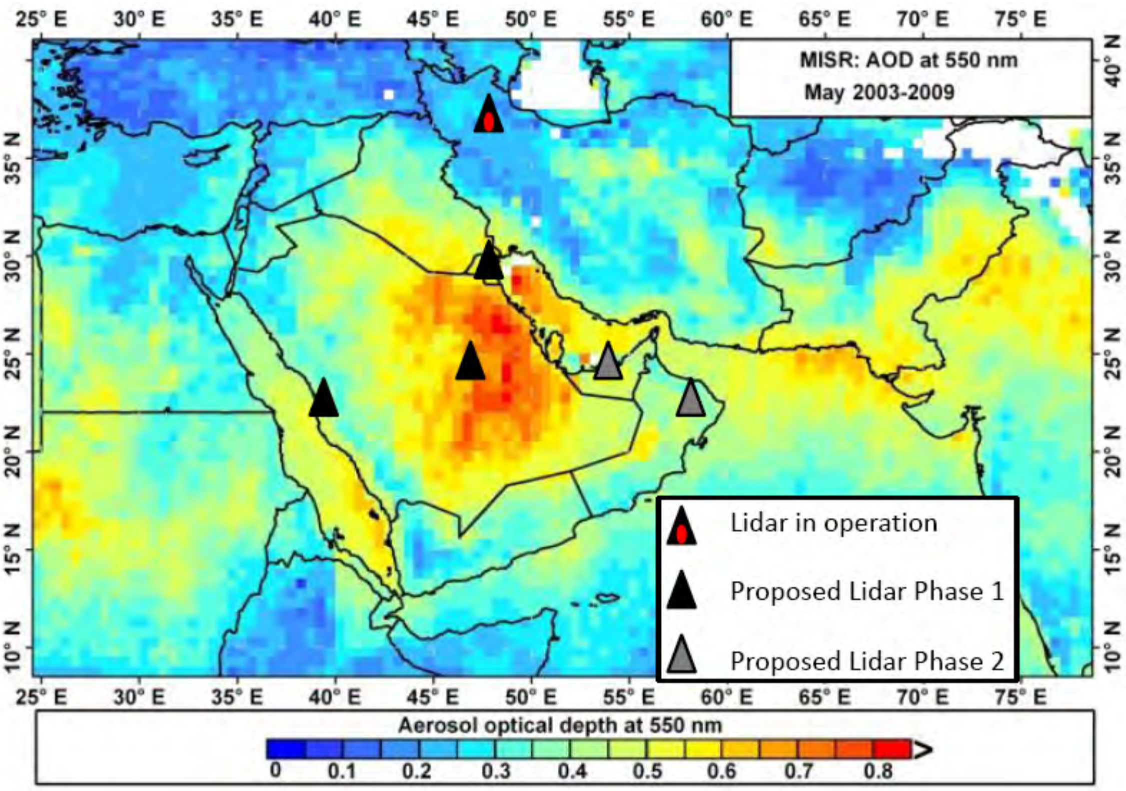

Figure 83 - Proposed lidar sites in West Asia

A second recommendation for a lidar site would be Kuwait, strategically located in the dust outflow from Iraq, and in the pathway of west-east-west dust clouds. Kuwait would be a key station of great interest for both operational and research activities. This lidar programme might be a collaborative exercise between a university/research institute group and the Kuwait Meteorological Centre. A potential site could be at Kuwait University, where an AERONET station was in operation until August 2012.

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The third recommendation concerns Saudi Arabia where two AERONET stations are in operation:

KAUST campus: this station could monitor intercontinental dust transport, especially dust plume, over the Red Sea.

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Solar Village at KACST

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Energy Research Institute
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In a second phase, and co-located with existing AERONET stations, two additional lidar stations could be set up in UAE and Oman, respectively. These stations, located in the dust corridor beginning in northern Iraq, could monitor dust transport along the Gulf to the Arabian Sea and between the Arabian Peninsula and Islamic Republic of Iran.

Initiatives from other groups of countries in the region would be most welcome and should be considered in a medium-term dust-monitoring plan. A lidar programme requires a commitment and a significant involvement of research groups, without which it would not be possible to implement the technique.

WMO (2007) provides a detailed technical description of lidar programmes and international lidar networks. See also the WMO-GAW Aerosols Programme (http://www.wmo.int/pages/prog/arep/gaw/aerosol.html).

The contact person who could advise West Asia countries on implementation of lidars and assist in training specialists is:

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Within the complex world of lidars, we would recommend the simplest approach that could be deployed as a first step to implementation. This technique is a combination of a micropulse lidar, as recommended in MPLNET (*Welton et al., 2001*), consisting of low-cost, eye-safe, automated 532-nm backscatter lidars, with an AERONET sunphotometer (*Holben et al., 1998*). In this approach, the sunphotometer provides accurate values of AOD, which is an important constraint for the lidar solution. The integral lidar-derived extinction profile must match the photometer-derived optical depth. This would allow an estimation of the column lidar ratio. Despite remaining uncertainties of about 20% in the extinction coefficients because of possible variability of the lidar ratio with height, and the fact that expected errors may be considerably larger when a mixture of different aerosol/clouds layers is present, this technique could provide an NRT vertical distribution of dust and would permit a first analysis of dust intrusions in the vertical.

This technique is being implemented by some groups at African sites with frequent Saharan dust intrusions. The LOA group (CNRS-University of Lille) has implemented a long-term Cimel lidar, AERONET cimel sunphotometer and lunar photometer in Dakar, Senegal. The Izaña Atmospheric Research Centre (AEMET) and the National Institute of Aerospace Technology of Spain are implementing a long-term MPLNET-lidar, AERONET Cimel sunphotometer and lunar photometer at Santa Cruz de Tenerife (Canary Islands, Spain). Both groups are working together to set up an NRT lidar-photometer mini-network in West Africa. Their experiences in places with similar environmental conditions to those in West Asia may be helpful for groups initiating these techniques.

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A novel aspect of lidar investigation of desert dust is its application for societal benefits and risk management. This moves the lidar community from science research towards the potential applications communities. The review article by *Mona et al. (2012)* deals with these and other aspects of lidar developments for desert-dust monitoring. Operation of, and research with, lidars is still a complex issue, however, and is basically still within the framework of research. The implementation of lidars in West Asia will therefore require close cooperation between universities, research institutes and NMSs.

Besides research-oriented lidar networks, a large number of ceilometers are distributed worldwide. Ceilometers (often called low-power lidars) are robust systems for continuous operation. They can provide useful information about the aerosol layers which can be used for operational dust monitoring and forecasting. Ceilometers are single-wavelength backscatter instruments and are relatively inexpensive (~US$ 20 000) that most airports use for cloud-base monitoring. Many NMSs, as well as airports, operate ceilometers networks, which provide fully automatic and continuous atmospheric measurements of, for example, cloud-base and PBL height but also profiles of atmospheric aerosol backscattering. The involvement of NMSs in gradually extending the use of ceilometer use to SDS activities is obvious and also relatively easy and inexpensive. A summary of the capabilities of ceilometers is provided by *Thomas (2012).*
(http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-109_TECO-2012/Session5/K5_02_Thomas_Ceilometers_Lidars.pdf).

As Thomas states, a global operational network for aerosol monitoring could, at a first stage, consist of easy-to-use and continuously measuring ceilometers, operated together with sun-tracking sunphotometers and lidar anchor stations equipped with aerosol lidars for the calibration, evaluation and quantification of ceilometer data. He describes a number of existing algorithms for retrieving aerosol parameters from different ceilometers. A semi-operational retrieval code for aerosol parameters is available for the Jenoptik CHM15K instrument of the DWD (*Flentje et al., 2010*). These algorithms may be shared with other operators using this instrument in their networks.

The Vaisala CL31 has been compared with a Raman lidar, which basically implies the availability of a retrieval code for this instrument (*McKendy et al., 2009*). The newer Vaisala CL51 was recently compared with an MPL in Spain during Saharan dust-intrusion events, as described by *Hernandez et al. (2011).*

The gradual transition to new-generation modern ceilometers which provide, at the moment, only semi-quantitative information of dust-layer profiles, is simple. As NMSs replace the old ceilometers installed in airports by modern ones, data may be used for both operational aeronautic purposes and SDS activities. A pilot project could be initiated with the use of the existing, dense, new-generation ceilometer network in Turkey for SDS activities. Evaluation and quantification of the ceilometer data can be carried out if the ceilometer is operated together with sun-tracking sunphotometers and lidar anchor stations equipped with aerosol lidars. Ceilometers have clear potential in West Asia for SDS monitoring and characterization.

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B.2.1.5 New or complementary developments

Total-sky cameras and webcams

NRT total-sky cameras and webcams might prove useful in remote sites for dust nowcasting. As demonstrated in UAE[2], total-sky cameras might be useful for NRT dust tracking, as they can provide images every few minutes (1–5 minute intervals). National forecasting centres might therefore perform an SDS NRT watch with a network of total-sky cameras.

Webcams have been used to study dust storm formation and development. They are normally oriented to directions in which dust storms originate. An interesting experience of dust monitoring with webcams set up by the US Geological Survey at Mesa Verde (Colorado) can be visited at http://www.nps.gov/meve/naturescience/dustmonitoring.htm.

An example of dust-intrusion detection with a total-sky camera is given in the following link:
http://izana.aemet.es/index.php?option=com_content&view=article&id=184&Itemid=159&lang=en.

Meteorological radiosondes can also be used to characterize dust layers. In combination with lidars or ceilometers, radiosondes can provide insight into meteorological variables (wind speed/direction, temperature and humidity) associated with the vertical structure of dust layers.

Ganor et al. (2010) performed a synoptic classification of lower-troposphere profiles for dust days. Vertical profiles of temperature, wind components and humidity for days with dust and no dust were compared and analysed in order to identify features accompanying dusty conditions.

Andrey et al. (2013) analysed the Saharan air layer over the North Atlantic in summertime and reported that it was normally confined between two temperature-inversion layers (at 1 km and 6 km altitude, respectively) with higher relative humidity in this interval compared to non-Saharan conditions. This pattern permits a backward reanalysis of radiosondes to be performed for obtaining dust climatologies.

Another good example of the utilization of typical meteorological sensors in dust monitoring is radar. *Bluestein et al. (2004)* documented the behaviour of several dust-devil vortices within a 1.5 km range, using a mobile Doppler radar. A C-band Doppler polarimetric radar installed in the UAE has captured topographically channelled dust intrusions, allowing a high temporal resolution and 3D analysis (Roelof Bruintjes, project scientist at the US National Center for Atmospheric Research and President of Advanced Radar Corporation, personal communication).

Inexpensive hand or automatic (with sun-tracker) sunphotometers and radiometers are now being implemented for dust monitoring and characterization in specific activities. For example, they can be used in mobile units in field campaigns for solar-power plant feasibility studies or for air-quality assessment analysis. Other "inexpensive" sensors could be used for NRT monitoring along motorways or high-speed railways. They constitute valuable instruments when it is not possible to install costly equipment.

B.2.2 Satellite observations

Many satellite-based sensors are devoted to dust and aerosol monitoring (see Table 6 in Section B.1).

The best sensor for continuous monitoring of dust storms is without doubt SEVIRI-MSG. Its high spatial resolution is complemented with a unique, powerful capacity, which is a very high temporal resolution (frames every 15 minutes now and soon to be every 10 minutes). While SEVIRI-MSG is the ideal satellite sensor for dust nowcasting at the moment, it does not provide reliable quantitative AOD. Research is being conducted with SEVIRI-MSG products aimed at obtaining quantitative and operational dust information (*Klüser and Schepanski, 2009*) and inferring dust-cloud movements from animated images (*Genkova et al., 2008*), with promising results.

The UK Met Office MSG dust product shows an estimation of DOD retrieved from the empirical relationship between SEVIRI infra-red (10.8 μm) radiance and AOD at 550 nm. It is generated by transforming original retrievals to regularly spaced grids (0.18°) using a simple averaging method. An example at the SDS-WAS NAMEE Regional Centre can be found at http://sds-was.aemet.es/forecast-products/dust-observations/msg-2013-u.k.-met-office.

Concerning the potential use of SEVIRI-MSG images, the contact person is:
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The CoE for Training in Satellite Meteorology in Oman, in collaboration with EUMETSAT

Contact person:
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MISR space-based aerosol products provide complementary information (*Kalashnikova and Kahn, 2008*). MISR is excellent for obtaining climatologies for dust sources and pathways. MISR normally overestimates AOD at low AOD range and underestimates AOD at high AOD range over bright surfaces (*Kalashnikova and Kahn, 2008*). MODIS and SeaWiFS are excellent for obtaining quantitative AOD over the oceans. CALIOP, on board the CALIPSO platform, and PARASOL (polarization and anisotropy of reflectances for atmospheric science coupled with observations from a lidar), also on board CALIPSO, provide aerosol backscatter and extinction coefficient profiles. Data from these space-based sensors are available in the corresponding databases. They can be used for case analysis and performing dust climatologies for West Asia.

Recommendations on satellite information can be summarized as follows:

For quick graphical aerosol imagery from different satellite sensors, for both current day and past days, a comprehensive database is provided by the US Naval Research Laboratory/Monterey satellite products web-page:
http://www.nrlmry.navy.mil/aerosol/#satelliteanalyses.

Other links to NRT images are the following:

MODIS: http://rapidfire.sci.gsfc.nasa.gov/realtime/
or the following link where several sites can be accessed:
https://earthdata.nasa.gov/data/near-real-time-data/rapid-response.

The latest available animation of SEVIRI-MSG can be found at: http://sds-was.aemet.es/forecast-products/dust-observations/msg-2013-eumetsat.

SeaWiFS: http://oceancolor.gsfc.nasa.gov/cgi/pcgac9000.pl

Long-term reanalysis from satellite-based observations of dust hotspots, specific stations (e.g. AERONET or SYNOP stations), as well as of sensitive dust-impacted areas (cities, industrial facilities, airports) will quickly increase the knowledge of the spatial-temporal variability of dust storms. The use of the Giovanni application is highly recommended for this type of analysis. Giovanni is a web-based application, developed by GES DISC, that provides a simple and intuitive way to visualize, analyse and access vast amounts of Earth science remote-sensing data without having to download them (http://disc.sci.gsfc.nasa.gov/giovanni). If so required, however, data can also be downloaded in different formats (ASCII, HDF, netCDF, KMZ, JPG).
For dust/aerosol quantitative analysis, a huge aerosol and dust database is freely accessible at the World Data Centre for Remote Sensing of the Atmosphere (WDC-RSAT), (http://wdc.dlr.de/data_products/AEROSOLS/).

Satellites can play a key role in monitoring soil conditions. For example, *Tsvetsinskaya et al. (2002)* proposed to relate soil groups (based on the United Nations Food and Agriculture Organization soil classification) and rock types (based on US Geological Survey maps) to MODIS-derived surface-albedo statistics. That was a first step towards incorporating the observed spatial variability in surface reflective properties into climate models. This is especially important in areas such as Mesopotamia, where dramatic changes in soil use and characteristics are taking place, which, in turn, might influence the frequency and intensity of dust storms. *Shi et al. (2013)* used the MODIS-land-cover type product to investigate the surface-vegetation distribution and quantify surface-dust emissions in Saudi Arabia. Thus, soil specialists should work together with the satellite-user community and initiate joint projects in dust sources, since West Asia has been poorly studied in this respect.

B.2.3 Multi-scale/downscaling dust forecasting

The modelling structure proposed for West Asia consists of a three-level nesting scheme shown in Figure 84. In order to develop a nested global-regional-mesoscale system, it is recommended that a portal for collection/provision of global and wide regional modelling outputs be developed by the future SDS-WAS Regional Centre for West Asia.

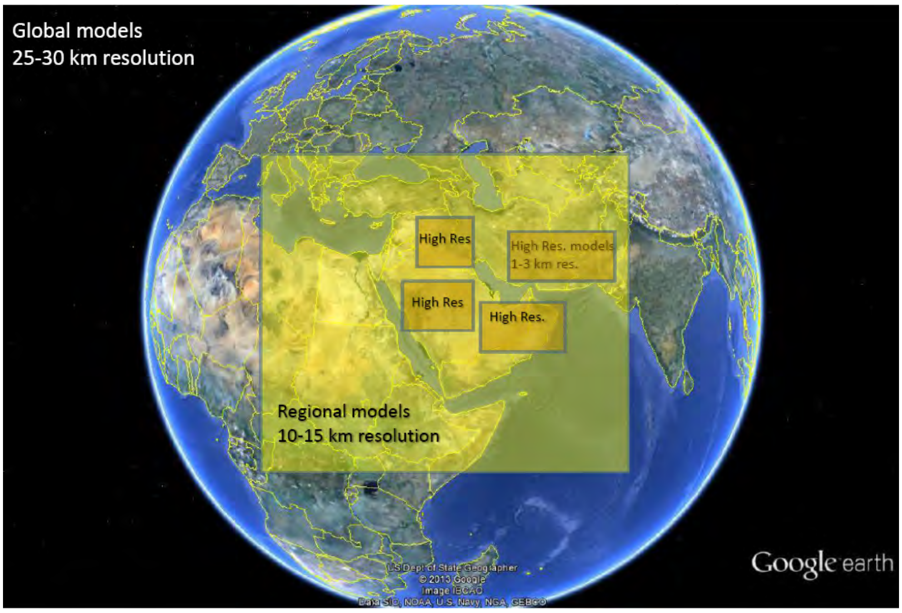

Figure 84 - Conceptual scheme of the three levels of dust-model nesting for the SDS-WAS West Asia Regional Node

B.2.3.1 Global models

Daily global model data could be provided by organizations/initiatives such as, for example, the International Cooperative on Aerosol Prediction (ICAP). Several institutions are participating in the intercomparisons with their own models: ECMWF (Europe), Japan Meteorological Agency, NASA (USA), US Naval Research Laboratory and the US National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP). Either an ICAP median of such model outputs or data from a particular global model group should be secured by the future SDS-WAS Regional Centre for West Asia through a special agreement with data providers. Nowadays, global models have a spatial resolution of ~50 km, which will soon be increased to ~25–30 km.

The SDS-WAS NAMEE Regional Centre also provides graphical and numerical outputs from the ECMWF Monitoring Atmospheric Composition and Climate (MACC) model, the UK Met Office Unified Model (MetUM), GEO-5 (NASA) and the National Geospatial Advisory Committee (NGAC) of the USA (see Table 7) through: http://sds-was.aemet.es/forecast-products/dust-forecasts.

B.2.3.2 Regional models

In the next nesting step, *global model* data should be used for the initial and boundary conditions in a large, regional dust-model area to feed regional models. Ideally, these models, ideally, should have ~10–15 km resolution. Over the last 20 years, a modelling community, specifically focused on dust models, has developed dust-source specification, dust-emission parameterization, radiation-dust and dust-cloud interaction parameterizations, etc., building up a robust dust-forecasting system. Fortunately, many of these regional models running over the West Asia geographical domain are currently available through the SDS-WAS NAMEE Regional Centre. In particular, it offers dust-forecasts outputs that are generated by different regional numerical models, both graphically and numerically, at: http://sds-was.aemet.es/forecast-products/dust-forecasts.

The availability of these products is the result of collaboration among a number of NMSs and research centres.

The global and regional dust models currently providing numerical outputs for the NAMEE region through the SDS-WAS Regional Centre are the following:

Table 7 - List of dust-forecasting models available through the SDS WAS NAMEE Regional Centre at http://sds-was.aemet.es/forecast-products/dust-forecasts

Model	Institution	Type	Output	PI or contact
GEOS-5 *Colarco et al. (2010)*	NASA	Global	Numerical and graphical	Da Silva Colarco
MACC-ECMWF *Morcrette et al. (2009)* *Benedetti et al. (2009)*	ECMWF	Global	Numerical and graphical	Morcrette/Benedetti
MetUM *Woodward (20011)*	UK Met Office	Global	Graphical	Walters
NGAC *Lu et al. (2010)*	NCEP	Global	Numerical and graphical	Lu
BSC-DREAM8b V2.0 *Pérez et al. (2006)* *Basart et al. (2012)*	BSC-CNS	Regional	Numerical and graphical	Baldasano
DREAM-NMME-MACC *Nickovic et al. (2001)* *Xie et al. (2008)*	SEEVCCC	Regional	Numerical and graphical (1 day delay)	Pejanovic
NMMB/BSC-Dust *Pérez et al. (2011)* *Haustein et al. (2012)*	BSC-CNS	Regional	Numerical and graphical	Baldasano
Median multimodel Ensemble	SDS WAS RC	Regional	Numerical and graphical	Terradellas

Contact persons:

GEOS-5 (NASA): Peter R. Colarco (peter.r.colarco@nasa.gov) and Arlindo Da Silva (arlindo.dasilva@nasa.gov)

MACC (ECMWF): Angela Benedetti (Angela.Benedetti@ecmwf.int) and Jean-Jacques Morcrette (morcrette@ecmwf.int)

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NGAC (NCEP): Sarah Lu (sarah.lu@noaa.gov)

BSC-DREAM8b V2.0: Jose María Baldasano (Jose.baldasano@bsc.es)

DREAM-NMM-MACC: Goran Pejanovic (goran.pejanovic@hidmet.gov.rs)

NMMB/BSC-Dust: Jose María Baldasano (Jose.baldasano@bsc.es)

Median multimodel ensemble (SDS-WAS NAMEE Regional Centre: Enric Terradellas (eterradellasj@aemet.es)

The availability of this set of specialized dust-prediction models constitutes an unprecedented breakthrough for the international community and particularly for the countries of West Asia, which will have six digital models outputs and an ensemble available to add to the current dust-forecasting capabilities of each country. Dust storms caused by shamal, passage of fronts and large convective processes are well predicted by these models. They should expand their geographic domain eastward, however, in order to properly include dust sources and pathways over Afghanistan and Pakistan, which, as seen in Section A.2.6 (Climatology in West Asia) are important.

On the regional scale, as in the case of global modelling, either a median or a separate model product could be used. A good candidate for median regional forecasts are the already existing daily data from the SDS-WAS NAMEE Regional Node but the current domain should also either be centred on the West Asia region or extended to the east. An alternative to the median region forecast is that one or more well-established dust-modelling groups provide(s) regional forecasts through a special agreement.

B.2.3.3 Mesoscale/local (high-resolution) models

Dust storms associated with small-scale convective processes in space and time, such as haboobs and cold cold-air downburst storms (see Section A.2.2), cannot be captured by either global or regional models, given the small size of these meteorological processes, and because most of these models have not implemented adequate parameterizations of Mesoscale, convective, cloud-resolving processes, low-level jets, etc. Hence, a third nesting level consists of mesoscale/local dust models fed by data from (a) regional-scale model(s). Such mesoscale modelling systems, which include non-hydrostatic atmospheric processes, should be downscaled to resolutions of ~1–3 km in order to resolve both atmospheric driving conditions and dust-soil sources. Such models will complement global and regional models. The spatial resolution of mesoscale/local dust models will depend largely on the region to be covered and available computational resources.

There are a couple of regional models currently running for the West Asia region, but in a window centred over North Africa, that can easily be upgraded for West Asia as high-resolution models on an ad hoc basis:

- NMM-DREAM8: the original DREAM with an eight particle-size bin model incorporated into the WRF system. It runs at the Serbian NMS (http://www.seevccc.rs/?p=8) with MODIS AOD data assimilation from MACC (DREAM8-NMME-MACC). This model achieved one of the best monthly skill performances for the 2012 dust season in comparison with other SDS-WAS models.
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  Goran Pejanovic (goran.pejanovic@hidmet.gov.rs)

- NMMB/BSC-Dust: developed at the BSC (http://www.bsc.es/earth-sciences/mineral-dust/nmmbbsc-dust-forecast). It uses advanced dust-parameterization physics for dust emission, convective vertical transport and wet in- and below-cloud deposition. This model can be run in global or regional mode.
  Contact person:
  Jose M. Baldasano (jose.baldasano@bsc.es)

Two global aerosol models with graphical dust outputs (normally AOD and surface dust concentration) are currently available for West Asia countries:

- NAAPS: http://www.nrlmry.navy.mil/aerosol/#currentaerosolmodeling

- MACC: http://www.gmes-atmosphere.eu/d/services/gac/nrt/nrt_opticaldepth

  MACC includes an on-line verification plots against AERONET observations at:
  http://www.gmes-atmosphere.eu/d/services/gac/verif/aer/nrt/

In many cases, mesoscale dust storms, which occur frequently in West Asia, can be simulated only with high-resolution, non-hydrostatic models with data assimilation. Data assimilation is a method used in NWP to incorporate observations into the model state in order to determine the initial state of the atmosphere. Dust-related data assimilation was emphasized in the early days of dust modelling as an essential condition for improving accuracy of dust forecasts by *Nickovic (1996).*

Nickovic et al. (2012(b)) presented results of the operational dust forecast based on the eight-bin DREAM8-NMME, driven by the NCEP/NMME non-hydrostatic model, with an assimilation module included, as provided by SEEVCCC at the NMS of Serbia. The operational DREAM8-NMME was run over North Africa and West Asia (Figure 85) during the 2012 dust season. In a sensitivity experiment, the model was run with and without data assimilation. Figure 85 shows a significant increase in model accuracy when data assimilation was included. Specification of sources is another critical element for successful dust modelling.

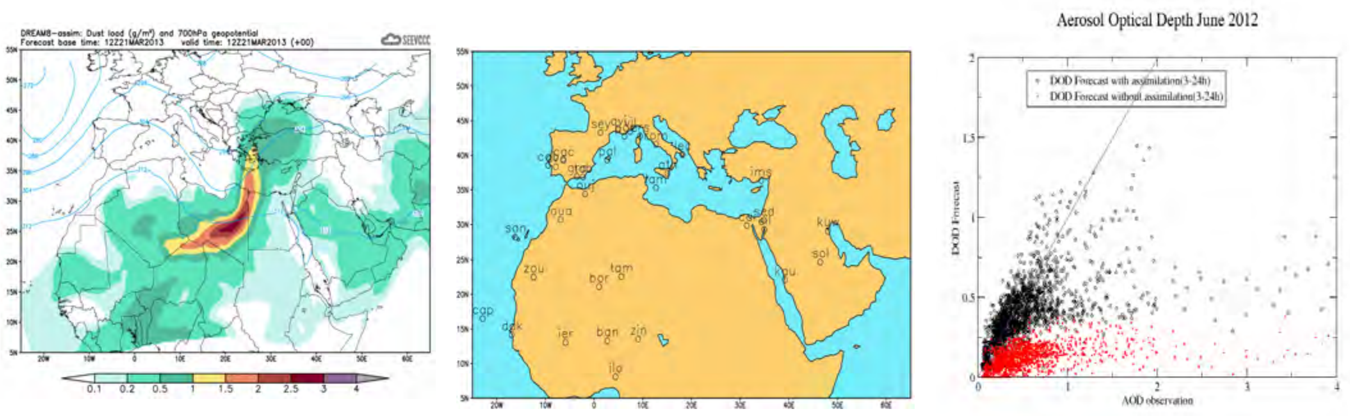

Figure 85 - Domain of operational DREAM8-NMME dust forecasts with MODIS AOD assimilation included (left); AERONET AOD observation sites (centre); AOD scatter diagram with (black points) and without (red points) assimilation, when compared with the AERONET AOD in the region (right) (after *Nickovic et al., 2012(b))*

Finally, it has recently been demonstrated that, in order to predict accurately the dynamics of a small-scale haboob caused by a convective downburst (July 2011 haboob in Phoenix, Arizona, USA), it was necessary to include most current high-resolution satellite data (MODIS MOD13A2 land cover and MODIS NDVI) (*Vukovic et al., 2013*). A similar approach should be considered for West Asia.

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Data assimilation is currently performed by the MACC-ECMWF global model using MODIS AOD data and, since 30 April 2013, the UK Met Office global NWP model. This model includes standard MODIS AOD over land, where the aerosol types mark the aerosol as dust and DB observations over bright desert surfaces.

In the 1990s, DSD was considered to be homogeneous as it was based on information about land-cover characteristics and soil texture that was available at the time. In the 2000s, the importance of so-called smaller-scale dust-source hotspots was recognized, followed by the use of more accurate information on major dust sources related to topographic depressions containing sediments in paleo-lakes and river beds (e.g. *Ginoux et al., 2001*). More recently *Ginoux et al. (2012),* made mapped sources based on satellite observations, distinguishing between natural, anthropogenic and hydrological dust sources. See Section A.2.1 (Dust sources).

Specific recommendations on dust forecasting for West Asia:

1. Establish a virtual centre with both graphical and numerical prediction products from outputs of global models, the information being provided by the SDS-WAS NAMEE Regional Centre, hosted by Spain, and dust-model outputs available from each member. This centre would avoid redundancy in every country. An accessible website should be set up, which could be replicated in countries with available computational resources.

2. Create a working group comprising weather forecasters of all countries and supported by researchers in each country who wish to participate in this exercise, to evaluate the quality of each model by comparison with dust storm events (mostly from satellite information). It may be assumed that the ideal model does not exist. In any case, it will be necessary to know which models best predict dust storms in the area of responsibility of each country. It should not be forgotten that the ultimate responsibility for national prediction lies with the NMS. In any case, the validation expert group may also use objective model validation tools proposed in Section B.2.4.

3. Provide model-comparison exercises during selected dust episodes in the region to answer questions arising from Point 2 above.

4. Provide continuous model validation (against ground-based or satellite-borne observations) for high-resolution models with data assimilation and comparisons with other models.

5. Reach agreements with the institutions currently running dust-forecast models, available through the SDS-WAS NAMEE Regional Centre, so that the geographical domains of the models are extended to the eastern West Asia region.

6. Develop and implement high-resolution models in order to predict dust storms associated with mesoscale convective systems by bilateral cooperation agreements or contracts with groups specialized in high-resolution dust modelling.

7. In close collaboration with UNEP and national environmental agencies, promote multidisciplinary studies leading to high-resolution maps of dust sources and their characteristics, in order to improve dust modelling with more accurate inputs and to organize collection of PM-type observations using UNEP communication links with national environmental authorities. Local/national data on land use, soil texture and land cover are ingredients in the model-emission parameterization. Land/soil information should be at the highest possible resolution, preferably finer than 1 km. As it appears that rapid soil degradation is taking place in some areas, it is necessary to update the list of dust sources there.

B.2.4 Dust-forecast validation

Dust-model verification is an important activity targeting knowledge of model performance and quantifying model reliability. SDS-WAS Regional Centre NAMEE has made great strides in model validation, which might be replicated for West Asia.

Validation activities are organized at different temporal frameworks:

1. *Near-real-time model evaluation.* Rather than a detailed validation of dust forecast, the model evaluation is an assessment of how the forecast behaves relative to a few key observations that are available in NRT (Figure 86). This allows modelling groups and end-users to have a quick overview of the quality of the forecast (see http://sds-was.aemet.es/forecast-products/forecast-evaluation). By clicking on a specific station, the comparison for the site can be seen (Figure 87). Model data are linearly interpolated to the sites' geographical coordinates.

2. *Near-real-time model comparison.* Products from different numerical prediction models are represented at a common geographical domain, which is intended to cover the main dust-source areas, as well as the main transport routes and deposition zones in the region (Figure 88). Products with lead-time up to 72 hours are represented using common colours. See http://sds-was.aemet.es/forecast-products/dust-forecasts/compared-dust-forecasts.

Figure 86 - Map of AERONET AOD stations used for validation of dust-model forecasts. NRT validation for selected dust-prone stations is shown at http://sds-was.aemet.es/forecast-products/forecast-evaluation

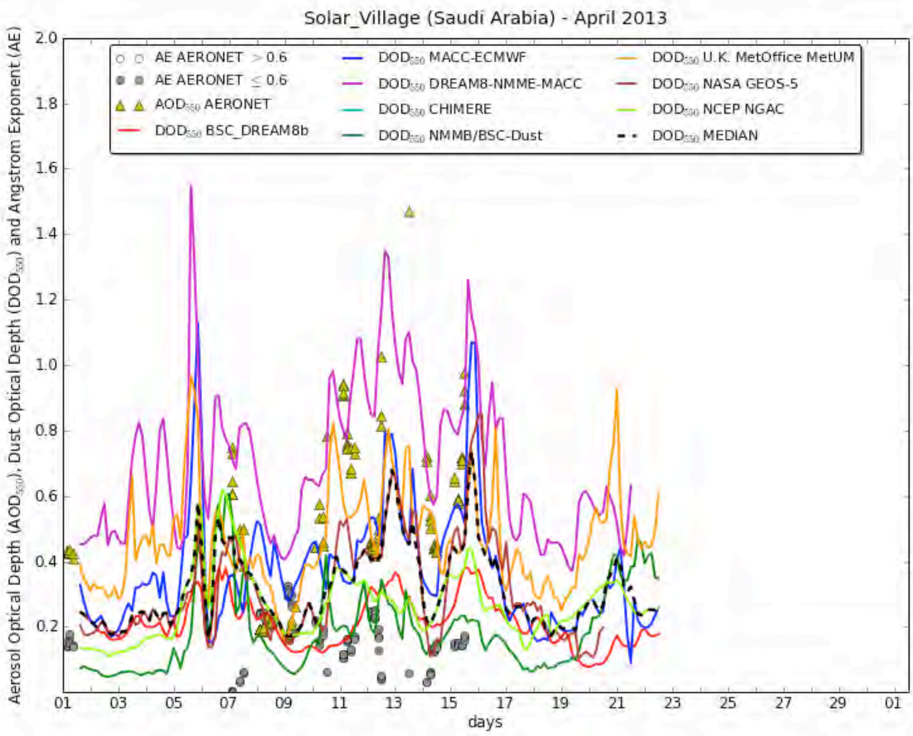

Figure 87 - Comparison of AOD forecast by SDS models against AOD observed at Solar Village AERONET station (Saudi Arabia) as yellow triangles from the beginning of April 2013, plus AOD prediction from models

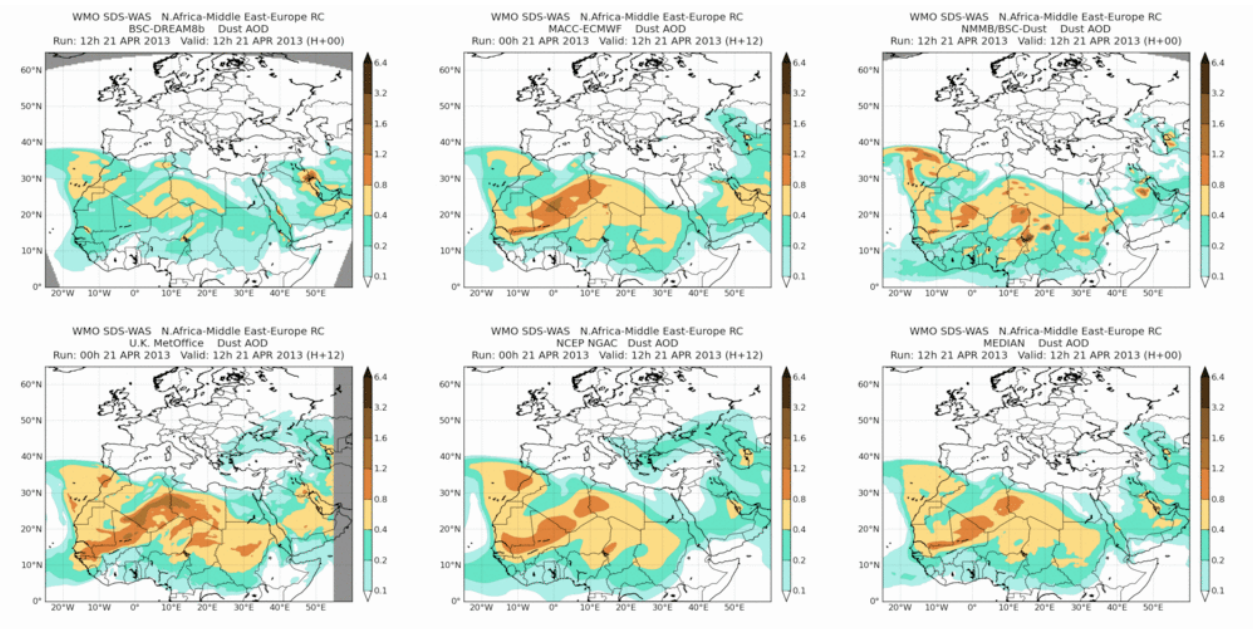

Figure 88 - DOD from six dust models for 21 April 21 at 12:00 UTC (http://sds-was.aemet.es/forecast-products/dust-forecasts/compared-dust-forecasts)

3. *Model-evaluation metrics, monthly scores.* The forecasts of DOD are compared with the total AOD provided by AERONET for 42 selected dust-prone stations located around the Mediterranean basin, Iberian Peninsula, North Africa and Middle East. The common metrics that are used to quantify the mean departure between modelled and observed quantities

are the mean bias error, the root-mean-square error, the correlation coefficient and the fractional gross error (see http://sds-was.aemet.es/forecast-products/forecast-evaluation/model-evaluation-metrics).

4. *Model-evaluation metrics, seasonal scores.* The same as for Point 3 but for winter, spring, summer and autumn of each year (see http://sds-was.aemet.es/forecast-products/forecast-evaluation/model-evaluation-metrics-seasonal).

5. *Model-evaluation metrics, annual scores.* The same as Point 3 but for annual data of each year (see http://sds-was.aemet.es/forecast-products/forecast-evaluation/model-evaluation-metrics-annual).

The contact person for evaluation/validation activities is: Enric Terradellas (SDS-WAS NAMEE Regional Centre) (eterradellasj@aemet.es)

Specific recommendations:

- Replicate for West Asia the evaluation/validation system developed at the SDS-WAS NAMEE Regional Centre incorporating the dust models currently run in West Asia countries (e.g. the COSMO_ART aerosol model run at the National Centre of Meteorology and Seismology of the UAE).
- Evaluate models for a few selected dust storm cases caused by both small-scale meteorological processes (such as convective-based haboobs, low-level jet dust storms) and large-scale processes (shamal, meteorological fronts).

It is to be noted that the most important and almost unique aerosol/dust observations, not only for the SDS WAS, but also for other global aerosol validation systems, are those obtained from AERONET, hence the enormous importance of significantly strengthening the AERONET observation network in the region, as proposed in Section B.2.1.3.

Future recommendations for model validation should be aimed at in situ measurements of PM10, visibility or vertical profiles with lidar techniques, but such validations are still under development by research groups.

B.2.5 Model reanalysis

A dust-model reanalysis is a dust dataset spanning an extended period, using a single consistent analysis scheme throughout. Long-term data series from model reanalysis permit dust climatological studies to be carried out, such as such those recommended below:

- Monthly/seasonal dust spatial distribution
- Identification of dust sources and pathways
- Dust/aerosol long-term trends
- Seasonal and interannual dust variability
- Changes in dust driven by meteorological pattern changes
- Changes in dust sources if weather patterns stay stable

Some of these studies are essential to understanding basic aspects of the spatio-temporal distribution of dust storms, as shown in Section A.2.6. (Dust climatology). An example of model reanalysis is shown in Figure 89.

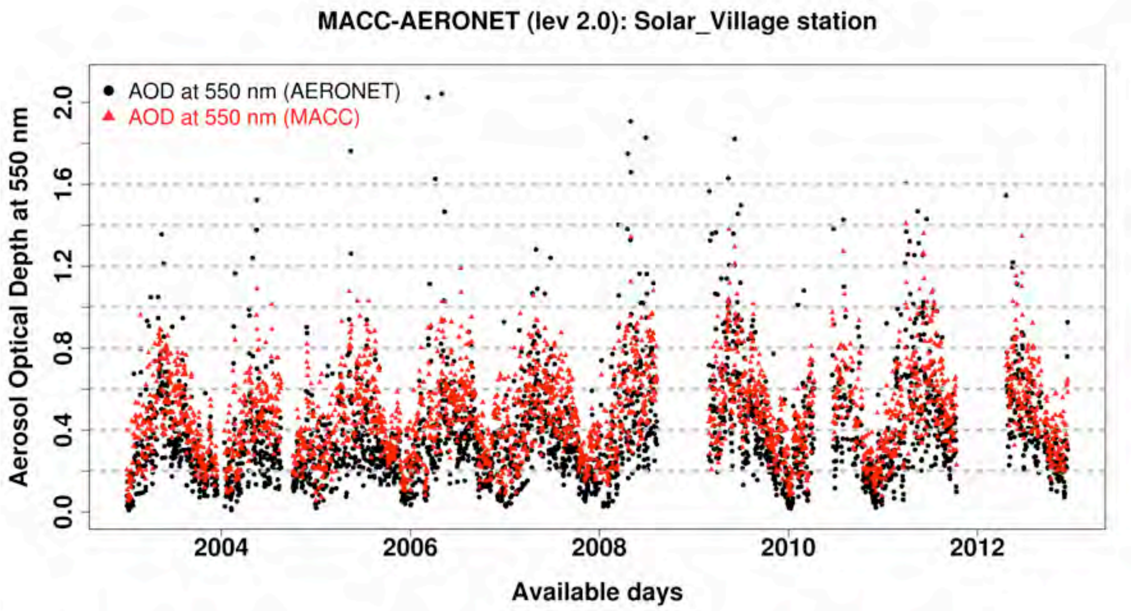

Figure 89 - Daily mean AOD from AERONET (black dots) and MACC reanalysis (red dots) for Solar Village (Saudi Arabia) (after *Cuevas et al. 2013(b)*)

The seasonal and interannual AOD variations from MACC reanalysis is excellent (Figure 89), with a good fit to AERONET. At first glance, it seems that both systems show a similar positive AOD.

There are several reanalyses available for West Asia:

- MACC-ECMWF (since 2003). MACC reanalysis is available from the ECMWF Meteorological Archival and Retrieval System (MARS) (http://www.ecmwf.int/services/archive/). MARS data are available free of charge to registered users in Member and Cooperating States. There is no public access to MARS. Contact person: Angela Benedetti (Angela.Benedetti@ecmwf.int)
- BSC-DREAM8b From (from 1 January 2000 to 31 December 2012). More information and data download at: http://www.bsc.es/earth-sciences/mineral-dust/catalogo-datos-dust Contact person: José María Baldasano (Jose.baldasano@bsc.es)
- BSC-DREAM (1958-–2006). Contact person: José María Baldasano (Jose.baldasano@bsc.es)
- NMMB/BSC-Dust (1985-–2006). Contact person: José María Baldasano (Jose.baldasano@bsc.es)
- NMMB/BSC-Dust (1979-–2010). Contact person: José María Baldasano (Jose.baldasano@bsc.es)
- GOCART reanalysis is publicly available for the period 1 January 2000 to 1 December 2007 through the NASA Giovanni application (http://gdata1.sci.gsfc.nasa.gov).

Other dust-model reanalysis results from the combination of a historical isentropic back-trajectory dataset with in situ observations, soil-condition maps, mineralogical maps, etc., might be of great interest, especially for dust-source studies. These reanalyses permit specific interesting analyses such as the following:

- Dust-source identification for key sites (large cities, industrial facilities, strategic sites, etc.), using air-mass historical back-trajectory datasets (e.g. HYSPLIT or Flextra).

- Dust-source identification for key sites, crossing air-mass historical back-trajectory datasets with in situ PM partitioning (if any), in situ AOD or mineralogical maps of the region. An interesting paper focused on Saharan dust mixed with industrial pollution transport from in situ PM10 chemical analysis at the Izaña Atmospheric Observatory and back-trajectories is *Rodríguez et al. (2011).*

B.2.6 Regional collaboration mechanisms

SDS monitoring and forecasting represent a technical and conceptual challenge for the NMSs of those countries affected by SDS, since they are officially mandated to report weather phenomena at the national level. SDS monitoring and forecasting activities have some added difficulties and complexities, however, that justify the strategy and collaboration mechanisms proposed below:

- Conventional meteorological observation systems do not allow the observation of atmospheric dust. Apart from visibility provided by meteorological observatories, ground-based systems for dust observations consist of new techniques such as sunphotometry and lidar, which are still under development, and on techniques normally confined to the field of air quality (PM10 and PM2.5 measurements and filter chemical analysis). Meteorological satellites do not provide quantitative information on dust. This is provided by sophisticated orbiting spectroradiometers, whose products are the result of complex algorithms, validations with ground-based, remote-sensing instruments, etc.

- The development of dust models is about 30 years behind that of NWP. Paradoxically, these do not include dust and aerosols as variables in the equations. Already in 1922, however, Lewis Fry Richardson developed the first NWP system, based on simplified versions of Bjerknes's "primitive equations" of motion and state, and included an eighth variable for atmospheric dust (*Edwards, 2000*). Although dust models can function operationally, they are not really operational models in the sense that this term has for meteorological services. Dust models still require developments and validations, so we need to work with them at operational and research levels simultaneously.

- Dust storms, unlike common weather storms, movement of fronts and clouds, are always generated in specific areas where natural processes or human activities have produced land degradation. Dust monitoring near sources must be set up in order to incorporate that information into models. For example, Kuwait is one of the countries that suffer the greatest impact of dust storms in West Asia, which are primarily caused by dust sources in Iraq. It would be inefficient to establish a dust-monitoring and prediction system for Kuwait, without including Iraq.

On another level, sophisticated, ground-based techniques (lidar, sunphotometers, etc.) are not simple "plug and play" pieces of equipment. The exploitation and analysis of huge amounts of satellite data often require data-processing skills in data processing and the implementation of dust models, as well as new parameterizations and settings, must be undertaken by modelling and computation experts. All this requires the participation of experts and researchers from universities and research centres.

On the other hand, SDS systems should have a major operational component: observation networks must be operated and maintained in the long term and must be communicated in real-time; numerical models need to run 365 days a year and 24 hours a day. NMSs have extensive experience, facilities, infrastructure and technical resources to achieve operational commitments. NMSs also have a long tradition of international relations through UN agencies and cooperation with other NMSs. Furthermore, NMSs have experience in dealing with national users who must exploit the SDS end products.

For all the above reasons, close cooperation between among NMSs, air-quality agencies, universities and research centres, both at national and regional level, is essential to implement an SDS-AWS Regional Node for West Asia. This, at least, has been the experience gained with SDS-AWS NAMEE Regional Node.

The WMO SDS-WAS Science and Implementation Plan (*WMO, 2012*) offers an operational structure for dealing with a diverse community anchored by well-established WMO systems of research, observations, numerical weather and climate prediction and service delivery. The community of practice for SDS observations, forecasts and analyses is diverse, requiring the development of interfaces with users through careful assessments. The WMO SDS-WAS Science and Implementation Plan proposes an architecture and information exchange that will secure efficient and balanced cooperation and participation of the major components of the SDS-WAS system: research, prediction, observations and service delivery. It is an activity that cuts across WMO programmes, as well as involving a substantive partnership outside the NMSs, particularly in research. In the framework of this conception, SDS-WAS is an international network of research, national operational centres and users, organized through regional nodes and assisted by an SDS-WAS regional centre (Figure 90). It is coordinated by the SDS-WAS Steering Committee, supported by the WMO Secretariat and reports to the Commission for Atmospheric Sciences through the World Weather Research Programme (WWRP) and GAW.

At the regional level, an SDS-WAS is structured as a federation of partners. The regional nodes, as an aggregate structure, comprise the SDS-WAS federation. What the term federation implies is an organized structure following minimum global standards and rules of practice. A federated approach allows flexibility, growth and evolution, while preserving the autonomy of individual institutions. It allows a variety of participants (such as regional centres, serving as hosts; university research centres, serving as partners; WMO-designated operational forecasting centres; meteorological operational services; health organizations, etc.) to cooperate and benefit without changes to their own internal structures and existing arrangements. The structure is scalable and allows for adaptability to changing research and operational environments.

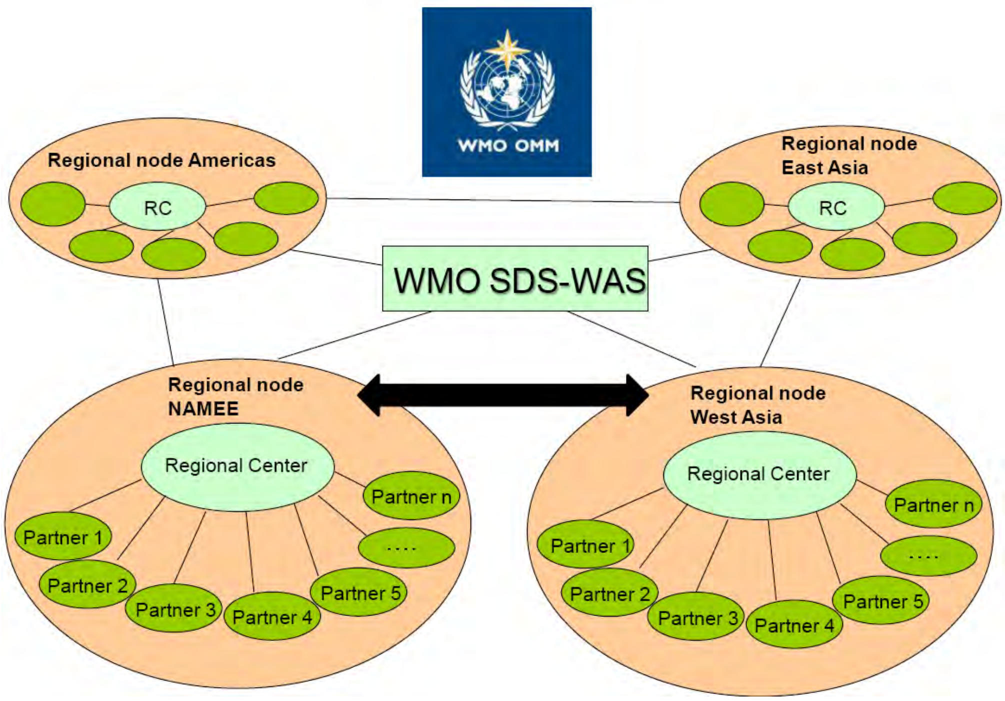

Figure 90 - The international SDS-WAS network comprised of federated nodes assisted by regional centres (*WMO, 2012*)

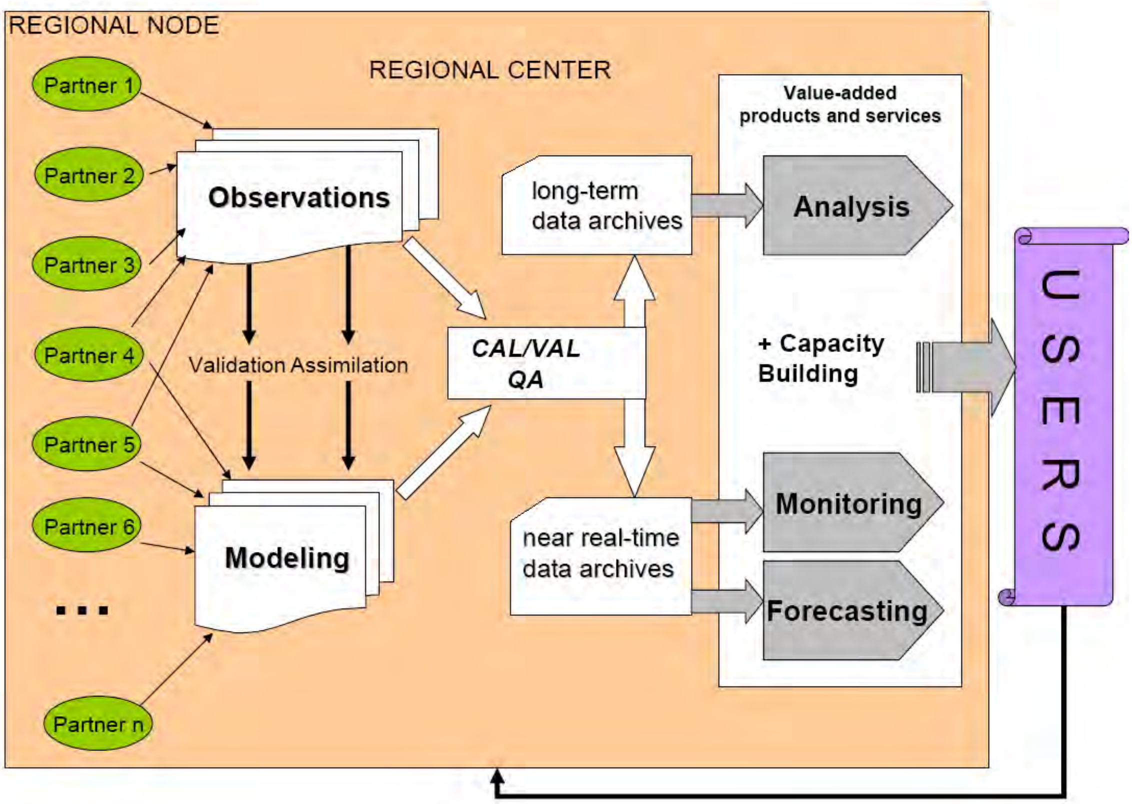

Figure 91 - Flow of information between SDS-WAS system components for a regional node, consisting of a consortium of partners supported by the regional steering group and regional centre (*WMO, 2012*)

Figure 90 highlights the necessary cooperation between the present SDS-WAS Regional Node for Northern Africa, Middle East and Europe with the future SDS-AWS Regional Node for West Asia during the transition period until the creation of the last node.

The flow of information between various SDS-WAS regional components and the role of an SDS-WAS regional centre is shown in Figure 91. The node is also organized according to federal principles.

According to the SDS-WAS Implementation Plan 2011–2015 (April 2012), global and regional SDS-WAS activities are harmonized by a SDS-WAS (global) steering committee and regional steering groups (RSGs), assisted by the WMO Secretariat. Each node has to implement the following tasks agreed upon by the corresponding RSG:

- Provide a web-based portal agreed between regional partners for user access to regional research and forecast activities and services.
- Support efficient observation data-sharing, providing neutral ground for SDS-WAS data exchange.
- Assist partners in implementing agreed research and forecast activities at the regional level.
- Cooperate with existing operational service delivery mechanisms, recognizing that warnings related to SDS-WAS are generally the responsibility of the NMSs and that SDS-WAS products provide input to NMSs.
- Report on implementation progress to the WWRP Joint Scientific Committee and to the SDS-WAS Steering Committee.
- Cooperate with existing operational service delivery mechanisms, recognizing that warnings related to SDS-WAS are generally the responsibility of the NMSs, so that SDS-WAS products represent input to NMSs.

- Support research among partners of a regional node and help implement operational SDS-WAS forecasts at the NMSs.
- Guide RSG on implementing agreed research and forecast activities at the regional level.
- Organize training workshops on the use of SDS-WAS products
- Convene symposia, conferences, workshops and other meetings, as necessary, to advance SDS research activities.
- Assist, when necessary, in resource mobilization through trust-fund contributions.

Through SDS-WAS Regional Node activities, partners can contribute, according to their capabilities. Considering that the most important areas of collaboration are observation, modelling and prediction, capacity-building and user support, and that these areas can be subdivided, in turn, into other more specific topics, partners may propose taking the responsibility of leading the coordination of a topic and implement a dedicated website with all the information agreed on that topic. Each topical website would be part of the SDS-WAS web portal of the regional node. This, in turn, could be mirrored in servers of countries with adequate computational resources. A web portal will be established at the regional node as a result of node activities and partners' coordination. Thus, it will not depend on a single institution and, if any member fails, another partner could assume its corresponding function. In this way, a robust, participatory, regional system that is transparent to all partners can be established. Any member of the region may join the regional node at any time.

To achieve this configuration, it is necessary to create several WGs addressing different subjects, which should be integrated by corresponding specialists and experts of the region. The WGs will identify activities and specific partners of the regional node should assume responsibilities and obligations. These WGs should emerge from a first meeting of the SDS-WAS RSG.

B.2.7 Data-exchange policy

According to the conception of a virtual or distributed regional node, NRT observations and model outputs should be shared freely through the virtual central facilities of partners.

Databases of observations and model outputs stored in the virtual centre facilities maintained by different partners should be freely accessible by other partners. Password-accessed FTP connections should permit partners to download data automatically in standardized formats.

A WG on data format and data access should be created. An alternative approach would be to incorporate data standardization and data exchange as primary activities in each of the WGs dealing with databases.

B.2.8 SDS products and services

A detailed description of the impacts of SDS has been given in Section A.3 and numerous SDS products could be identified as being useful to many socio-economic sectors in West Asia.

One of the most important products that NMSs could provide to the general public and specific users and professionals in different sectors is accurate SDS early warnings, anticipating their impacts and reducing costs. Environment, health, transport and civil defence authorities need to be notified of observed or predicted SDS events in a timely fashion.

A challenging, and probably profitable, orientation of SDS products would be the support to emerging activities for which the SDS can be critical: solar power plants (production efficiency and maintenance), electronics, airport operations and aviation maintenance, high-speed rail operations, farm and livestock management and future regulations on air quality.

End-products should be agreed upon with potential users on the one hand and SDS products must be "translated" in readily understandable language for the end-user on the other. Thus, a WG on user-oriented SDS products and services should also be also created within the SDS-WAS West Asia Regional Centre.

An important aspect concerns the building-up of a basic body of data and knowledge on SDS observations. The limited data available on SDS and their impacts means that policymakers do not respond. To mobilize resources, stakeholders need unquestionable evidence and proven results published in scientific and technical reports. In the case of air quality, for example, when scientific papers demonstrate the direct impact of pollution on health and the media broadcast this information, there is a demand from society for control measures to be taken, inciting decision-makers to act.

Concerning the regional node web portal, some basic information should be provided:

- Maps with NRT observations of visibility, AOD (sunphotometers), in situ PM10 and aerosol vertical profiles when available
- Latest satellite dust products for the region
- Homogenized graphical outputs of regional dust models for visual intercomparisons
- NRT model validations.

B.2.9 Training and capacity-building

Capacity-building in SDS-WAS involves technology transfer with self-sustaining capability and long-term partnership in mind (*WMO, 2012*). It is coordinated by various mechanisms, including those well established in WMO through the Development and Regional Activities Department. Elements include consultation meetings with national users to develop effective and realistic products and tools for their needs, training courses on the use of services that are available, research workshops and the provision of guidance and outreach material.
Depending on available resources, capacity-building and training activities should include:

- Regular scientific exchange through scientific workshops or seminars, which will provide a forum for discussion of recent SDS developments, such as observations, modelling and forecasting, and users.

- Specialized capacity-building includes training in specific technical issues, such as satellite-data access and analysis, dust storm forecast and simulation model output analysis, targeting user needs through new information products, measuring and monitoring particulate air quality through remote-sensing (sunphotometers or lidar) and in situ air-sampling instruments, etc.

- Medium-term (several months) stays at specialized centres to learn specific techniques or methodologies.

The most practical and effective observation training courses are those that combine theory and practice, taking advantage of any instruments installed.

In relation to the implementation of dust models, it is essential that specialists are trained for a time in centres that run dust models and are tutored externally during the implementation of the model and in subsequent phases of early operation and model validation.

For example, the experience gained by the CoE at Muscat (Oman) in training scientists from Middle East countries in the use of satellite data, should benefit the Regional Node.

B.3 SUMMARY AND CONCLUDING REMARKS

This report, *Establishing a WMO SDS-WAS Regional Node for West Asia: Current Capabilities and Needs*, has been elaborated under the overall supervision of the WMO Atmospheric Research and Environment Branch, with the support of the UNEP Regional Office for West Asia.

Its aim is to assess the observation and prediction capabilities of sand- and dust storms in West Asia and provide guidance in establishing a WMO Sand- and Dust Storm (SDS) Warning Advisory and Assessment System (WAS) Regional Node for West Asia, by presenting the essential actions and activities to be implemented.

The specific objectives of this report are to:

- Review published information on dust storm incidence in West Asia, including the Islamic Republic of Iran and Turkey.
- Compile existing information on dust sources, frequency/intensity of dust storms and socio-economic and environmental impacts of dust.
- Recommend a strategy for dust-model validation.
- Establish regional and national institutional mapping.
- Propose regional institutional collaboration mechanisms for the monitoring, prediction and delivery of dust-related products and services.
- Propose types and density of measurements in the region, based on existing observation capacity.
- Propose a multiscale/downscaling dust-forecasting strategy for the region, based on identified existing numerical modelling facilities.
- Propose a regional data-exchange policy.
- Advise on regional training and capacity-building programmes.

The WMO SDS-WAS mission is to enhance the ability of countries to deliver timely and high-quality SDS forecasts, observations, information and knowledge to users through an international partnership of the research and operational communities. It is proposed that the WMO SDS-WAS Regional Node for West Asia be established in collaboration with the UNEP Regional Programme to Combat Sand and Dust Storms. Through collaborative partnership with UNEP, the WMO SDS-WAS Regional Node for West Asia will provide SDS phenomena assessment and secure an SDS monitoring and early warning system for the region.

B.3.1 Dust climatology and trend analysis in West Asia

Sandstorms and dust storms are two completely different phenomena that require different treatments and approaches. While sandstorms are very local and confined to the first few metres above ground, dust storms occur at an altitude of a few kilometres (1–6 km) with horizontal extensions of thousands of kilometres. Dust storms cannot be stopped by natural or artificial physical barriers. Action is required at their source – degraded lands, which are often hundreds or thousands of kilometres from the points of impact. Basically, WMO SDS-WAS refers to dust storm assessment, monitoring and forecasting.

SDS are a major problem in West Asia but their main characteristics (intensity, extent and frequency) are not well known or, at least, have not yet been addressed in a scientific and systematic way. The absence of a basic climatology of dust sources and pathways in a regional context has hindered the compilation of a regional SDS picture.

Given the absence of a regional climatology of dust storms – and although not initially foreseen in this report – a basic climatology of dust storms from AERONET (http://aeronet.gsfc.nasa.gov) data, satellite information and reanalysis outputs of global and regional dust models has been performed. Different climatologies obtained from dust-model simulations and satellite observations show some differences but common patterns can be distinguished in all of them.

West Asia is part of the well-known “dust belt” stretching from the western Sahara (with long dust intrusions to the west over the Atlantic Ocean) to central and eastern Asia (with long dust intrusions to the east over the Pacific Ocean). The climatology shows the existence, from March to September, of active dust sources and pathways. It is worth noting the pronounced dust corridor from eastern Syrian Arab Republic to Oman, with significant dusty areas over Iraq impacting the Gulf under a northern airflow. A second prominent dust source is observed over the Empty Quarter and central Saudi Arabia. South-western Islamic Republic of Iran and areas on the Iranian Gulf coast are also active dust sources. Dust sources in the Iranian-Afghan-Pakistan border region contribute to high dust levels observed over the northern Arabian Sea. In summer, the Tokar Gap in north-eastern Sudan, near the Red Sea, impacts the Arabian Peninsula and the Arabian Sea. Under different synoptic and mesoscale weather conditions, most of the region – apart from Turkey – is a potential dust source.

Of particular interest is the presence in the air in many areas – mainly in Gulf countries – of a mixture of mineral dust from desert and industrial aerosols. Unfortunately, the ground-based observation networks are not sufficiently comprehensive nor the network topologies the most suitable to perform a detailed spatial-temporal analysis of this characteristic aerosol distribution.

Concerning trend analysis, West Asia – especially the Arabian Peninsula and Mesopotamia – is the only region in the world where a positive trend of AOD is found. AOD, a parameter that indicates the total content of aerosol in the atmospheric column, is basically constituted by dust in this region. The positive trend found over Iraq might be linked to the increase in the number of dust sources in the last decade identified in eastern Syrian Arab Republic and Iraq. On the other hand, a negative trend of EVI has been found for the period 2002–2013 across Mesopotamia. EVI is a measurement of the “greenness” of the Earth’s land surface, with increasing greenness indicating increased ground covered by growing vegetation. The positive trend in AOD values over this region might therefore be a result of land degradation, probably due to reduced water availability and changes in land use.

On the other hand, global warming has the potential to cause major changes in dust emissions. IPCC (2007) suggests that, under most scenarios, many dryland areas will suffer from lower rainfall regimes and drier terrains because of higher rates of evapotranspiration. Lower rainfall will favour the formation of shallow or extremely shallow soils that are often characterized by a high content of airborne particles and small fractions of rock-erosion elements. Under this scenario, dust storm activity could increase, though this conclusion depends on how winds may change – a matter of great uncertainty.

According to the averaged projection of 21 climate models for West Asia, the percentage changes in average annual temperature by 2100 from the 1960–1990 climate baseline, are up to 4°C over most of the region. The agreement between the models is good. Similarly, it is expected that a broad swathe of West Asia between 19°N and 41°N will experience mainly decreases in precipitation of up to 20% or more, while increases of up to 20% or more are projected for the far south-eastern Arabian Peninsula.

Projected higher temperatures and reduced rainfall could favour desertification processes and thus the strength of dust mobilization in West Asia. The WAS-SDS will most probably play a more important role in this domain over the next few decades.

B.3.2 Impacts of dust storms in West Asia

The Middle East is the second largest source of global dust after the Sahara desert, but, unlike North Africa, where large population centres are concentrated along the coasts of the Mediterranean and the Atlantic Ocean, relatively far away from dust sources, much of the population in West Asia lives inside, or in the vicinity of, dust sources. The impact on ecosystems and on many economic and social activities is therefore of utmost importance.

There is some evidence to indicate enormous impacts on many aspects of human health and on road and air transport, the latter owing to the severe reductions in visibility caused by dust storms. These studies are scarce in the region and, in most cases, consist of simple notes and internal reports, not rigorous scientific studies which have been carried out and validated.

In the health sector, based on a systematic review of the literature using the Web of Knowledge database, very few publications in West Asia report the impacts of atmospheric dust on the population.

The impacts of SDS on terrestrial and marine ecosystems are huge. To those on land must be added the movement of dunes invading farmlands. In marine ecosystems – and considering the importance of fisheries in the region – attention is drawn to the absence of studies regarding the effect of dust deposition on the ocean, which contributes to marine primary production. Moreover, deposition of dust over the ocean can also produce HABs, popularly known as red ties. Photosynthetic activity in the Gulf and the Arabian Sea due to fertilization by dust nutrients may well be important in mitigating the increase in anthropogenic CO_2 in the atmosphere.

In relation to the rapid diversification of energy sources that is being experienced in West Asia, particularly in relation to solar power, few studies have analysed the role of atmospheric dust in the extinction of solar radiation, as in decreased solar-plant performance arising from the deposition of dust on collecting surfaces and reflectors. Even fewer studies have been carried out on the use of applications, such as dust observations and predictions, to improve the operation of solar plants and to better manage the distribution of energy in national grids.

Atmospheric dust affects weather, atmospheric composition and climate through a wide range of interactions and both positive and negative feedbacks. For example, dust has a significant effect on SST retrievals from satellites. Although cloud-screening algorithms will often detect thick layers of aerosol, biases up to 3°C will remain, depending on the SST retrieval algorithm and brightness-temperature impacts of the dust, affecting NWP models. Mineral dust may also affect air temperature through the absorption and scattering of radiation. Mineral dust is one of the major contributors to Earth's radiative balance, since its radiation backscattering is remarkable. Depending on the size distribution, chemical composition and shape of the dust particles and the vertical position/extent of the dust layer and the local surface albedo, mineral dust particles may have a positive (heating of the climate system) or negative (cooling) radiative forcing. *IPCC (2007)* reported that the dust radiative effect due to mineral aerosols lies in the range of -0.56 to +0.1 W/m^2, and we know that dust also affects the hydrological cycle. Firstly, when dust cools, the surface inhibits both evaporation and precipitation. Secondly, dust modifies the size distribution and the phase of cloud particles by acting as cloud condensation and ice nuclei, modifying the development of precipitation. Mineral dust must, therefore, affect regional the weather and climate of West Asia decisively. These terms are used because there are no studies that evaluate and quantify these impacts in the region.

The assessment and quantification of the different impacts that atmospheric dust exerts on ecosystems and on numerous socio-economic activities in the region have yet to be performed. There are several reasons for this wide gap in our knowledge of dust impacts but the most important is probably the significant lack of a comprehensive and long-term dust-observation system. The lack of dust databases means that studies crossing information with databases of an entirely different nature in the fields of health, agriculture, industry, oceans, etc., cannot be carried out. Epidemiological studies on the role of dust in respiratory diseases are impossible, for example, without a relatively long series of PM10 in which the contribution of mineral dust is known.

All the countries of the region should start – and as soon as possible – to build an organized body of knowledge that provides scientifically backed information about the importance and impacts of SDS, so that policymakers can take concrete actions aimed at obtaining, and supported by the use of, such information.

The problem of the weak observation system in the region is addressed in the next section.

B.3.3 Dust monitoring in West Asia

The SDS observation system currently available in the region is far below what is actually needed for dust storm monitoring, prediction and characterization. Minimum efforts focused on improving, expanding and adapting existing dust-observation networks will result in significant improvements.

The most basic network with conventional meteorological observations are provided in SYNOP and METAR reports, in which horizontal visibility is a first indication of the presence of dust, is, in general, well distributed and with a relatively good density of stations. Some gaps exist, such as the Empty Quarter in Saudi Arabia, adjacent regions of Oman and Yemen and also certain lowland areas of the Islamic Republic of Iran. Most of the countries have operational automatic devices for visibility ranges such as MOR and RVR and all of them are important in airports, since one of the activities most affected by dust is air traffic. Visibility reduced by atmospheric dust from SYNOP observations would be an interesting product, at least for dust nowcasting. Some value-added activity should be implemented in near-real-time, such as filters for including relative humidity and present-weather data, in order to avoid including reduced visibility due to fog or heavy rain. Long-term climatologies might already be obtained, for example, by computing the monthly mean number of days in which visibility is below a threshold value. Climatology from visibility data on the regional scale would constitute a simple but unique picture of the spatial-temporal distribution of dust storms and an interesting first approach to indirectly determine dust trends.

The second dust-observation network type, based on dust-deposition gauges, is highly recommended. Although this method does not provide data on dust concentrations or enable determination of dust levels from a particular event, it does enable determination of the relative "dustiness" of sampling locations and so might provide a temporal and spatial climatology of breathable dust at surface level. A regional network of dust-deposition gauges should be installed in each country, using standardized sampling and evaluation methodologies and a network topology that meets objective criteria, taking into account dust sources and pathways, and filling observation gaps.

Stations measuring particulate matter constitute the third level of in situ observations. These useful atmospheric parameters are normally monitored within air-quality programmes. The number of PM10/PM2.5 stations in the countries reporting this information is reasonable and proportional to their population and geographical extension; some countries even have an excellent density of stations.

PM10/PM2.5 networks for dust characterization and for understanding impacts of dust on the population are of great importance and in situ PM10 measurements are crucial to validate surface-dust concentration from models. In situ PM measurements provide information about aerosols/dust inhaled by people and, therefore, how dust storms directly affect people and ecosystems. Most of the information provided by satellites corresponds to the total content of aerosol/dust in the atmospheric column and this does not necessarily have a direct correspondence with surface-dust concentrations. Furthermore, the chemical composition of surface aerosol/dust is another critical aspect in health impacts and other applications and cannot be provided by remote techniques, only by in situ PM sampling. From the point of view of SDS monitoring, the major deficiencies identified are the following:

- Too few stations are located in rural background conditions to monitor mineral dust only (mainly PM10) which would allow us to know its impact on air quality in the cities. PM10 and PM2.5 measurements in urban air-quality networks represent a mix of anthropogenic pollution (vehicles, gas-flares, industries, ships) and natural contributions. It is difficult to separate the contribution of each source if there are no background stations unaffected by anthropogenic contributions monitoring natural PM10.

- There are no standards of air quality common to all countries of the region, especially for PM10.
- A regional centre managing a common and homogenized quality-assurance system is lacking.

For these reasons, efforts should be made in the design and strategy of at least part of the PM measurement programme, in order to obtain optimal performance in the characterization of aerosol/dust background. Some PM10 stations should be set up in rural sites, far away from the direct impacts of anthropogenic sources located in cities and industrial centres in order to obtain aerosol background measurements which should be affected, basically, by mineral dust from local resuspension or transported from other regions.

Because of the complexity and vastness of West Asia, it is not possible to make recommendations on specific geographic locations for rural background stations. At national level, all dust storm pathways should be explored. As a rough estimate, about 10% of PM10 stations in each country should be located in rural background conditions. The rural background PM10 station network would provide useful information regarding the spatial and temporal variability of surface mineral-dust concentration and, at the same time, help to distinguish and understand the different sources of PM pollution measured by the air-quality networks in each country.

Since soil deterioration, together with wind, is one the primary causes of dust sources and consequently of SDS, improvement of in situ observation networks at dust hotspots is crucial for effective monitoring and forecasting. Mesopotamia should be properly monitored in collaboration with neighbouring countries that suffer most from the impacts of land degradation.

A fourth level of dust monitoring is found in ground-based, remote-sensing techniques, mainly sunphotometers and lidars or ceilometers.

Concerning sunphotometers, we have to highlight the role of AERONET (http://aeronet.gsfc.nasa.gov), a federation of regional networks based on photometric instruments located at ground stations (currently more than 400 worldwide) for monitoring atmospheric aerosols, including atmospheric mineral dust. It requires the standardization and calibration of instruments, data processing and distribution. AERONET seeks to provide continuous and easily accessible time series of aerosol measurements, such as microphysical and radiative properties in the atmospheric column. It is dedicated mainly to the characterization of aerosols and the validation of satellite data and aerosol models, as well as synergies with other databases.

The two most important dust sources in the world (North Africa and West Asia) have few AERONET stations. In West Asia, network coverage is sparse – only six stations are operational and these are unevenly distributed. AERONET does not cover dust hotspots or large cities affected by SDS.

As AERONET is the largest and most important network in the world for aerosol monitoring and the validation of both satellite and aerosol models, we propose the following actions aimed at improving AERONET in the region:

- Re-start operations at the following former AERONET sites:

  - Kuwait University, Khalidiyah campus
  - Bahrain (re-start operations in the most convenient free-horizon site)
  - Dhadnah (UAE)

- Set up new AERONET sites chosen for the geographical location of dust storm pathways and topology of the regional network:

  - Arar (northern Saudi Arabia)
  - Najran (south-western Saudi Arabia)
  - Somewhere in the Empty Quarter (Saudi Arabia)
  - Dayr az Zawr (eastern Syrian Arab Republic)
  - Mosul (northern Iraq)
  - Baghdad (central Iraq)
  - As Smawah (southern Iraq)
  - Faud, Dhahirah (Oman)
  - Bani Bu Hassan (Oman)
  - Ahvaz, Khuzestan (south-western Iran)
  - Zabol (preferable) or Zahedan (Sistan basin, eastern/south-eastern Islamic Republic of Iran)
  - Tehran (Islamic Republic of Iran)

Annual maintenance and calibration of AERONET sunphotometers, following standardized protocols, are absolutely mandatory. The possibility of creating a regional AERONET centre should be seriously considered.

The situation concerning lidars and ceilometers, there are still substantial data-sparse areas in West Asia compared to North Africa and the Sahara. There is one lidar station at Zanjan (Islamic Republic of Iran) and more than 20 new-generation ceilometers in Turkey with potential use for SDS activities but, at present, they are operated only for aeronautic meteorology purposes. Lidars, however, permit the analysis of desert dust that has intruded into the PBL and the mixing processes of dust with other aerosol types, as well as the transport of dust at upper levels, which might be interesting for aviation in the region. Lidar measurements in combination with other techniques, such as sunphotometry, are ideal for investigating certain aspects of atmospheric composition, transport, deposition of dust and dust-cloud interaction, including cloud-formation processes. Nevertheless, lidars are advanced, expensive (>US$ 100 000) instruments that require specialists specifically trained for their operation, as well as dedicated personnel to retrieve vertical profiles with data-inversion algorithms. Maintenance costs are also high. Compared to sunphotometers, the lidar technique is more expensive and requires much more experienced specialists to work in both operations and data processing.

A lidar network similar to that proposed for AERONET sunphotometers would be the ideal scenario. Nonetheless, given the enormous complexity of the lidar technique, its high cost, and the level of development of this technology in the region, caution must be exercised when proposing lidar sites. For this reason, a first recommendation is to strengthen what has already been achieved. Support to the IASBS group that has designed, developed and operated two lidars in Zanjan (Islamic Republic of Iran) is therefore highly recommended.

A second recommendation for a lidar site would be Kuwait, strategically located in the dust outflow from Iraq and in the pathway of west-east-west dust clouds. Kuwait would be a key station of great interest for both operational and research activities. This lidar programme might be a collaborative effort between a university/research institute group and the Kuwait Meteorological Centre. A potential site could be at Kuwait University, where an AERONET station was in operation until August 2012.

The third recommendation concerning concerns Saudi Arabia, where two interesting sites with AERONET stations are in operation: the KAUST campus and the Solar Village at the Energy Research Institute of KACST. The KAUST campus station could monitor intercontinental dust transport, especially dust plumes over the Red Sea, while Solar Village would be an interesting site to monitor and characterize vertical dust distribution in the central Arabian Peninsula at or near dust sources.

In a second phase, and co-located at existing AERONET stations, two additional lidar stations could be set up in the dust corridor (beginning in northern Iraq) in the UAE and Oman, respectively. These stations could monitor dust transport along the Gulf to the Arabian Sea and between the Arabian Peninsula and the Islamic Republic of Iran.

Initiatives from other groups of countries in the region would of course be welcome and should be considered in a medium-term dust-monitoring plan. A lidar programme requires a commitment and a significant involvement of research groups, without which it would not be possible to implement the technique.

Besides research-oriented lidar networks, a large number of ceilometers are distributed worldwide. Ceilometers (often called low-power lidars) are robust systems for continuous operation that can provide useful information about the aerosol layers, which can be used for operational dust monitoring and forecasting. Ceilometers are single-wavelength backscatter instruments that are relatively inexpensive (~US$ 20 000) and are used at most airports for cloud-base monitoring. Many NMSs, as well airports, operate ceilometer networks, providing atmospheric measurements fully automatically and continuously of, for example, cloud-base and PBL height, but also profiles of atmospheric aerosol backscattering. The involvement of NMSs in gradually extending the use of ceilometers into SDS activities is obvious, relatively easy and inexpensive.

Satellite observations are crucial for monitoring SDS events and providing SDS climatologies in the region, filling the huge gaps identified by in situ observations but they have marked limitations. Satellite observations require validation with accurate ground observations and satellite products are still limited both in time (usually once a day for quantitative dust observations) and variety of useful products for many applications. For example, satellites do not provide information about dust-surface concentrations affecting people and ecosystems and they cannot address chemical composition or aerosol size distribution.

Most of the countries in West Asia use the SEVIRI-MSG sensor for dust storm monitoring. In some countries, MODIS Aqua/Terra (both images and quantitative AOD) and MISR are used, but to a lesser extent and mainly for case analysis or for short short-term studies of a few years. NOAA satellite dust information is used mainly for meteorological analysis. The degree of utilization of aerosols/dust data from satellites is low in West Asia and, in most cases, quite basic, focused on immediate use for weather forecasting. Satellite pictures of dust storms are used for illustrating analysed events in some scientific articles.

The best sensor for continuous monitoring of dust storms is, without doubt, SEVIRI-MSG. Its high spatial resolution is complemented with a unique and powerful capacity: a high temporal resolution (15 minutes now and 10 minutes in the near future). While SEVIRI-MSG is currently the ideal satellite sensor for dust nowcasting, it does not provide reliable, quantitative AOD.

Aerosol products from MISR are excellent in generating climatologies for dust-source and pathway regions, while MODIS and SeaWiFS are excellent for quantitative AOD over the oceans. CALIOP and PARASOL on board the CALIPSO platform provide aerosol backscatter and extinction-coefficient profiles. Data from these space-based sensors are available in the corresponding databases and can be used in case analysis and for establishing climatologies for West Asia.

Long-term reanalysis of satellite-based observations at dust hotspots, specific stations (e.g. AERONET or SYNOP stations), as well as sensitive dust-impacted areas (cities, industrial facilities, airports) will quickly improve knowledge of the spatial-temporal variability of dust storms. Use of the Giovanni application is highly recommended for this type of analysis. Giovanni is a web-based application developed by GES DISC that provides a simple and intuitive way to access, visualize and analyse vast amounts of Earth-science remote-sensing data without having to download them.

The CoE for Training in Satellite Meteorology in Muscat (Oman), that forms part of the WMO-CGMS Virtual Laboratory for Education and Training in Satellite Meteorology (VLab) and is sponsored by EUMETSAT, could play a special role in satellite observations in West Asia.

Regarding observations, a particularly important requirement in West Asia is an accurate inventory (1 km resolution if possible) of dust sources, soil texture and land use. This inventory would greatly help the development of better dust models, since the sources are used as model inputs.

SDS monitoring will help facilitate timely and accurate dust storm forecasting and nowcasting but, in the long term, and in collaboration with UNEP national institutions, it will also support monitoring of the evolution of dust sources and dust pathways and the assessment and verification of measures implemented to reduce the impact of SDS after action has been taken in land-degraded, dust-source regions.

B.3.4 Dust modelling and forecasting in West Asia

Only two countries, the Islamic Republic of Iran and Turkey, run appropriate regional dust models. DREAM8 Eta has been run at IRIMO since 2012 as a result of cooperation with SEEVCCC. BSC-DREAM8b has been run at the TSMS since July 2010, thanks to cooperation with BSC, Spain. In the case of ASMERC (Islamic Republic of Iran), the use of WRF-CHEM as a dust model for operational purposes does not seem to be an appropriate solution. The CHEM module associated with WRF was not conceived and developed for dust, but for chemical processes in air-quality issues, as is also the case in the UAE with the COSMO_ART aerosol model.

Capabilities in the area of modelling are rather poor. A marked improvement can be quickly achieved through collaboration with model-provider institutions. Recently, the SDS-WAS NAMEE Regional Centre made available a set of dust-model outputs to West Asia countries, so there are real and immediate ways to improve notably the modelling and prediction of dust storms.

The modelling structure proposed for West Asia consists of a three-level nesting scheme. At the first level, daily global dust-model data could be provided by organizations/initiatives such as ICAP. Either an ICAP median of such model outputs or data from a particular global model group should be secured by the future West Asia Regional Centre through a special agreement with data providers. Nowadays, global models have a spatial resolution of ~50 km, which will be increased to ~25–30 km in the near future.

In the next nesting step, global model data should be used for the initial and boundary conditions in a large regional dust-model area to feed regional models. Ideally, these models should have a resolution of ~10–15 km. Over the last 20 years, a modelling community focused on dust models has developed dust-source specifications, parameterizations of dust emissions, radiation-dust and dust-cloud interactions, parameterizations, etc., building up a robust dust-forecasting system. Fortunately, many of these regional models running over the West Asia geographical domain are currently available through the SDS-WAS NAMEE Regional Centre. In particular, this Centre offers dust-forecast outputs generated by different regional numerical models, both graphically and numerically, at:
http://sds-was.aemet.es/forecast-products/dust-forecasts.

The availability of this set of specialized dust-prediction models constitutes an unprecedented breakthrough for the international community and especially for the countries of West Asia, which will have six digital models outputs and an ensemble available to add to the current dust-forecasting capabilities of each country. The geographical domain of these models should be expanded eastward in order to include dust sources and pathways in Afghanistan and Pakistan.

Dust storms associated with small-scale convective processes in space and time, such as haboobs and cold-air downburst storms, can be captured neither by global models nor by regional models, given the small size of these meteorological processes, and because most of these models have not carried out adequate parameterizations of mesoscale convective cloud-resolving processes, low-level jets, etc. The third nesting level therefore consists of mesoscale/local dust models fed by data from (a) regional scale model(s). Such mesoscale modelling systems, which include non-hydrostatic atmospheric processes, should be downscaled to resolutions of ~1–3 km in order to resolve both atmospheric driving conditions and dust soil sources and will complement global and regional models. The spatial resolution of mesoscale/local dust models will depend largely on the region to be covered and available computational resources. Two regional models that might easily be upgraded to mesoscale high-resolution models are SEEVCCC NMM-DREAM8 and NMMB/BSC-Dust.

Dust-model verification is an important activity targeting knowledge of model performance and model reliability quantification. A great effort should be made to secure proper NRT and offline validation of dust models. The example of the SDS-WAS NAMEE Regional Centre could be followed. Model validation, in a first stage, requires a significant strengthening of AERONET in the region.

Dust-model reanalysis (model simulation) is essential for understanding basic aspects of the spatio-temporal distribution of dust storms.

Some specific recommendations concerning dust modelling and forecasting are the following:

- Establish a web-based virtual centre with both graphical and numerical prediction products from outputs of global, regional and mesoscale dust models. The SDS-WAS NAMEE web portal concept would be a good starting point.

- Create a working group formed by weather forecasters of all countries and supported by researchers in each country to evaluate the quality of each model by comparison with dust storm events (mostly from satellite information).

- Provide model-comparison exercises during selected dust episodes, as well as continuous model validation against ground-based or satellite-borne observations.

- Reach agreements with the institutions currently running the dust-forecast models available through the SDS-WAS NAMEE Regional Centre, so that the geographical domains of the models are extended to the eastern West Asia region.

- Develop and implement high-resolution models in order to predict dust storms associated with mesoscale convective systems by bilateral cooperation agreements or contracts with groups specialized in high-resolution dust modelling.

- Replicate for West Asia the evaluation/validation system developed at the SDS-WAS NAMEE Regional Centre, incorporating the dust models currently run in West Asia.

- Evaluate models for a few selected dust storm events caused by both small-scale meteorological processes (such as convective-based haboobs, low-level jet dust storms) and large scale processes (shamal, meteorological fronts).

- Use dust-model reanalysis to obtain dust climatologies at the regional scale and long-term trend analysis.

- Promote, in close collaboration with UNEP and national environmental agencies, multidisciplinary studies leading to the establishment of high-resolution maps of dust sources and their characteristics and PM-type observations, in order to improve modelling, using UNEP communication links with national environmental authorities. Local/national data on land use, soil texture and land cover are ingredients in the model emission parameterization. Land/soil information should be at the highest possible resolution, preferably finer than 1 km.

Modelling is a complex issue requiring well-trained, qualified personnel. A thorough training plan for modellers of the region, in collaboration with recognized international dust-modelling institutions and providers is therefore necessary.

B.3.5 User-oriented products and services

There are no specific user-oriented products and services on sand- and dust storms in West Asia.

NMSs, environment protection agencies, health institutions, aviation authorities, energy departments, marine resources and fishery agencies, wildlife, forestry and agriculture agencies, disaster risk and civil protection agencies, research institutions and universities should participate in the SDS-WAS Regional Node for West Asia, as contributors and/or as specialized users.

One of the most important products that NMSs could provide to the general public and specific users and professionals in different sectors would be accurate SDS early warnings, anticipating their impacts and reducing societal and economic losses. Environment, health, transport and civil defence authorities need to be notified of observed or predicted SDS events in a timely fashion. A challenging, and probably profitable, orientation of SDS products would be the support to emerging activities for which SDS can be critical: solar-power plants (production efficiency and maintenance), the electronics industry, airport operations and aviation maintenance, high-speed rail operations and farm and livestock management. SDS-WAS will be an essential tool to help environmental authorities in formulating future air-quality regulations. The WMO SDS-WAS Regional Node for West Asia will provide unique complementary information to climate services concerning drought and desertification monitoring.

End-products should be agreed with potential users and SDS products must be “translated” into language that is understandable to the end-user. Thus, a WG specialized in user-oriented SDS products and services should also be created within the SDS-WAS Regional Centre for West Asia. This WG would ask potential users to state their needs, at the same time explaining the capacities and limitations to delivering different SDS products and services.

B.3.6 Training and capacity-building

Most countries in the region have an interest in both general and specific SDS capacity-building. The Islamic Republic of Iran and Turkey have notable experience in organizing general SDS training courses and workshops. Oman, with the CoE for Training in Satellite Meteorology, has valuable experience in organizing international courses on satellite observations and applications to SDS monitoring and forecasting. There is, however, a clear gap in capacity-building in the areas of in situ observation, ground-based remote-sensing and modelling techniques and methodologies. The importance of training in standardized methods and techniques on a regional scale is to be emphasized.

Regional cooperation in capacity-building and training, within the SDS-WAS Regional Node, will lower costs and allow all countries to work with common rules and standardized procedures, facilitating data exchange and information sharing. Capacity-building within the WMO SDS-WAS involves technology transfer with self-sustaining capability and long-term partnership in mind. It will be coordinated through various mechanisms, including those well established in WMO through its Development and Regional Activities Department.

Depending on available resources, capacity-building and training activities should include:

- Regular scientific exchange through workshops or seminars to discuss recent developments in general SDS issues, such as observation, modelling, forecasting and users.
- Specialized capacity-building, including training in specific technical issues such as, for example, satellite-data access and analysis, dust storm forecast and simulation model-output analysis, targeting user needs through new information products, measuring and monitoring air quality through remote-sensing (sunphotometers or lidar) and in situ air-sampling instruments, etc.

- Medium-term (several months) stays at specialized centres to learn techniques or methodologies regarding observations, modelling and elaboration of user-oriented products.

B.3.7 Collaboration mechanisms for the SDS-WAS Regional Node for West Asia

Unfortunately, there are currently no mechanisms for collaboration in SDS activities in West Asia. Each country deals with the issue in an isolated manner and within each country there is little or virtually no collaboration between different actors who can contribute to SDS activities such as those of NMSs, air-quality authorities, research centres and universities.

Countries have minimal preparation for monitoring and forecasting activities and managing background information on SDS.

Like other meteorological parameters and variables, dust has no international borders. Countries cannot address dust monitoring and forecasting individually. Most of them are dust sources and at the same time are impacted by dust transported from neighbouring countries. A smooth and rapid exchange of information between countries is therefore essential for an effective and useful SDS-WAS. This can only be achieved by implementing an SDS-WAS Regional Node for West Asia as proposed by WMO.

SDS-WAS was established in 2007 as a WMO programme in response to the intention of 40 WMO Member States to improve capabilities for more reliable SDS forecasts. The SDS-WAS mission is to achieve comprehensive, coordinated and sustained observations and modelling capabilities in order to improve monitoring and so increase the understanding of dust processes and enhance dust prediction. SDS-WAS integrates the research and user communities.

The WMO SDS-WAS Science and Implementation Plan offers an operational structure for dealing with a diverse community underpinned by well-established WMO systems of research, observations, numerical weather and climate prediction and service delivery. The diverse requirements of SDS research and user communities for observations, forecasts and analyses require the development of interfaces through careful assessments. A comprehensive, coordinated observing network for the monitoring of SDS and improved modelling capabilities will increase the understanding of dust processes and enhance their prediction. The WMO SDS-WAS Science and Implementation Plan thus proposes an architecture and information exchange that will secure efficient and balanced cooperation and participation of the major components: research, prediction, observations and service delivery. It is an activity that cuts across WMO programmes, as well as involving a substantive partnership outside the NMSs, particularly in research. In the framework of this concept, SDS-WAS is an international network of research, national operational centres and users organized through regional nodes, assisted by the SDS-WAS regional centres. It is coordinated by the SDS-WAS Steering Committee, supported by the WMO Secretariat, and reports to the Commission for Atmospheric Sciences through WWRP and GAW programmes.

At the regional level of nodes, SDS-WAS is structured as a federation of partners. What the term federation implies is an organized structure following minimum global standards and rules of practice. A federated approach allows flexibility, growth and evolution, while preserving the autonomy of individual institutions. It allows a variety of participants, such as NMSs, air-quality agencies/authorities, universities and research centres and user institutions serving as hosts or/and partners, to cooperate and benefit without changes to their own internal structures and existing arrangements. The structure is scalable and allows for adaptability to changing research and operational environments.

A regional node is also organized according to federal principles. Activities within each node are harmonized by an SDS-WAS RSG, assisted by the WMO Secretariat. Each node has to implement the following tasks agreed by a corresponding RSG:

- Provide a web-based portal agreed between regional partners for user access to regional research and forecast activities and services.
- Support efficient observation data-sharing, providing neutral ground for SDS-WAS data exchange.
- Assist partners in implementing agreed research and forecast activities at regional level.
- Cooperate with existing operational service delivery mechanisms, recognizing that warnings related to SDS-WAS are generally the responsibility of the NMSs and that SDS-WAS products provide input to them.

- Report on implementation progress to the WWRP Joint Scientific Committee and to the SDS-WAS RSG.
- Support research among partners of the SDS-WAS regional node and help implement operational SDS-WAS forecasts at the NMSs.
- Guide the RSG on implementing agreed research and forecast activities at a regional level.
- Organize training workshops in the use of SDS-WAS products.
- Convene symposia, conferences, workshops and other meetings, as necessary, to advance research SDS activities.
- Assist, when necessary, in resource mobilization through trust-fund contributions.

Partners can contribute to SDS-WAS regional node activities, according to their capabilities. Considering that the most important areas of collaboration within the SDS-WAS are observation, modelling and prediction, capacity-building and user support, and that these areas can be subdivided, in turn, into other more specific topics, partners may propose to take the responsibility of leading the coordination of a topic and implement a dedicated website with all the information agreed on that topic. Each topical website would be part of the SDS-WAS web portal of the regional node. This, in turn, could be mirrored in servers of countries with adequate computational resources. A web portal will be established in the regional node as a result of node activities and partners' coordination. Thus, the regional node will not depend on a single institution, and if any member fails, another partner could assume its corresponding function. In this way, a robust, participatory regional system can be established, which is transparent to all partners. Any member of the region may join the regional node at any time.

To achieve this configuration, it is necessary to create several WGs addressing different subjects, which should be integrated by corresponding specialists and experts of the region. They will identify activities, and specific partners of the regional node should assume responsibilities and obligations. These WGs should emerge from a first meeting of the SDS-WAS RSG.

B.3.8 The WMO SDS-WAS Regional Node for West Asia: a collaborative partner of the UNEP Regional Programme to Combat Sand and Dust Storms

The proposed WMO SDS-WAS Regional Node for West Asia is self-sufficient and builds on a model that has already been successfully implemented in other regions. The WMO SDA-WAS Regional Node for West Asia will be a fundamental tool for dust storm monitoring and early warning, as well as for long-term monitoring of the evolution of dust hotspots at different spatial and temporal scales.

SDS originate in dry and desert regions. Many of these areas have been extremely dry for hundreds or thousands of years, owing to natural causes. They currently emit atmospheric dust and are expected to continue to do so in the future with no remedy in the medium term. These dust emissions require monitoring and early warning systems. In other regions, soils have been degraded over a few decades, directly by human activities such as mismanagement of water resources and land misuse, and indirectly by climate change. This results in new dust sources and increasing dust emissions to the atmosphere, which have been intensifying rapidly in recent decades, adding to emissions from natural dust sources. In this sense, an SDS-WAS Regional Node for West Asia is essential for understanding, monitoring and combating desertification in collaboration with the UNEP Regional Programme to Combat Sand and Dust Storms, with the participation of the affected countries and support from other UN organizations and agencies and other partners.

The UNEP SDS Programme has the following four objectives:

1. To strengthen cooperation among countries of the Region (and within countries) to address the SDS problem through collaborative and innovative solutions, institutions and adequate resources.
2. To enhance scientific and societal knowledge about the causes, sources, impacts and dynamics of, and coping with, SDS.
3. To reduce occurrence and impacts of SDS through the design and implementation of innovative and scalable solutions that will at the same time promote investment in the green economy, benefiting local communities and livelihoods.
4. To establish systems of coordinated and state-of-the art monitoring and early warning, including the development of specialized regional centres.

The WMO SDS-WAS Regional Node for West Asia will help to achieve all the objectives, but will play a key role in Objectives 1, 2 and 4.

The UNEP SDS Programme will be built and developed in a logical, four-step approach:

1. Understand and diagnose the problem
2. Propose and reach consensus on the solutions
3. Implement the agreed actions
4. Monitor, learn and scale up

The WMO SDS-WAS Regional Node for West Asia will help to understand and diagnose the problem, using proven scientific techniques and methodologies in the first step of the UNEP SDS Programme and will contribute to the fourth step, measuring success of implemented actions, and providing knowledge to define and implement carefully tailored strategies for the scaling-up of these actions.

The well-defined collaboration mechanisms of the WMO SDS-WAS regional nodes ensure collaboration between groups within a country, collaboration between countries in a region and exchange of information and collaboration at the interregional level under the WMO umbrella. The fact that the WMO SDS-WAS Regional Node for West Asia is a collaborative partner of the UNEP SDS Programme ensures the interconnection and coordination of United Nations Programmes.

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