Environment International 130 (2019) 104867

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review article

Monitoring the impact of desert dust outbreaks for air quality for health studies

X. Querol[a,*], A. Tobías[a], N. Pérez[a], A. Karanasiou[a], F. Amato[a], M. Stafoggia[b], C. Pérez García-Pando[c], P. Ginoux[d], F. Forastiere[e], S. Gumy[e], P. Mudu[e], A. Alastuey[a]

[a] Institute of Environmental Assessment & Water Research, Barcelona, Spain
[b] Department of Epidemiology, Lazio Regional Health Service, Rome, Italy
[c] Department of Earth Sciences, Barcelona Supercomputing Center, Barcelona, Spain
[d] Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, USA
[e] Department of Public Health, Environmental and Social Determinants of Health, World Health Organization, Geneva, Switzerland

ARTICLE INFO

Handling Editor: Hanna Boogard

Keywords:
Mineral dust
Atmospheric particulate matter
Aerosols
Epidemiology
Natural and anthropogenic contributions

ABSTRACT

We review the major features of desert dust outbreaks that are relevant to the assessment of dust impacts upon human health. Our ultimate goal is to provide scientific guidance for the acquisition of relevant population exposure information for epidemiological studies tackling the short and long term health effects of desert dust. We first describe the source regions and the typical levels of dust particles in regions close and far away from the source areas, along with their size, composition, and bio-aerosol load. We then describe the processes by which dust may become mixed with anthropogenic particulate matter (PM) and/or alter its load in receptor areas. Short term health effects are found during desert dust episodes in different regions of the world, but in a number of cases the results differ when it comes to associate the effects to the bulk PM, the desert dust-PM, or non-desert dust-PM. These differences are likely due to the different monitoring strategies applied in the epidemiological studies, and to the differences on atmospheric and emission (natural and anthropogenic) patterns of desert dust around the world. We finally propose methods to allow the discrimination of health effects by PM fraction during dust outbreaks, and a strategy to implement desert dust alert and monitoring systems for health studies and air quality management.

1. Introduction

'Desert dust' is the mixture of particulate matter (PM) emitted from the surface of arid and semi-arid regions. Due to the aridic nature of these regions, soils are poor, and therefore this PM is mostly made up of mineral matter. According to Dubief (1977), Prospero et al. (2002) and Ginoux et al. (2012) large emitting regions are inland basins sporadically flooded (such as the Chad Lake and surroundings) by ephemeral surface water streams that do not reach the sea but terminate in these internal basins, but other types and scales of emitting zones are also frequent. High winds can then suspend the minerals deposited by the washout-deposition processes. This process of suspension causes extremely high PM levels locally; we commonly define this phenomenon as a 'dust storm'. Furthermore, the frequent nocturnal thermal inversions keep a 'dust layer' at high atmospheric levels that, when winds of the mid-troposphere are intense, might be transported thousands of kilometres ('long-range transport') from the source. These processes of emission and transport are not continuous in time for a given area, although large regions, such as North Africa, feature dust activity quasi-permanently throughout the year. We will use the term 'episode' to refer to the distinctive sequence of dust emission from a source or ensemble of sources, and the transport of the dust towards a receptor area. We define a receptor area as an area located either close or far away from the emission source, whose air quality is affected by desert dust transport. The term 'desert dust outbreak' is used to describe the dust event in the receptor area only. Desert dust is typically mixed with the locally or regionally emitted PM at the receptor area; it may also become mixed with other PM during the transport towards the receptor area. Thus the increase of PM in the receptor regions during dust outbreaks might be due not only to desert dust itself but also to other anthropogenic and natural (e.g. sea salt) PM.

There are a number of relevant reviews or books on the phenomenology of desert dust outbreaks, dust particle size and composition, including the biological fraction, as well as on the health effects of dust

* Corresponding author.
E-mail address: xavier.querol@idaea.csic.es (X. Querol).

https://doi.org/10.1016/j.envint.2019.05.061
Received 6 March 2019; Received in revised form 2 May 2019; Accepted 23 May 2019

storms in different regions of our planet (Dubief, 1977; Prospero, 1999; Prospero et al., 2002, 2012; Reid et al., 2003; Griffin, 2007; Hashizume et al., 2010; Ginoux et al., 2012; Karanasiou et al., 2012, De Longueville et al., 2010; Goudie, 2014; Knippertz and Stuut, 2014; Zhang et al., 2016; Schuerger et al., 2018; Middleton et al., 2019; Duniway et al., 2019, Achakulwisut et al., 2019; Bullard and Baddock, 2019; among others). In spite of the above reviews, there is a need for a review on health impact assessment of desert dust exposure in receptor regions taking into account the different phenomenology of dust outbreaks (e.g., varying intensity, anthropogenic mix of PM, meteorological patterns, among others). We aim here to answer the following questions: How do we quantify dust and anthropogenic PM contributions during dust outbreaks? What PM features might be relevant for the assessment of health effects? These are key questions for devising an exposure analysis to feed epidemiological studies for desert dust affected territories. It might be or not the case that part of the conflicting results obtained in epidemiological studies of desert dust are due to the use of different methods to characterize exposure to dust or dust-related components (Tobías et al., 2019).

In the first five sections of this review-assessment paper we provide some light on the characterisation of exposure to dust and dust-related PM components for short and long term cross-sectional epidemiological studies, both at desert areas and dust receptor regions, with special emphasis on those having a special importance to evaluate the potential health impact of desert dust outbreaks. Following this we use this know how to yield some recommendations to implement alert and monitoring systems to provide health relevant data on exposure to air pollution for health studies, and also to provide relevant information to apply measures to reduce this exposure during these dust events. This does not intend to be a systematic review, but our intention is to review major patterns of desert dust outbreaks and potentially associate co-pollutants that might be relevant to design epidemiological studies, and on the other side to highlight relevant health-related patterns of desert dust events to atmospheric scientist.

This summarises the first part of a WHO–report on the Health Effects of Dust and Sand Storms'. This report consists of a systematic review of the scientific evidence on the health effects of desert dust and sand storms, undertaken within the framework of the WHO air pollution global activities and the current update of the WHO Air Quality Guidelines (AQGs). This systematic review revealed that there is an urgent need to harmonise the characterisation of the exposure to desert dust and co-pollutants to obtain consistent worldwide conclusions on the health effects associated to desert dust outbreaks.

2. Source regions and emissions

Oceans and arid regions provide most of the atmospheric aerosol load of the Earth, with 6.3–10.1 and 1.2–1.8 Giga (10^9)-tons (t)/year (yr) of sea salt and PM10 soil dust, respectively, emitted into the troposphere (Textor et al., 2006; Andreae and Rosenfeld, 2008; Huneeus et al., 2011; Ginoux et al., 2012; Kok et al., 2017). Sea salt is made of PM derived from sea/ocean droplets suspended into the atmosphere that are subsequently evaporated and yielding salts, such as sodium, chloride, magnesium, calcium, potassium, and sulphate. Soil dust aerosols are created by wind erosion within arid regions, where soil particles are loosely bound by the low soil moisture and absence of vegetation. Dust sources have been identified empirically from satellite radiance measurements (Prospero et al., 2002; Walker et al., 2009; Ginoux et al., 2010) over the last few decades. Ginoux et al. (2012) were able to derive the global distribution of dust sources at 10 km resolution by counting the frequency of days marked by high dust optical depth (DOD) (Fig. 1). The Sahara and Sahel regions in Northern Africa are the most active dust sources in terms of emissions (790–840 million t/yr), followed by the Gobi and Taklamakan deserts in East Asia (140–220 million t/yr), the Middle East region (13–20 million t/yr), Central Asia, Eastern Australia, South America (Atacama) and South Africa (10–60 million t/yr each), and Southern US-Northern Mexico (2–60 million t/yr) (Prospero et al., 2002; Washington et al., 2003; Huneeus et al., 2011; Ginoux et al., 2010, 2012; Varga, 2012). There are also other sparse sources of dust in different climatic regions, such as the active glacial outwash plains of Iceland and specific areas in Alaska, Spain and Turkey (Prospero et al., 2012; Ginoux et al., 2012). Dust source regions are active throughout the year (Fig. 1) with the frequency and intensity of emission peaking in specific seasons (see Section 3).

On the large scale, prolific dust sources correspond to topographic depressions where a deep layer of alluvium has accumulated (Prospero et al., 2002). However, many of the most important dust sources are not always large regions with uniform emissions across them (Gillette, 1999). Dry lakes with unconsolidated fine-grained sediments are among the most important sources. Also, ephemeral streams-rivers, lakes, and playa-lakes or sebkhas (ephemeral lakes in inland basins without connection with coastal areas), where sediments are deposited intermittently can be prolific sources, as known from several decades ago (Dubief, 1977).

Concerning the anthropogenic contribution to dust emission, land dissection, disturbance and desiccation of lakes and playa-lakes, agricultural practices, and expansion of livestock grazing, among others, have been identified as major causes of increased emissions in the last century (Gill, 1996; Stout, 2001; Orlove, 2005; Neff et al., 2008; Cook et al., 2009; Ma et al., 2010; Lee et al., 2012; among others). The present-day contribution of land use (anthropogenic) dust emission remains still subject to debate, with values ranging from 10% (Tegen et al., 2004) to 50% (Tegen et al., 1996; Mahowald et al., 2004) due to the large modelling discrepancies. Ginoux et al. (2012) attributed sources to human activity in regions where the cultivated fraction exceeded 30%, according to the land use atlas of Klein Goldewijk (2001). Maps of both natural and cultivated sources were introduced into a dust transport model and the anthropogenic fraction of present-day dust emission was estimated to be around 25%. However, the distinction between natural and anthropogenic dust sources remains imprecise (Ginoux et al., 2012). A region may contain both natural and anthropogenic PM source types, and their distinction may not be possible with the satellite retrievals at 10 km resolution. In Australia, 76% of the dust sources were associated with land use by Ginoux et al. (2012). Within the climatically important region of the Asian summer monsoon, the anthropogenic emission fraction was estimated to be close to 30% towards the Middle East and the Indian subcontinent, and 40% towards East Asia. At the other extreme, the fraction due to human activity is as little as 8% in Northern Hemisphere Africa, in part because of expansive natural sources within harsh desert environments that are inhospitable to cultivation.

Both natural and anthropogenic dust emissions are highly influenced by the hydrological cycle and consequently these are highly affected by climate variability (Bullard and Baddock, 2019; Achakulwisut et al., 2019; among others). For example, a clear relationship between the prior year rainfall in the Sahel region and the dust outbreak occurrence in the Caribbean region was demonstrated by Prospero and Lamb (2003).

3. Transport and duration

The emitted soil dust is transported and distributed across the planet. Both models and observations show that dust is highly variable in space and time. Temporal variability is evident at multiple timescales, from the diurnal cycle to seasonal variations to multiannual changes that are mostly driven by meteorological factors controlling both the emission and transport processes. Fig. 2 shows the pathways of long range transport and seasons of dust activity. Major pathways are from the Sahara and Sahel towards the Caribbean, South America and US; from the Sahara to Southern Europe, Turkey and Israel; from the Taklamakan and Gobi regions towards the Pacific and reaching as far as

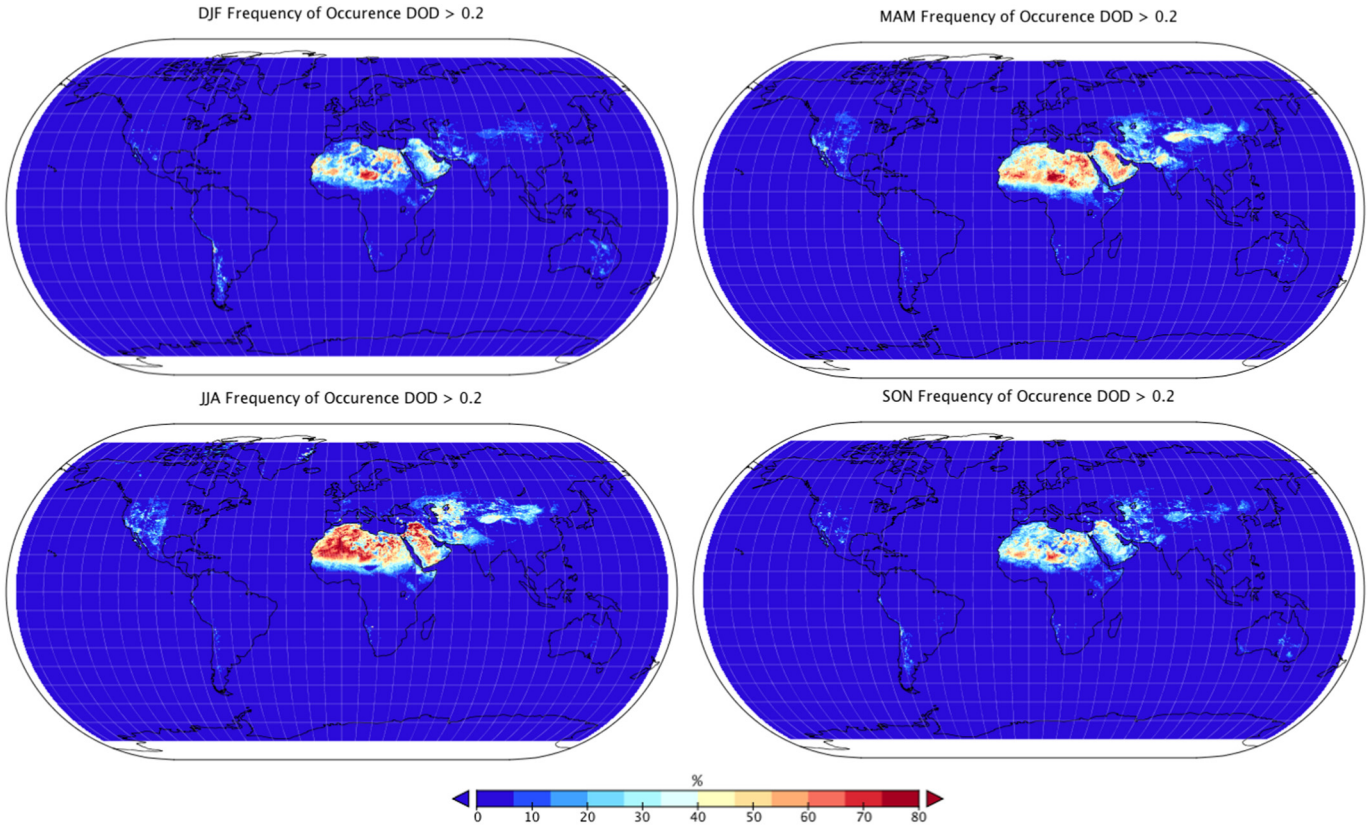

Fig. 1. Frequency of occurrence of dust optical depth (DOD) > 0.2 by season. Aerosol optical depth was retrieved at 10 km resolution using the MODIS Deep Blue algorithm (Hsu et al., 2004, 2006), and the contribution by dust aerosols was attributed based upon the spectral dependence of the measured radiances. DJF refers to December–January–February, MAM to March–April-May, JJA to June–July–August, and SON to September–October–November. Derived from Ginoux et al. (2012).

the US; from Southern US towards Mexico and vice versa; from Southern US towards Eastern US; from South Africa towards the Atlantic; from South America to the Southern Atlantic; from the Middle East towards Central and Southern Asia; from central Australia to different regions around, from Iceland towards Europe; and from Ukraine towards Central Europe, among others. These dust events have a marked seasonality (Figs. 1 and 2) and, although the above dust source regions are active throughout the year, emissions peak in spring and summer in Northern Africa, in summer and autumn in the Middle East, Central Asia and Australia, and US, and autumn-winter in South America, in summer in North and South America and Southern Africa, and in autumn in Eastern Asia and winter and spring in India (Prospero

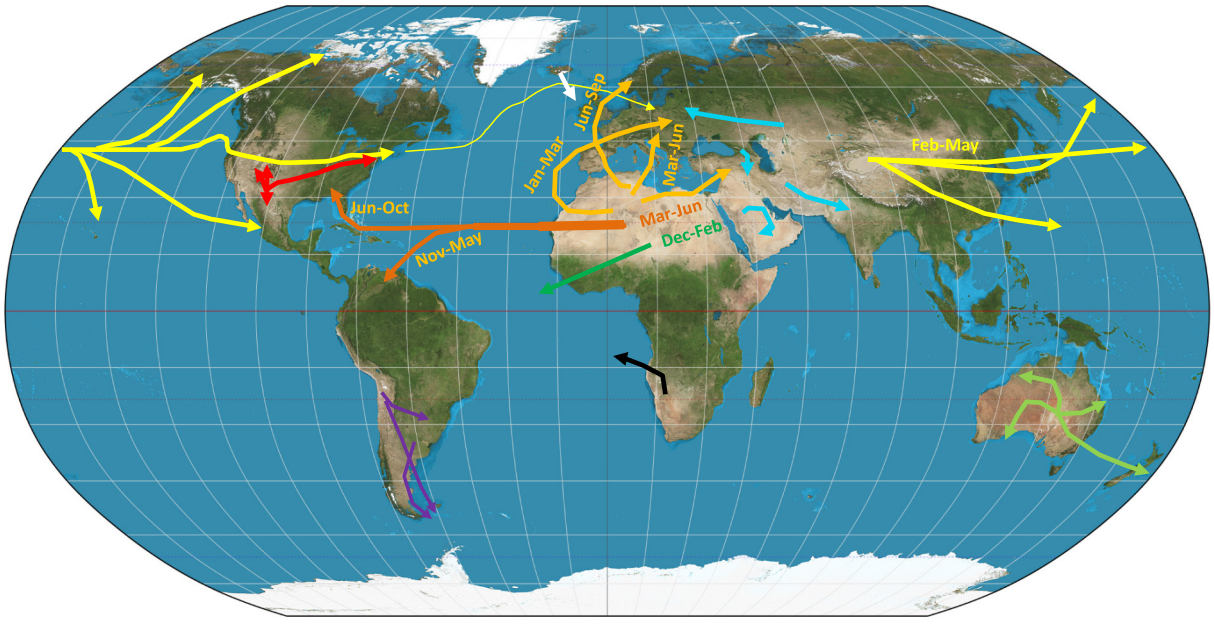

Fig. 2. Major desert dust transport fluxes, modified from Griffin (2007).

et al., 2002; Ginoux et al., 2012).

Dust storms usually last from 1 to 24 h at the source points (Goudie, 2014), but this does not mean that high levels of dust in the atmosphere persist only during these intervals. In desert areas, according to Dubief (1977) and a large number of subsequent papers, such as Duce et al. (1980), Zhang et al. (1997), Prospero et al. (2002); Ginoux et al. (2012), Richter and Gill (2018), and Yu et al. (2019), among others, convective processes inject dust at high atmospheric altitudes where synoptic circulations are able to transport injected dust to very large distances. During the night, thermal inversions isolate upper and lower atmospheric layers and favour the continuous transport of dust.

Depending on the meteorological scenario, dust can be transported near surface levels or lofted to high altitudes, becoming subject to long-range transport. For example, Saharan dust is transported towards the Canary Islands at surface levels in winter and at higher altitudes in summer (Viana et al., 2002). In the first case, air quality is degraded both due to the direct dust contribution and local pollution, whereas in the second the dust plumes influence surface PM concentrations to a lesser extent (Alastuey et al., 2005). Furthermore, the thickness of the planetary boundary layer (PBL, a layer where air is continuously mixed by convective turbulence caused by the diurnal heating of the surface) might be significantly reduced during dust storms, due to the following processes: i) dust layers decrease the insolation at surface levels and accordingly the convective mixing, and ii) other dust-transport processes cause atmospheric subsidence phenomena or thermal inversions, resulting in a surface increase of local pollutant concentrations (Pandolfi et al., 2014; Alastuey et al., 2005).

Dust reaches up to 5–6 km height over Western Africa (Tesche et al., 2011). LIDAR instruments show that the altitude of dust-enriched air masses leaving Western Africa towards the Caribbean region typically ranges from 0.1 to 4–5 km (Ansmann et al., 2011; Rittmeister et al., 2017). Over Europe, multiple dust layers of variable thickness (0.3–7.5 km, mean 1.5–3.4 km, depending of the European region) are transported at mean altitudes of 2.5 (base) and 5.9 km (top) and have a maximum height of up to 10 km (Papayannis et al., 2005, 2008; Mona et al., 2006). A thickness of 1 to 4 km was reported for the dust layer over Eastern Asia and the Pacific during a *Kosa* event by Yumimoto et al. (2009).

Over the continental areas the PBL might reach high altitudes and accordingly, even if dust layers travel at high altitudes, dust might be transported down to the surface by convective mixing. This effect is very clear when observing surface dust maps showing low concentrations below dust plumes over sea (where the marine boundary layer is thin) and much higher over the land. See Fig. 3 as an example of a dust episode over the Mediterranean on February 2016, when the column of dust (right) is similar over Spain and the Mediterranean Sea, but dust surface (left) levels are much higher over land.

4. PM concentrations during dust outbreaks

The long range transport of dust impacts significantly air quality over large receptor regions. Carlson and Prospero (1972), Prospero and Carlson (1980/1981), Prospero et al. (1995), Chiapello et al. (1995, 1997) and Prospero (1999) described the large influence of African dust outbreaks on the levels of ambient total suspended particles (TSP) over the equatorial and tropical Atlantic. Prospero and Lamb (2003) and Prospero et al. (2001) demonstrated this influence in ambient levels of PM10 (particles with a size lower than 10 μm) in the Caribbean and Florida; Van Curen and Cahill (2002), Jaffe et al. (2003), Fairlie et al. (2007) reported similar results on the Asian dust contributions to surface PM in western North America. In Europe Bergametti et al. (1989a, 1989b), Dayan et al. (1991) and Kubilay and Saydam (1995) reported on the high influence of African dust outbreaks on ambient levels of TSP. Querol et al. (1998a) reported that a number of annual exceedances of the daily air quality limit value for PM10 (first air quality daughter directive, 1999/30/CE) in Spain were due to African dust contributions. Thereafter, a number of studies have described similar findings in Spain (including the Canary Islands) and Southern Europe (Querol et al., 1998b, 2009; Viana et al., 2002; Rodríguez et al., 2001; Escudero et al., 2005, 2007a; Pey et al., 2013; among others). While the influence is particularly pronounced for ambient TSP and PM10, PM2.5 (particles with a size lower than 2.5 μm) levels also peak, especially during strong events. There are many other studies evidencing the large effects of dust on the air quality of different regions including among other, Northern Africa (e.g., Gillies et al., 1996; De Longueville et al., 2010), the Mexican desert region (e.g., Rivera Rivera et al., 2010; Grineski et al., 2011), Central Asia (e.g., Wiggs et al., 2003), Australia (e.g., Aryal et al., 2012); East Asia (e.g., Mori et al., 2003), Israel (Krasnov et al., 2014); and the Middle East (Engelbrecht et al., 2009).

PM10 and PM2.5 concentrations can reach very high levels during desert dust episodes, especially in the proximity of the source areas, but also at distant regions. These episodes are known as *Kosa* (or *Yellow Dust*) in the Pacific region and *Calima* in the Canary Islands. Mori et al. (2003) measured ambient PM at eight locations in China and Japan during a *Kosa* episode (March 2001). TSP concentrations reached up to 6700 μg/m^3 on a 8 h basis in the Inner Mongolia Autonomous Region (China); 1500 μg/m^3 at Beijing (on a 6 h basis, with 93% of the mass concentration being in the 2.1–20 μm fraction); and 230 μg/m^3 at a remote island in Japan (on a 24 h basis, with 64% in the 2.1–20 μm fraction). Sotoudeheian et al. (2016) reported daily PM10 concentrations up to 650 μg/m^3 in central Iran cities during July 2009. Querol et al. (2009) and Achilleos et al. (2014) reported daily PM10 concentrations during African dust episodes reaching up to 250 μg/m^3 in remote sites of Spain and up to 470 μg/m^3 in Nicosia. Viana et al. (2002) reported daily PM10 concentrations reaching up to 675 μg/m^3

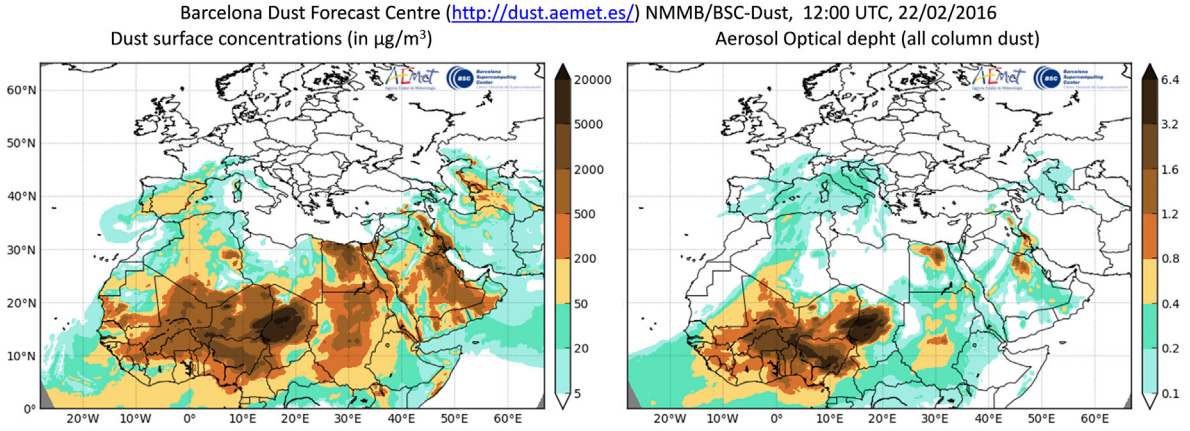

Fig. 3. NMMB-BSC modelling outputs for a dust episode over the Mediterranean on 22nd February 2016. Left: dust surface concentrations. Right: aerosol optical depth (representing the aerosol load in the whole atmospheric column).

during a *Calima* event in February–March 2000 at Tenerife (Canary Islands, Spain). In Sydney, during a very intense dust episode in September 2009, up to 11,800 μg/m^3 hourly PM10 levels were recorded, with 50% of TSP made up of PM10 (Aryal et al., 2012). According to Querol et al. (2009) and Pey et al. (2013), African dust impacts air quality around the Mediterranean Basin 17 to 37% of the days within a year, with a contribution of 9 to 43% of the annual ambient PM10 levels measured at remote sites of this region. This represents a contribution to the annual mean from 1 to 8 μg/m^3 of PM10. These contributions decrease from south to north and from east to west, although also with the altitude over sea level (since desert dust layers are transported preferentially at high altitudes, see below). They also found that in most southern regions of Europe the proportion of African dust days exceeding daily dust concentrations of 25 μg/m^3 in PM10 reached 25–30%; whereas in the Northern Mediterranean it was around 10%. Closer to the source regions these contributions greatly increase. For example, PM10 concentrations of up to 2000 μg/m^3 have been observed in the city of Beer-Sheva, Negev, Israel, with 10% of the days exceeding 71 μg/m^3, and an average daily net contribution of dust to PM10 of 122 μg/m^3 for the dust days during the period of 2001–2012 (Krasnov et al., 2014). Prospero et al. (2005) reported that around 35 days per year in Barbados recorded African dust contributions higher than 50 μg/m^3, and 7 days exceeded 100 μg/m^3.

Table 1 summarises the findings of a review by Goudie (2014) on desert dust levels. Maximum levels of 43–86, 63–700 and 42–911 μg/m^3 of PM2.5 during dust outbreaks over Southern Europe, Eastern Asia and other regions (Iran, Australia, US, Israel), respectively, are reported, with 43–47, 11–61 and 13–40%, respectively, of the PM10 mass falling in PM2.5. Also, Engelbrecht et al. (2009) reported mean annual data from the Middle East in a range of 72–303 and 35–111 μg/m^3 of PM10 and PM2.5, respectively, with a PM2.5/PM10 ratio of 21–60%. Goudie (2014) also compiled information on maximum PM10 concentrations at receptor sites, ranging from 150 to 2500 μg/m^3 in Southern Europe and from 134 to 3006 μg/m^3 in Japan-China-Taiwan-Korea receptor sites; and at sites closer to sources from 266 to 15,366 μg/m^3 in Australia, 312 to 5000 μg/m^3 in Western Africa, 123 to 65,112 μg/m^3 in North America, and 700 to 5619 μg/m^3 in the Middle East.

5. Size of desert dust

Reid et al. (2003) reviewed and inter-compared methods for characterizing desert dust size distributions and concluded that the median desert dust mass diameter equals to 4.5 ± 1.3 μm (9 ± 2 μm if optical counters are taken into account), with values ranging from 3.0–3.5 ± 0.5–1 μmin remote oceans, Sahara, Algeria, Barbados and Puerto Rico to 5.0–7.0 ± 1 μm in Turkey-Libya, Negev, Canary Islands, Texas, Owens and Tadzhikistan (5 to 13 ± 1.5 to 2 μm with optical counters in the two later groups). Similar modes are reported by Mahowald et al. (2014) for a number of sites around the globe. Mori et al. (2003) determined that the largest mass fraction for the crustal element concentrations in the aerosol collected at Yamaguchi in Japan during an intense *Kosa* episode was in the size range of 3.3–4.7 μm, whereas in Beijing (closer to the Gobi-Taklamakan desert) it was in the range 4.7–7.0 μm in aerodynamic diameter. In a dust episode affecting Australia, > 50% of the TSP fell in the PM10 fraction (Aryal et al., 2012), and 13% of the PM10 fell in the PM2.5 fraction (Jayaratne et al., 2011). Thus, it seems that far from sources, a 3–5 μm mean/median mass-size is very often measured, whereas close to them, 5–7 μm are obtained. These values refer to the mean/median values but obviously when high concentrations of dust are recorded, the finer and coarser size tails influence highly PM2.5 and PM10–20 absolute concentrations. As an example Kandler et al. (2009) found that close to the source points and for the most acute episodes, only 3% of TSP was made of PM10, and < 35% of PM10 was PM2.5. For other dusty days, PM10 to TSP proportions varied from 1 to 9%, and PM2.5 to PM10 ones from 15 to 36%.

Table 1
Ranges of PM10 and PM2.5 maxima levels, and % of PM2.5 in PM10, in sites affected by desert dust outbreaks in different regions of the planet. Data obtained from Goudie (2014) Ranges reflect the lowest and highest maxima values reported for different areas of a given region.

	PM10	*PM2.5*	*PM2.5/PM10*
Region	μg/m^3	μg/m^3	%
Southern Europe	150–2500	43–86	43–47
Eastern Asia	134–3006	63–700	11–61
Australia	266–15366		
Western Africa	312–5000	42-1368	13-40
North America	123–65112		
Middle East	700 to 5619		

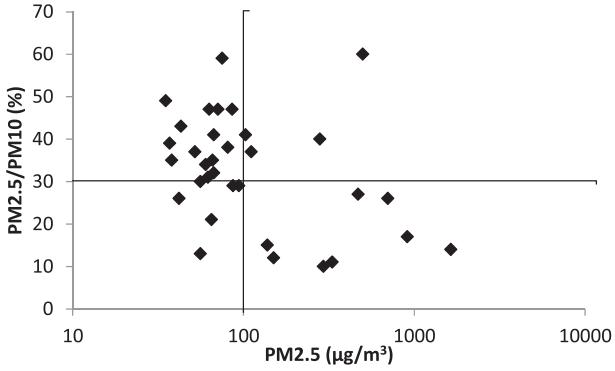

Fig. 4. Cross correlation plot of PM2.5 maximum or annual mean concentrations, as well as % of PM2.5 in PM10 in sites affected by desert dust outbreaks in different regions of the planet. Data obtained from Goudie (2014) for maximum concentrations over the world, Jayaratne et al. (2011) for a dust storm in Brisbane, and Engelbrecht et al. (2009) for annual mean concentrations in Middle East sites.

Fig. 4 includes the data compiled by Goudie (2014) and Engelbrecht et al. (2009) on PM2.5/PM10 proportions from desert dust influenced sites. Taking only PM2.5 concentrations exceeding 100 μg/m^3, in 92% of the cases the proportion PM2.5/PM10 ranges between 10 and 40%, and in 67% of the cases between 10 and 30%; whereas for lower PM2.5 levels the range of percentage of PM2.5 in PM10 is much wider (10–60%). Studies on the ultrafine particle concentrations during dust outbreaks are scarce. Jayaratne et al. (2011) and Wehner et al. (2004) reported data for desert dust outbreaks in Brisbane and Beijing, respectively. Both studies found a decrease in levels of ultrafine particles, probably due to dispersion of local pollution and agglomeration and coagulation of locally emitted ultrafine particles on the abundant dust particles.

6. Dust composition

6.1. The mineral load

Mineral dust is typically made up of crustal components (Table 2) such as quartz (SiO_2), a large variety of clay minerals (kaolinite, illite, chlorite/clinochlore, montmorillonite/smectite and palygorskite/vermiculite), Ca (Fe, Mg) carbonates, Na/K/Ca feldspars-plagioclase, Fe-oxides (goethite, hematite, magnetite), and a variable proportion of salts such as gypsum (Ca-sulphate) (Coudé-Gaussen et al., 1987; Schütz and Sebert, 1987; Molinaroli et al., 1993; Gomes, 1990; Sabre, 1997; Caquineau, 1997; Caquineau et al., 1998; Avila et al., 1997; Moreno et al., 2006; Formenti et al., 2008; Claquin et al., 1999; Scheuvens et al., 2013; Nickovic et al., 2012; Journet et al., 2014, Scanza et al., 2015; Ito

Table 2
Minerals typically present in desert dust. Asterisks indicate abundance: ***** very high (tens of wt%) to * low (< 1 wt%).

Silicates & aluminium-silicates	Silicates	Quartz	SiO_2 (mineral grains or diatomea fragments)	*****
	Clay minerals	Kaolinite	$Al_2Si_2O_5(OH)_4$	****
		Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$	****
		Chlorite	$((MgFe)_5Al)(AlSi_3)O_{10}(OH)_8$	***
		Palygorskite	$(Mg,Al)_2Si_4O_{10}(OH)\cdot 4(H_2O)$	***
		Montmorillonite	$(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2\cdot nH_2O$	***
	Feldspars	Albite	$NaAlSi_3O_8$	**
		Anorthite	$CaAl_2Si_2O_8$	**
		Microcline/orthocl.	$KAlSi_3O_8$	**
	Other silicate	Zircon	$ZrSiO_4$	*
		Hornblende	$Ca_2(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH)_2$	*
Carbonates	Ca & Mg carb.	Calcite	$CaCO_3$	****
		Dolomite	$(CaMg)_2CO_3$	**
Oxides	Iron oxides	Hematite	Fe_2O_3	**
		Magnetite	Fe_3O_4	*
		Goethite	α-FeO(OH)	**
	Other oxides	Anatase & rutile	TiO_2	*
Salts	Chlorides	Halite	NaCl	*
	Sulphates	Gypsum	$CaSO_4.2H_2O$	**
		Tenardite	Na_2SO_4	*
		Epsomite	$MgSO_4$	*
Phosphates		Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	*

and Wagai, 2015). Fresh water diatomea skeletons are also a frequent component of African dust (Darwin, 1845; Ehrenberg, 1862; Moreno et al., 2006; Querol et al., 2008). Journet et al. (2014) provide estimates of soil mineralogy at global scale for the clay and silt size ranges of the soil sediment. Note that the emitted dust is a mixture of clay and silt size particles or aggregates of particles. In the clay size fraction (< 2 μm), phyllosilicates are the main mineral components (63–71% in most desert areas and 80–83% in those from N. Africa, Fig. 5). Quartz contents vary much less, with 3–5% in all regions, as free iron oxides minerals do (3–5%, Fig. 5). Calcite contents range in 2–4% in most areas and 6–9% in Asia, Sahara and M. East dust (Fig. 5). Concerning the clay minerals, illite content is relatively homogeneous, making up 25–29% of the clay minerals, whereas kaolinite 36–42% of the clay content in most areas and 49–51% in S. African and S. American dust. The variation of the contents of smectite is reverse to the one of kaolinite, with 20–26 and 10–11% of the clay minerals of these regions, respectively (Fig. 5). In the silt size range (~2 to 50 μm) calcite, quartz and feldspars are the key minerals, with an increased dominance of quartz and feldspar with particle size.

Many of the above experimental and modelling studies have shown that kaolinite, quartz and hematite prevail in the Sahel region, whereas illite-palygorskite, quartz, and calcite dominate Saharan dust composition. Experimental data on North-eastern China desert dust proved that this is made of illite, kaolinite (around 47–52% total clay content), quartz (25–27%), feldspar and plagioclase (6–7%), calcite and dolomite (13–18%), with traces of gypsum, hornblende (an Al-silicate), and halite (NaCl) (Shen et al., 2009). Engelbrecht et al. (2009) reported that dust from Middle East-Central Asia was made up also by quartz, other silicate minerals, carbonates, oxides, sulphates, and salts in various proportions. In comparison with the Sahara, China, US, and world dusts (Goudie and Middleton, 2006 and Labban et al., 2004), Middle East samples had lower SiO_2 and higher CaO and MgO contents (the latter present as carbonate minerals); however, Fe- and Mn-oxides occurred in lower contents. Australian desert dust is made up of a composite mixture of quartz, anatase (TiO_2), calcite, feldspars, halite, hematite, and clays (kaolinite, illite-muscovite and montmorillonite) (Aryal et al., 2012). Thus, concerning the mineral load of dust outbreaks it is mainly made up of quartz, a variety of clays, with a lower content of ions (K^+, Fe^{2+}, Mg^{2+}, Cl^-, F^-) in their frameworks as increasing the degree of weathering of the geological terrains, and variable contents of carbonate minerals (mostly calcite and dolomite), iron oxides and salts, such as gypsum. Accordingly, the major oxides madding up the dust are SiO_2, Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, Na_2O, TiO_2, MnO and P_2O_5. Relatively high contents of dust related elements, such as Ti, Mn, Rb, V, Cr, Li, Sc, Be, Rare Earth Elements, among others, can be also expected compared with non-dust days data.

6.2. Mixtures of anthropogenic pollutants and desert dust

In addition to the mineral matter (typically the dominant PM component during dust outbreaks), the anthropogenic PM contribution may be significant. The following processes might give rise to an increase of the anthropogenic PM load of the dust: i) specific desert areas with nearby anthropogenic emission sources, such as the large petrochemical and power plants and industrial states present in Northern Africa, China, and Middle East deserts (Moreno et al., 2010; Pérez et al., 2010; Rodríguez et al., 2011); ii) the transport of aged air masses from highly polluted regions towards or through deserts might cause their interaction with dust particles, and also the deposition of anthropogenic pollutants that subsequently are re-suspended with dust (Kallos et al., 1998, 2008; Gangoiti et al., 2006; Chin et al., 2007); iii) relatively unaltered dust particles are transported towards areas with high anthropogenic emissions and interactions of organic and inorganic pollutants and sea salt with mineral dust particles might occur locally in the receptor area, or before arriving to the receptor area (Levin et al., 1996; Zhang et al., 2003; Alastuey et al., 2005; Hwang and Ro, 2006; Sullivan et al., 2007; Tobo et al., 2009; Abdelkader et al., 2015), having a major role in the mineralogy of the dust particles (Krueger et al., 2004); and iv) as stated above, according to Pandolfi et al. (2014), the PBL height is progressively reduced with increasing intensity of dust outbreaks (due to the lower incident radiation reaching the surface, thermal inversions or subsidence flows), thus causing a progressive accumulation of anthropogenic pollutants and favouring the increase of concentrations, or even the formation of new fine particles, and also the condensation of health relevant species on dust particles surface.

The above four processes might enrich dust PM with sea salt and anthropogenic pollutants, increasing the hygroscopicity of particles and also the load in organic pollutants, sulphate, nitrate, ammonium, black or elemental carbon (BC or EC) and metals, which in turn might increase the health impact of dust outbreaks. There is large body of literature on these issues, mainly concerning to process of enrichment, reactions, and comparison of levels of co-pollutants between dust and non-dust days, but not much on their actual effects on the impacts on human exposure and health.

Long data series of PMx and gaseous pollutants analysed by Pandolfi et al. (2014) revealed very high non-dust PM1, CO and NO_2 levels

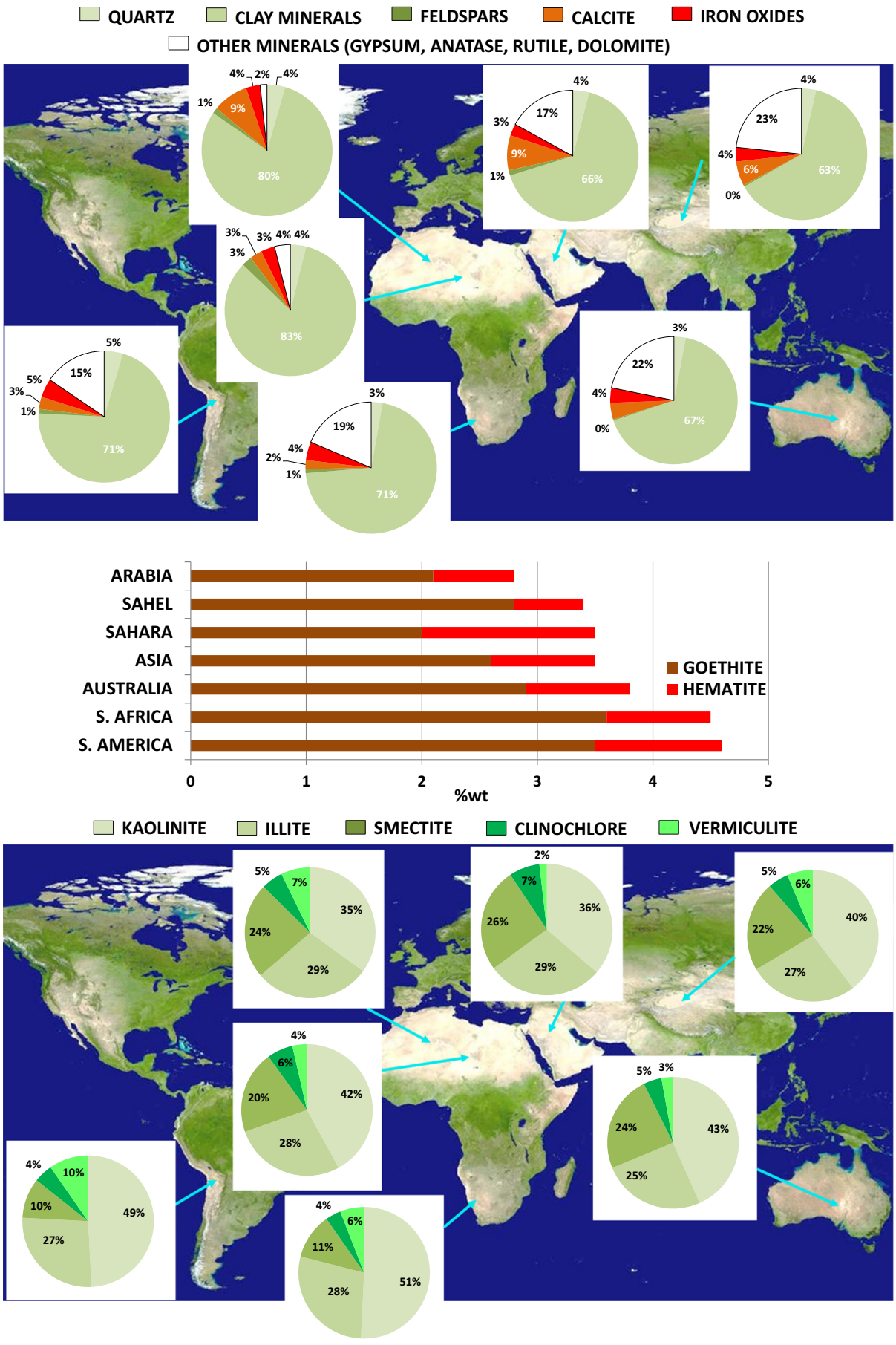

Fig. 5. Mineralogy of desert dust from different regions. Top: content of different mineral groups, in wt%. Middle: content of free iron oxide minerals, in wt%. Bottom: proportion of different minerals to the above contents of clay minerals. Data from Journet et al. (2014) on mineralogy of desert dust modelled from soil

during the most intense dust episodes over Barcelona (NE Spain), attributed to the thinning of the PBL caused by the dust events. Also long data series of PMx speciation in the Western Mediterranean evidenced the marked increase of sulphate and nitrate levels during African dust outbreaks over Spain (Querol et al., 2001, 2019; Galindo et al., 2008; among others). Over the Canary Islands, in July 2002, sulphate levels of around 3.7 and 2.5 μg/m^3 were measured in TSP and PM2.5 in the dust plume in the free troposphere, whereas 25 and 8.3 μg/m^3 were obtained simultaneously at surface levels for the same period (Alastuey et al., 2005), suggesting the interaction of dust with locally emitted gaseous S-bearing pollutants. Li et al. (2012) demonstrated that surface levels of HNO_3, SO_2 and O_3 decreased by up to 90, 40 and 30%, respectively during *Kosa* events in 2010, due to the heterogeneous reactions on dust particles. Kandler et al. (2009) reported that the hygroscopicity of the finer dust particles (< 0.72 μm) increased by a factor of two in a Morocco June 2006 episode, due to an increased load of ammonium sulphate ($(NH_4)_2SO_4$), as a main component of the anthropogenic aerosol. In China and Japan the simultaneous increase of sulphate, nitrate and dust was already reported by Mori et al. (1999) and Arimoto et al. (2004) and Wang et al. (2005), among others; and Huang et al. (2009) described the pathways of sulphate enhancement by natural dust in China.

Concerning organic aerosols, in Barcelona, Querol et al. (2019) reported also an enrichment of organic carbon during African dust outbreaks compared to non-dust days, although this enrichment was much less marked than for sulphate. Garrison et al. (2006) suggested that Saharan dust might act as a carried of persistent organic pollutants, metals (Pb in their specific study), and microbes to the Caribbean. In fact, some organic persistent pollutants, such as pesticides have been described to be potentially emitted from desert areas such as the Aral Sea (Ataniyazova et al., 2001; O'Hara et al., 2000). García et al. (2017) reported long data series on organic speciation of dust in the free troposphere over the Canary Islands, on his way to the Caribbean, and they identified levoglucosan, dicarboxylic acids, saccharides, n-alkanes, hopanes, polycyclic aromatic hydrocarbons and organic compounds formed after oxidation of α-pinene and isoprene; and revealed a high correlation of secondary organic and inorganic aerosols during dust episodes.

Concerning the enhancement of anthropogenic metals during dust episodes, Querol et al. (2019) by interpreting long datasets of PM10 speciation in the city of Barcelona showed an enrichment of elemental carbon metals from local road traffic (Sb, Sb, Cu, Zn) and industrial sources (As, Pb, Mn) during dust days, again probably due to the thinning of the PBL. Ho et al. (2019) found an increase of biorecativity of particles during dust episodes in Xi'an, China, due to increase of metals from local emissions. Garrison et al. (2014) reported that Inhalable PM from dust episodes in Bamako, Mali, was enriched in transition metals, known to produce reactive oxygen species and initiate the inflammatory response, and other potentially bioactive and biotoxic metals/metalloids. They found that most enriched metals/metalloids were likely emitted from oil combustion, biomass burning, refuse incineration, vehicle traffic, and mining activities. Moreno et al. (2010) measured the composition of a dust outbreak plume leaving Western Africa over the Atlantic and showed that the La/Ce/Sm rates obtained for specific 24 h samples approached the typical ones from oil refining using the La-cracking process and not the typical dust-crustal Rare Earth Element ratios. Ravelo-Pérez et al. (2016) found also that Fe solubility from dust collected over the Canary Islands increased with the aging of dust particles. The Fe solubility rose from 0.5% in the pure Gobi dust to 3–5% in the Northwestern Pacific, resulting from oxidization of SO_2 on dust particles (Li et al., 2012). Radionuclides from nuclear accidents (Chernobyl), regions were nuclear test were carried out in the past, and uranium mining areas, seem to be enriched in desert dust from some regions (Papastefanou et al., 2001; Ogorodnikov, 2011; Csavina et al., 2012; among others).

There is a small body of evidence that the non-dust load of PMx during dust outbreaks over Spain might be very relevant, even more relevant that the miner dust PMx load, when evaluating the health effects of African desert dust outbreaks over the Western and Central Mediterranean (Pérez et al., 2012). Based on this in the last section of this article we propose a monitoring strategy that allows measuring bulk PMx concentrations during dust episodes and calculate the mineral dust PMx and the non-dust PMx, and thus evaluate health effects for these three components, and in later case compare the effect modification with bulk PM during non-dust days.

6.3. The bio-aerosol load

Goudie (2014) reports at least 11 studies on biological material in dust storms from Kuwait, Iraq, Iran, West Africa, Taiwan, Japan, Korea, Israel, Southern Europe and Turkey for the period 2006–2013; 14 were reported by Griffin (2007) for prior years. According to Griffin (2007), Griffin and Kellogg (2004) and Kellogg and Griffin (2006) this biomaterial consist of pollen spores, bacteria, fungi and viruses, that are capable of surviving during long-range transport of dust and then dispersed globally. Many of these have potential health implications (Griffin, 2007).

African dust storms over Southern US have been known as an exposure pathway for various fungal diseases including *coccidioidomycosis* (Williams et al., 1979). Microorganisms are present in African dust transported towards the Atlantic and Caribbean (Griffin et al., 2003; Kellogg et al., 2004; Prospero et al., 2005; Kellogg and Griffin, 2006; Weir-Brush et al., 2004), also in Australian dust outbreaks (Lim et al., 2011). In Taiwan, ambient air aspergillosis fungi peak events were attributed to the effect of Gobi dust storms (Chao et al., 2012). Polymenakou et al. (2008) identified 23 microorganisms and pathogens in winter African dust outbreaks over the Eastern Mediterranean, both in the fine and the coarse PM factions. Sánchez de la Campa et al. (2013) found a low microbial biodiversity associated with the African dust over Southern Spain, dominated by Firmicutes and Proteobacteria and results suggested that the transported microbes were alive or present as spores that germinated under favourable conditions. These cultivable microbes in the form of spores were highly resistant to desiccation, heat, and UV light. Favet et al. (2013) concluded that few pathogenic strains were found in the Bodelé dust (Sahel), suggesting that bioaresol in African dust is not a large threat to public health. In any case, Schuerger et al. (2018) recently reported on science questions and knowledge gaps to study microbial transport and survival in Asian and African dust plumes reaching North America.

It seems that only in some cases a direct relation between the bioaerosol load of dust storms and health effects are demonstrated. In Japan Watanabe et al. (2011a, 2011b) found a relationship between asthma and pollen in *Kosa* dust air masses, not so clear during dust days without pollen. Metcalf et al. (2012) reported the occurrence of cyanotoxines in desert dust. *Coccidioides* (*C. immitis* and *C. posadasii*) fungi cause Valley fever (coccidioidomycosis or cocci) when inhaled (Pappagianis and Einstein, 1978; Leathers, 1981; Comrie, 2005; Zender and Talamantes, 2005). Anderson (2013) reported 150,000 cases/year in US. According to Sprigg (2016) the exact location of these endemic fungi in North America is poorly known, but these occur in alternately damp and dry soils of hot areas of US. Also according to this author, it is clear that the *Coccidioides* fragments (3–5 μm) might be transported with dust, from North American desert areas to neighbouring populated areas, and he gave a number of references reporting of dust-Valley fever outbreaks in Mexico and Southern US regions, reaching even the Washington State (Litvintseva et al., 2015). As an example, Pappagianis and Einstein (1978) attributed 379 cases of Valley fever in California to a dust outbreak. Nguyen et al. (2013) reviewed the state of the science of the Valley fever.

The broad spatial pattern and seasonality of meningitis epidemics in the African Sahel (Sultan et al., 2005; Martigny and Chiapello, 2013) suggests that certain environmental factors, such as low absolute

humidity (Cheesbrough et al., 1995; Molesworth et al., 2003) and relative humidity (Dukic et al., 2012), temperature (Dukic et al., 2012) and dusty atmospheric conditions (Sultan et al., 2005; Thomson et al., 2006, 2009; Agier et al., 2013; Deroubaix et al., 2013; Pérez García-Pando et al., 2014; Sprigg, 2016) play an important role. Identifying the specific climate factors that drive meningitis epidemics is challenging because many environmental variables have a prominent seasonal cycle that co-varies with disease incidence, and the effects of climate and dust on the pathogenesis and transmission of the bacteria have not been studied in vivo. The most accepted hypothesis is that the transition from endemic to ubiquitous hyperendemic conditions would be caused by an increased risk of invasion of a virulent strain due to damage of the pharyngeal mucosa by dry and dusty climate (Thomson et al., 2006, 2009; Pérez García-Pando et al., 2014).

7. What might cause health effects during desert dust and what should be monitored of a dust outbreak to evaluate its potential health effects?

7.1. Possible causes of health effects of desert dust

Based on the review outputs of prior sections, we provide in this section a short overview of the dust-related scenarios that have a direct or indirect potential relationship with health effects. The first potential health impact might be related with the high concentrations of mineral dust, exceeding 1000 μg/m^{3}of PM10 on a daily basis close to emission areas, but also daily concentrations reaching up to 400–600 μg/m^{3}of PM10 at receptor sites influenced by dust transport (see prior section on dust concentrations). Furthermore, Derbyshire (2007) proposed that acute exposure to mineral dust can, at its extreme, cause silicosis ("desert lung" syndrome). As also evidenced in prior sections, desert dust grain size modes reach 3–7 μm in most cases, so that the most influenced size is PM10; however for high concentrations of dust, even if the proportion of PM2.5 in PM10 reaches only 5–35%, the PM2.5 absolute concentration might be very high as well (see particle size distribution above).

Another cause of health impacts of dust outbreaks might be related with the anthropogenic load of dust outbreaks. As stated abive, this man made pollution load of dust outbreaks can be attributed to the following processes: i) co-emission of anthropogenic pollutants with dust in specific areas (i.e., large petrochemical plants in Northern Africa, Rodríguez et al., 2011); ii) co-transport of pollutants with dust (i.e., Chinese industrial and urban pollution incorporated into the high dust air mass during *Kosa-Yellow Dust* episodes from Taklamakan desert towards the Pacific Ocean (Kang and Kim, 2014; Majbauddin et al., 2016; Kim et al., 2012, Onishi et al., 2012), or the mix of European pollution and dust caused by Northern air mass fluxes affecting the Mediterranean Basin and transporting the polluted air masses over Libya and Algeria, Kallos et al., 1998, 2008; Gangoiti et al., 2006); iii) coating of dust with anthropogenic pollutants due to chemical and physical interactions of mineral dust with local pollutants emitted in the receptor region where dust arrives (Levin et al., 1996; Alastuey et al., 2005); and iv) concentration of locally emitted pollutants caused by the decrease of the thickness of the PBL during dust outbreaks (Pandolfi et al., 2014, see prior sections on the causes of the thinning of the PBL during dust episodes).

These four processes might result in an increase of the PM2.5 and PM1 fractions, but it is also possible that coarse particles (PM2.5–10) become coated or mixed with anthropogenic pollutants.

A third cause of the possible health impacts of dust is the biological and microbiological load of dust. Examples are the asthma episodes during dust outbreaks loaded with pollen over Japan (Watanabe et al., 2011a, 2011b), the impact of dust loaded with the fungi *coccidioidomycosis* on Valley fever in US dry regions (Williams et al., 1979), and other potential effects caused by microorganisms present in desert dust (viruses and bacteria among others, Griffin, 2007). See the section on bio aerosols reported in prior sections.

7.2. Parameters to be monitored to evaluate health impact of desert dust outbreaks

The first indicator to be used is the mass of PM10 (highly affected by dust outbreaks, most of them with PM modes from 3 to 7 μm as reported in prior review sections). However, this will include both the desert dust and the anthropogenic PM mixed or transported with dust. If PM2.5 is added to the monitoring, the ratio PM2.5/PM10 will provide the load of fine particles that in part might be attributable to anthropogenic pollution. However, PM2.5/PM10 ratios in pure mineral dust might also vary as a function of the source area and the transport pathways and duration. Most of the anthropogenic PM pollution falls in the PM2.5 fraction and if increased it will increase the PM2.5/PM10 ratio.

To evaluate the direct health effects of desert dust, the best indicator would be the net mineral load of PM10 dust during dust outbreaks. Chemical speciation of PM10 samples collected using high or low volume samplers can provide the mineral dust load. Low volume samplers equipped with Teflon® filters and subsequent analysis by XRF might be a good approach. If wet chemistry is used for the analysis of PM samples (ICP-AES or ICP-MS), be aware that sample digestion methods for desert dust require the use of hydrofluoric acid (HF) in the sample dissolution procedure. Otherwise silicates and aluminium silicates will not be dissolved (Querol et al., 2001). Also note that when HF is used and evaporated before introducing the sample in the spectrometers, Si is lost. If wet chemistry is the only available tool for chemical analysis, we recommend using quartz microfiber filters, high volume samplers, $HF:HNO_3:HClO_4$ digestion, evaporation of HF, and calculation of SiO_2content from the experimental Al_2O_3*2.5 to 3.0 (Querol et al., 2001; Alastuey et al., 2016). There are also online XRF analysers that might supply concentrations of dust elements on a 15 min to 1 h basis if required, but the costs of the instrument (approx. 150 K€) and its maintenance are high in the order of 10 K€ a year. These procedures might result in large monitoring expenses because daily PM10 samples shall be analysed. To avoid these costs, Escudero et al. (2007b) developed a statistical approach based on the evaluation of PM10 mass concentration measured at twin stations (an urban and a close by remote or regional background site). See in the next section the description of the method.

Furthermore, modelling outputs for surface dust concentrations might also be used as reference parameters for health studies. We caution that although these models have improved significantly their performance in recent years, current uncertainties to reproduce the actual PMx surface concentrations may still be too large for accurate health studies. However, modelling outputs are basic to detect the occurrence of dust outbreaks (also supported by surface PM concentration data), to evaluate the source region of dust and the transport pathways, as well as the thickness and dust load of the atmospheric dust layer to evaluate possible effects of reducing the PBL depth, and consequently on the concentration of local pollutants. Models are especially relevant for forecasting dust episodes to inform the most susceptible population and/or allow preparations for more detailed measurements during the episode.

In addition to the mineral dust load, levels of metals and other inorganic and organic pollutants with specific interest in health studies might also be analysed when dust arises from highly polluted regions or is transported over them before reaching the dust receptor site.

For specific areas where the biological (fungi, pollen, bacteria, viruses) dust load might be relevant for health effects, it is also recommended to evaluate it. Prospero and Lamb (2003) reported a large range of ratios for microorganisms and dust concentrations for the different dust outbreaks. In specific areas, such as the Valley fever regions in US and the north African high meningitis region, the control of the biological load of dust might be very relevant to evaluate or discard

health effects of dust. It is important to note that the effect of dust in the development of specific health problems might be indirect, such as favouring transmission of pathogens in intense episodes when population is preferentially confined to indoor environments, of the deterioration of epithelia and other pathogen barriers due to their damage by extremely high dust concentrations (Thomson et al., 2006, 2009; Pérez García-Pando et al., 2014).

Finally, in this section it is also relevant to state that the review presented above indicates that atmospheric dust layers over receptor regions influenced by long range dust transport might reach a thickness of several kilometres. In many cases dust might not directly affect the surface, but affects indirectly by reducing the PBL depth by a relevant proportion (up to 40% as a mean for the most intense dust episodes over Barcelona, Spain, Pandolfi et al., 2014) than in turn might cause an increase inof the concentration of local pollutants at surface levels. Therefore, models, sounding or LIDAR measurements might help detecting the presence of high altitude and thick atmospheric dust layers, even if dust concentrations at surface are low. This is usually frequent in summer over the Canary Islands. Under this scenario it may also be relevant to evaluate the PM health effects of high anthropogenic PM levels.

Based on the above key parameters and process that might be of relevance for monitoring the desert dust impact on air quality in health studies and to protect population, in the next section we describe a desert dust alert and monitoring system that might be implemented in region affected by this air quality problem.

8. Desert dust alert and monitoring systems for health studies and air quality management

Besides the above scenarios we consider that desert dust alert and monitoring systems might be a very powerful tool for i) alerting the most sensible or exposed population to air pollution to take special measures to protect themselves from high desert dust exposure levels; ii) alerting in advance the administrations to take special measures to reduce local/regional atmospheric emissions to abate anthropogenic pollutants that might be intensively concentrated during dust outbreaks; iii) to obtain reliable data on exposure to anthropogenic pollutants and desert dust to evaluate health effects of PMx and its different mineral and non-mineral components during dust outbreaks.

We describe here the monitoring and alert systems build up by Spain and Portugal, which operates continuously since 2001. This system is made up of three modules allowing the forecasting and subsequent demonstration of the occurrence of desert dust events, as well as the quantification of the daily desert dust contributions to PM10 and PM2.5 ambient concentrations.

8.1. The forecast system

The forecast or alert module mainly consists of two concatenated tasks.

The first one consists in obtaining forecast air mass back-trajectories using different tools such HYSPLIT (NOAA, Stein et al., 2015) or FLEXPART (NILU, Stohl et al., 2005), among others, to detect the transport of African air masses over the receptor areas of Spain and Portugal (see Fig. 6 as an example for Spain) from which data will be reported.

The second one is based on evaluating free available outputs from different modelling teams for the emission, transport and surface desert dust concentrations. To this end we recommend using the information provided the WMO (World Meteorological Organization) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS, http://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html), consisting in a model inter-comparison and evaluation of desert dust forecasts, with three regional centres, one for Northern Africa, Middle East and Europe; another for China, Japan and South Korea; and another for the Americas and Barbados. This system provides comparable modelling output information from a large number of research teams. Table 3 as an example summarises the models and contact details for the models included by the Regional Centre for of Northern Africa, Middle East and Europe. We recommend taking daily information on the forecast of the different models included in one of the three regional centres, depending on the location of the receptor region, in order to obtain an expert evaluation and recommendation for the forecast of dust outbreaks and feed the first module of the alert system. The Spanish-Portuguese system sends by email to a large list of air quality stake holders the report of the forecast 24 h in advance of each event. The forecast is also updated in the websites of the respective ministries of environment. See at https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/calidad-del-aire/evaluacion-datos/fuentes-naturales/default.aspx, the case of Spain, as an example.

8.2. Validation and reporting on the occurrence of desert dust episodes

We built up a very important module for the demonstration of recent (the year under evaluation) dust outbreaks that consists of three consecutive sub-tasks: i) evaluating the data provided from a network of surface regional background or remote air quality monitoring stations reporting online PM10 and PM2.5 concentrations in order to demonstrate or discard the occurrence of dust episodes (for Spain and Portugal this is made by a network of 25 remote stations, Fig. 6); ii) running air mass back trajectories with the above tools with validated meteorological data for recent dust outbreaks in order to demonstrate or discard the occurrence of dust episodes; iii) evaluation of the above model outputs but this time focusing on validated outputs and not on the forecast ones.

For the actual validation and reporting on the demonstration of the occurrence of the desert dust outbreaks for each of the regions considered, as reported in Fig. 6 (see https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/episodiosnaturales2017_tcm30-482151.pdf as an example for the 2017 annual report for Spain) we developed a module for the calculation of the daily desert dust contribution to ambient air PM10 and PM2.5 levels (Escudero et al., 2007a, 2007b; EC, 2011) involves the five tasks described below.

First, we collected daily data of PM10 and PM2.5 levels measured at the network of regional background or remote air quality monitoring stations reported in Fig. 6. Following this, at each of the reference sites, we exclude the levels of PM10 or PM2.5 of the dust days and then calculate the 30 days moving 40th percentile (originally was a 30th percentile, but later the method was modified to be accepted as a reference method by the EC, EC, 2011) for these days, with the specific dust day being in position 15 of the 30 moving average. This 40th percentile value for the dust day will be equivalent to the PM10 background without the dust contribution. Obviously, methods using other approaches, such as chemical speciation or other statistical approaches might be applied to this end. For example Barnabaa et al. (2017) do not use the regional background monitoring data but they modified the method by applying it directly to the individual urban background sites for which dust loads are calculated and by reducing the number of days for the moving average percentile. In a third step, we subtract this background PM10 value to the bulk PM10 concentration to obtain the net mineral dust PM10 load.

Following these calculations, in a given urban twin (of a given reference remote station) site we obtain the urban PM10 concentration for a given dust day, and we subtract from this the net dust PM10 load as obtained in the reference site for this day to obtain the anthropogenic PM10 load during the dust day. Thus according to the results of our review reported in the first sections on health relevant parameters when monitoring air quality in desert dust outbreaks, these three parameters (bulk PMx, net dust load in PMx, and the non-dust fraction of PMx during the specific dust day, as non-dustPMx = PMx-dustPMx) might

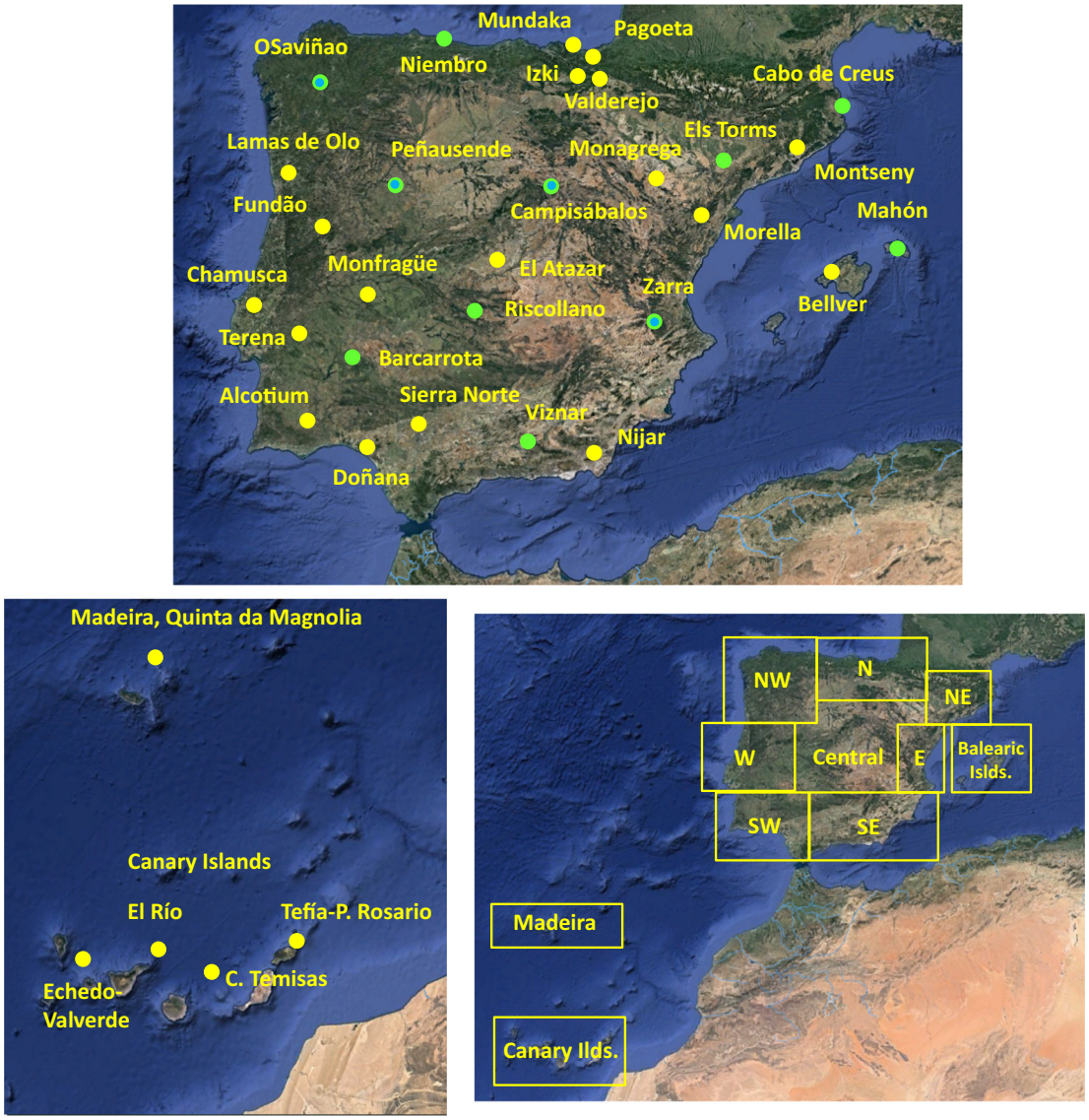

Fig. 6. Right: zones for specific reporting on the forecast and occurrence of African dust outbreaks over Spain and Portugal. Top and left: regional background air quality monitoring sites reporting PM10 and PM2.5 surface concentrations for the demonstration of African dust outbreaks over Spain and Portugal for the daily calculation of PM10 and PM2.5 desert dust contributions to ambient particulate levels. Yellow dots, indicate monitoring sites from the regional air quality monitoring network; green dots, EMEP monitoring sites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

be used independently in cross-over studies or other health related studies in providing basic information for air quality policy actions. Epidemiological studies with PMx from urban areas should also evaluate health effects of PMx during desert dust episodes compared with non-desert dust episodes, but also health outcomes derived from desert dust PMx and from non-dustPMx during desert dust episodes, and how the later compare with health outcomes for PMx in non-dust days.

Also according with the review presented in the first sections, and additionally to these modules, others such as the one on the characterisation of the bio-aerosol load, the chemistry of PM or the use of instrumentation for the characterisation of the PBL depth or the thickness of the dust layer (such as LIDAR and ceilometers) can be also implemented to monitor direct and indirect effects on health of dust outbreaks. According also with the review of the first sections, the monitoring of the height of the PBL during and out of the desert dust episodes in the receptor site might give very relevant information to interpret the air quality data and the possible causes of marked increases of local pollution during dust outbreaks. To this end ceilometers might yield very valuable information (Gobbi et al., 2019, and references therein; among others).

This system can also be used for alerting populations and also to implement some exposure abatement measures, such as reducing local emissions of pollutants, washing and sweeping dust from streets after intense episodes to avoid resuspension by road traffic.

8.3. Source apportionment with receptor modelling

Another possible approach to characterize the daily dust PMx and non-dust PMx load during and out of desert dust outbreaks is the implementation of source apportionment analyses based on receptor modelling (Zheng et al., 2005; Zhao et al., 2006; Song et al., 2006; Yuan et al., 2008; Nicolás et al., 2008; Amato et al., 2016; Cardoso et al., 2018; Ho et al., 2019; are examples). This is based on the sampling and chemical analysis of PMx (see sections above on sampling and analytical requirements needed to proper accounting for mineral dust when analysing PMx). For epidemiological analysis it is necessary having long

Table 3
List of modelling tools (and institutions, domains and contact details) included in the Regional Centre for Northern Africa, Middle East and Europe of the WMO SDS-WAS.

Model	Institution	Domain	PI or contact
BSC-DREAM8b_c2	BSC-CNS	Regional	Sara Basart < sara.basart@bsc.es >
CHIMERE	LMD	Regional	Laurent Menut < menut@lmd.polytechnique.fr >
LMDzT-INCA	LSCE	Global	Michael Schulz < michael.schulz@geo.uio.no >
CAMS-ECMWF	ECMWF	Global	Angela Benedetti < Angela.Benedetti@ecmwf.int >
DREAM-NMME-MACC	SEEVCCC	Regional	GoranPejanovic < goran.pejanovic@hidmet.gov.rs >
MONARCH[a]	BSC-CNS	Regional	Carlos Pérez García-Pando < carlos.perez@bsc.es >
MetUM	Met Ooffice	Global	Malcolm Brooks < malcolm.e.brooks@metoffice.gov.uk >
GEOS-5	NASA	Global	Arlindo da Silva < arlindo.dasilva@nasa.gov >
NGAC	NCEP	Global	Jun Wang < Jun.Wang@noaa.gov >
EMA REG CM4	EMA	Regional	Ashraf Zakey < ashraf.zakey@yahoo.com >
DREAMABOL	CNR-ISAC	Regional	Alberto Maurizi < a.maurizi@isac.cnr.it >
WRF-CHEM	NOA	Regional	Emmanouil Flaounas < flaounas@noa.gr >
SILAM	FMI	Global	Mikhail Sofiev < mikhail.sofiev@fmi.fi >
WRF-Chem	NOA	Regional	Vassiliki Kotroni < kotroni@meteo.noa.gr >
LOTOS-EUROS	TNO	Regional	Astrid Manders-Groot < astrid.manders@tno.nl >

[a] Previously known as NMMB/BSC-Dust.

data series and to carry out cross over studies for short term effects, and multi-annual averages to evaluate long term effects. Due to the high costs of these long term source apportionment studies, multiyear source apportionment data are not very common in desert dust affected regions. Most of the studies cover one year or less, and use multivariate receptor models because the availability of libraries on emission chemical profiles is very limited. The most common receptor model used nowadays is Positive Matrix Factorization (PMF, Paatero and Tapper, 1994), whose version 5 (Norris and Duvall, 2014) might be free downloaded from the US-EPA.

Most of the studies in urban areas identified, bulk Al, Si, Ti, Fe, and K concentrations as tracers of desert dust (Querol et al., 2001; Zhao and Hopke, 2004; Yuan et al., 2008; Nicolás et al., 2008; Amato et al., 2016; Cardoso et al., 2018; Ho et al., 2019). Chloride, sea-salt-Na^+, -Mg^{2+} and -SO_4^{2-} trace the sea salt contribution; Vi-Ni and SO_4^{2-} (and in some cases a low Ce/La rate) the one from fuel-oil combustion and petrochemical emissions; soluble K^+ and polysaccharides the one form biomass burning; As and Se the one from coal combustion; EC OC, Cu, Ba, Zn, Sb the one from road traffic; Cu, As, Pb, Zn, Fe, Mn, or some of them, metallurgical emissions; among others (Zhao and Hopke, 2004; Nicolás et al., 2008; Yuan et al., 2008; Amato et al., 2016; Ho et al., 2019).

Focusing on dust, and in urban areas, the ratios Ca/Al, Fe/Al, K/Al and Si/Al might widely vary among the different source regions (see section on compositional patterns of dust from the first sections). This is an important inconvenience for source apportionment, because a constant chemical profile is required to properly identify relevant sources, but these geography tracing patterns can be used to identify source areas for the dust outbreaks that might complement the back-trajectory analysis. As examples, high free-Fe/Al and low Ca/Al have been reported for dust outbreaks from Sahel, whereas high Ca/Al were measured for Saharan dust outbreaks (Chester et al., 1971, 1993; Chiapello et al., 1997; Moreno et al., 2006, among others), and high Ca/Al was used as a tracer of Western China deserts in PMx from Beijing, while lower ratios pointed to a Northern China desert origin (Yuan et al., 2008). Other tracers of source regions for dust are stable isotopes and radionuclides (Papastefanou et al., 2001; Aba et al., 2018; Goudie and Middleton, 2006, and references therein; among others) (see also section on compositional patterns of dust).

In spite of the high potential of the source receptor models it is important to note that this tool is very useful for receptor sites where the impact of dust outbreaks on air quality is frequent and severe. In urban areas relatively far from the dust emission sources where other important sources of non-desert dust are common, problems of compositional co-linearity might difficult separating local soil dust or urban dust from desert dust. Thus, Amato et al. (2016) carried out simultaneously a source apportionment analysis in five Mediterranean cities, and they were only to individually apportion for contributions of desert dust with this chemically based source receptor approach in one of the cities, the most heavily impacted by dust outbreaks. For the other four cities the 40th percentile method described above had to be applied to identify desert dust outbreaks and quantify the net desert dust loads. Nicolás et al. (2008) were able to identify individually urban dust and desert dust in Elx (E Spain); Zheng et al. (2005), Zhao et al. (2006), Yuan et al. (2008), and Ho et al. (2019); among others, in several Chinese cities; and Cardoso et al. (2018) in Cabo Verde. Usually, urban dust is having a very high Ca/Al and Fe/Al as compared to desert dust (see again section on compositional patterns above and Querol et al., 2019). A possible solution to properly identify and quantify desert dust contributions using receptor modelling in urban areas with high dust load is implementing the analysis in a reference rural/remote site close to the population where the epidemiological study is going to be carried out.

It is also important to highlight that the receptor modelling tool might be a very relevant one to validate the results obtained with the statistical method described in the prior section.

Acknowledgements

The systematic review was funded by WHO with as part of a Grant Agreement with Ministry of Foreign Affairs, Norway. Thanks are also given to the Spanish Ministry for the Ecological Transition for long term support in the last 2 decades to our projects on African dust effects on air quality over Spain; to the Spanish Ministry of Science, Innovation and Universities and FEDER Funds for the HOUSE project (CGL2016-78594-R), and to the Generalitat de Catalunya (AGAUR 2017 SGR41). Carlos Pérez García-Pando acknowledges long-term support from the AXA Research Fund, as well as the support received through the Ramón y Cajal program (grant RYC-2015-18690) of the Spanish Ministry of Science, Innovation and Universities.

References

Aba, A., Al-Dousari, A.M., Ismaeel, A., 2018. Atmospheric deposition fluxes of ^{137}Cs associated with dust fallout in the northeastern Arabian Gulf. J. Environ. Radioact. 192, 565–572.

Abdelkader, M., Metzger, S., Mamouri, R.E., Astitha, M., Barrie, L., Levin, Z., Lelieveld, J., 2015. Dust–air pollution dynamics over the eastern Mediterranean. Atmos. Chem. Phys. 15, 9173–9189.

Achakulwisut, P., Anenberg, S.C., Neumann, J.E., Penn, S.L., Weiss, N., Crimmins, A., Fann, N., Martinich, J., Roman, H., Mickley, L.J., 2019. Effects of increasing aridity on ambient dust and public health in the U.S. southwest under climate change. Geohealth 3, 1–18. https://doi.org/10.1029/2019GH000187.

Achilleos, S., Evans, J.S., Yiallouros, P.K., Kleanthous, S., Schwartz, J., Koutrakis, P.,

2014. PM10 concentration levels at an urban and background site in Cyprus: the impact of urban sources and dust storms. J. Air Waste Manag. Assoc. 64 (12), 1352–1360.
Agier, L., Stanton, M., Soga, G., Diggle, P.J., 2013. A multi-state spatio-temporal Markov model for categorized incidence of meningitis in sub-Saharan Africa. Epidemiol. Infect. 141 (8), 1764–1771.
Alastuey, A., Querol, X., Castillo, S., Avila, A., Cuevas, E., Estarellas, C., Torres, C., Exposito, F., García, O., Diaz, J.P., Van Dingenen, R., Putaud, J.P., 2005. Characterisation of TSP and PM2.5 at Izaña and Santa Cruz de Tenerife (Canary Islands, Spain) during a Saharan dust episode (July 2002). Atmos. Environ. 39 (26), 4715–4728.
Alastuey, A., Querol, X., Aas, W., Lucarelli, F., Pérez, N., Moreno, T., Cavalli, F., Areskoug, H., Balan, V., Catrambone, M., Ceburnis, D., Cerro, J.C., Conil, S., Gevorgyan, L., Hueglin, C., Imre, K., Jaffrezo, J.-L., Leeson, S.R., Mihalopoulos, N., Mitosinkova, M., O'Dowd, C.D., Pey, J., Putaud, J.-P., Riffault, V., Ripoll, A., Sciare, J., Sellegri, K., Spindler, G., Yttri, K.E., 2016. Geochemistry of PM10 over Europe during the EMEP intensive measurement periods in summer 2012 and winter 2013. Atmos. Chem. Phys. 16 (10), 6107–6129. https://doi.org/10.5194/acp-16-6107-2016.
Amato, F., Alastuey, A., Karanasiou, A., Lucarelli, F., Nava, S., Calzolai, G., Severi, M., Becagli, S., Gianelle, V.L., Colombi, C., Alves, C., Custódio, D., Nunes, T., Cerqueira, M., Pio, C., Eleftheriadis, K., Diapouli, E., Reche, C., Minguillón, M.C., Manousakas, M.I., Maggos, T., Vratolis, S., Harrison, R.M., Querol, X., 2016. AIRUSE-LIFE+: A harmonized PM speciation and source apportionment in five southern European cities. Atmos. Chem. Phys. 16, 3289–3309.
Anderson, C., 2013. Agent-based Modelling of Coccioidomycosis (Doctoral dissertation). University of Pittsburg, USA 135 pp. http://d-scholarship.pitt.edu/18000/, Accessed date: 15 March 2017.
Andreae, M.O., Rosenfeld, D., 2008. Aerosol-cloud-precipitation interactions. Part 1. The nature and sources of cloud-active aerosols. Earth Sci. Rev. 89, 13–41.
Ansmann, A., Petzold, A., Kandler, K., Tegen, I., Wendisch, M., Müller, D., Weinzierl, B., Müller, T., Heintzenberg, J., 2011. Saharan mineral dust experiments SAMUM–1 and SAMUM–2: what have we learned? Tellus B 63 (4), 403–429.
Arimoto, R., Zhang, X.Y., Huebert, B.J., Kang, C.H., Savoie, D.L., Prospero, J.M., Sage, S.K., Schloesslin, C.A., Khaing, H.M., Oh, S.N., 2004. Chemical composition of atmospheric aerosols from Zhenbeitai, China, and Gosan, South Korea, during ACE-Asia. J. Geophys. Res. 109, D19S04. https://doi.org/10.1029/2003JD004323.
Aryal, R., Kandel, D., Acharya, D., Chong, M.N., Beecham, S., 2012. Unusual Sydney dust storm and its mineralogical and organic characteristics. Environ. Chem. 9, 537–546.
Ataniyazova, O.A., Baumann, R.A., Liem, A.K.D., Mukhopadhyay, U.A., Vogelaar, E.F., Boersma, E.R., 2001. Levels of certain metals, organochlorine pesticides and dioxins in cord blood, maternal blood, human milk and some commonly used nutrients in the surroundings of the Aral Sea (Karakalpakstan, Republic of Uzbekistan). Acta Paediatr. 90, 801–808.
Avila, A., Queralt, I., Alarcón, M., 1997. Mineralogical composition of African dust delivered by red rains over northeastern Spain. J. Geophys. Res. 102 (D18), 21977–21996.
Barnabaa, F., Bolignano, A., Di Libertoa, L., Morelli, M., Lucarelli, F., Nava, S., Perrino, C., Canepari, S., Basart, S., Costabile, F., Dionisi, D., Ciampichetti, S., Sozzi, R., Gobbi, G.P., 2017. Desert dust contribution to PM10 loads in Italy: methods and recommendations addressing the relevant European Commission Guidelines in support to the Air Quality Directive 2008/50. Atmos. Environ. 161 (1–18).
Bergametti, G., Dutot, A.L., Buat-Menard, P., Losno, R., Remoudaki, E., 1989a. Seasonal variability of the elemental composition of atmospheric aerosol particles over the NW Mediterranean. Tellus 41B, 353–361.
Bergametti, G., Gomes, L., Coude-Gaussen, G., Rognon, P., Le Coustumer, M.N., 1989b. African dust observed over Canary Islands: source regions identification and transport pattern for some summer situation. Journal of Geophysical Research 94, 14855–14864.
Bullard, J., Baddock, M., 2019. Chap 4. Dust: sources, entrainment, transport. In: Livingston, I., Warren, I. (Eds.), Aeolian Geomorphology: A New Introduction. Wiley Blackwell, pp. 81–106.
Caquineau, S., 1997. Les sources des aérosols sahariens transportés au dessus de l'Atlantique tropical nord: Localisationet caracteristiques minéralogiques (Ph.D. thesis). 12 Univ, Paris.
Caquineau, S., Gaudichet, A., Gomes, L., Magonthier, M.C., Chatenet, B., 1998. Saharan dust: clay ratio as a relevant tracer to assess the origin of soil derived aerosols. Geophys. Res. Lett. 25 (7), 983–986.
Cardoso, J., Almeida, S.M., Nunes, T., Almeida-Silva, M., Cerqueira, M., Alves, C., Rocha, F., Chaves, P., Reis, M., Salvador, P., Artiñano, B., Pio, C., 2018. Source apportionment of atmospheric aerosol in a marine dusty environment by ionic/composition mass balance (IMB). Atmos. Chem. Phys. 18, 13215–13230.
Carlson, T.N., Prospero, J.M., 1972. The large scale movement of Saharan air outbreaks over the northern equatorial Atlantic. J. Appl. Meteorol. 11, 283–297.
Chao, H.J., Chan, C.C., Rao, C.Y., Lee, C.T., Chuang, Y.C., Chiu, Y.H., Hsu, H.H., Wu, Y.H., 2012. The effects of transported Asian dust on the composition and concentration of ambient fungi in Taiwan. Int. J. Biometeorol. 56, 211–219.
Cheesbrough, J.S., Morse, A.P., Green, S.D., 1995. Meningococcal meningitis and carriage in western Zaire: a hypoendemic zone related to climate? Epidemiol. Infect. 114, 75–92.
Chester, R., Elderfield, H., Griffin, J.J., 1971. Dust transported in the north-east and south-east trade winds in the Atlantic Ocean. Nature 233, 474–476.
Chester, R., Nimmo, M., Alarcón, M., Saydam, C., Murphy, K.J.T., Sanders, G.S., Corcoran, P., 1993. Defining the chemical character of aerosols from the atmosphere in the Mediterranean Sea and surrounding regions. Oceanographica Acta 16, 231–246.
Chiapello, I., Bergametti, G., Gomes, L., Chatenet, B., 1995. An additional low layer transport of Sahelian and Saharan dust over the north-eastern TropicalAtl antic. Geophys. Res. Lett. 22 (23), 3191–3194.
Chiapello, I., Bergametti, G., Chatenet, B., Bousquet, P., Dulac, F., Santos Soare, E., 1997. Origins of African dust transported over the north-eastern tropical Atlantic. J. Geophys. Res. 102, 13701–13709.
Chin, M., Diehl, T., Ginoux, P., Malm, W., 2007. Intercontinental transport of pollution and dust aerosols: implications for regional air quality. Atmos. Chem. Phys. 7, 5501–5517.
Claquin, T., Schulz, M., Balkanski, Y.J., 1999. Modeling the mineralogy of atmospheric dust sources. Journal Geophysical Research 104 (D18), 22243–22256.
Comrie, A.C., 2005. Climate factors influencing Coccidioidomycosis seasonality and outbreak. Environ. Health Perspect. 113, 688–692.
Cook, B.I., Miller, R.L., Seager, R., 2009. Amplification of the North American "dust bowl" drought through human induced land degradation. Proc. Natl. Acad. Sci. U. S. A. 106, 4997–5001.
Coudé-Gaussen, G., Rognon, P., Bergametti, G., Gomes, L., Strauss, B., Gros, J.M., Le Coustumer, M.N., 1987. Saharan dust over Fuerteventura Island (Canaries), chemical and mineralogical characteristics, air mass trajectories and probable sources. Geophys. Res. 92, 9753–9771.
Csavina, J., Field, J., Taylor, M.P., Gao, S., Landázuri, A., Betterton, E.A., et al., 2012. A review on the importance of metals and metalloids in atmospheric dust and aerosol from mining operations. Sci. Total Environ. 433, 58–73.
Darwin, C., 1845. An account of the fine dust which often falls on vessels in the Atlantic Ocean. Q.J. Geol. Soc. London 2, 26–30.
Dayan, U., Heffter, J., Miller, J., Gutman, G., 1991. Dust intrusion events into the Mediterranean basin. J. Appl. Meteorol. 30, 1185–1199.
De Longueville, F., Hountondji, Y.C., Henry, S., Ozer, P., 2010. What do we know about effects of desert dust on air quality and human health in West Africa compared to other regions? Sci. Total Environ. 409, 1–8.
Derbyshire, E., 2007. Natural minerogenic dust and human health. Ambio 36 (1), 73–77.
Deroubaix, A., Martiny, N., Chiapello, I., Marticoréna, B., 2013. Suitability of OMI aerosol index to reflect mineral dust surface conditions: preliminary application for studying the link with meningitis epidemics in the Sahel. Remote Sens. Environ. 133, 116–127.
Dubief, J., 1977. Review of the North African climate with particular emphasis on the production of aeolian dust in the Sahel zone and in the Sahara. In: Morales, C. (Ed.), Saharan Dust: Mobilization, Transport, Deposition. Wiley, New-York, pp. 27–48.
Duce, R.A., Unni, C.K., Ray, B.J., Prospero, J.M., Merrill, J.T., 1980. Long-range atmospheric transport of soil dust from Asia to the tropical North Pacific: temporal variability. Science 209 (4464), 1522–1524.
Dukic, V., Hayden, M., Forgor, A.A., Hopson, T., Akweongo, P., Hodgson, A., Monaghan, A., Wiedinmyer, C., Yoksas, T., Thomson, M.C., Trzaska, S., Pandya, R., 2012. The role of weather in meningitis outbreaks in Navrongo, Ghana: a generalized additive modeling approach. J Agr. Biol. Envir. St. 17 (3), 442–460.
Duniway, M.C., Pfennigwerth, A.A., Fick, S.F., Nauman, T.W., Nichole, J.B., Barger, N., 2019. Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. Ecosphere 10, e02650. https://doi.org/10.1002/ecs2.2650.
EC, 2011. Commission Staff Working Paper establishing guidelines for determination of contributions from the re-suspension of particulates following winter sanding or salting of roads under the Directive 2008/50/EC on ambient air quality and cleaner air for Europe. European Commission, SEC 2011, 207. 43 pp. http://ec.europa.eu/environment/air/quality/legislation/pdf/sec_2011_0207.pdf.
Ehrenberg, C.G., 1862. Erläuterungen eines neuen wirklichen Passatstaubes aus dem atlantischen Dunkelmeere vom 29 Okt. 1861. Monatsber. Kgl. Preuss.Akad. Wiss., Berlin. pp. 202–224.
Engelbrecht, J.P., McDonald, E.V., Gillies, J.A., Jayanty, R.K.M., Casuccio, G., Gertler, A.W., 2009. Characterizing mineral dusts and other aerosols from the Middle East—part 1: ambient sampling. Inhal. Toxicol. 21 (4), 297–326.
Escudero, M., Castillo, S., Querol, X., Avila, A., Alarcón, M., Viana, M.M., Alastuey, A., Cuevas, E., Rodríguez, S., 2005. Wet and dry African dust episodes over Eastern Spain. J. Geophys. Res. 110, D18S08 (10.1029).
Escudero, M., Querol, X., Ávila, A., Cuevas, E., 2007a. Origin of the exceedances of the European daily PM limit value in regional background areas of Spain. Atmos. Environ. 41, 730–744.
Escudero, M., Querol, X., Pey, J., Alastuey, A., Pérez, N., Ferreira, F., Cuevas, E., Rodríguez, S., Alonso, S., 2007b. A methodology for the quantification of the net African dust load in air quality monitoring networks. Atmos. Environ. 41, 5516–5524.
Fairlie, T.D., Jacob, D.J., Park, R.J., 2007. The impact of transpacific transport of mineral dust in the United States. Atmos. Environ. 41, 1251–1266.
Favet, J., Lapanje, A., Giongo, A., Kennedy, S., Aung, Y.-Y., Cattaneo, A., Davis-Richardson, A.G., Brown Ch, T., Kort, R., et al., 2013. Microbial hitchhikers on intercontinental dust: catching a lift in Chad. ISME J 7 (4), 850–867.
Formenti, P., Rajot, L., Desboeufs, K., Caquineau, S., Chevaillier, S., Nava, S., Gaudichet, A., Journet, E., Triquet, S., Alfaro, S., Chiari, M., Haywood, J., Coe, H., Highwood, E., 2008. Regional variability of the composition of mineral dust from western Africa: results from the AMMA SOP0/DABEX and DODO field campaigns. J. Geophys. Res. 113, D00C13. https://doi.org/10.1029/2008JD009903.
Galindo, N., Nicolás, J.F., Yubero, E., Caballero, S., Pastor, C., Crespo, J., 2008. Factors affecting levels of aerosol sulfate and nitrate on the Western Mediterranean coast. Atmos. Res. 88 (3–4), 305–313.
Gangoiti, G., Alonso, L., Navazo, M., García, J.A., Millán, M.M., 2006. North African soil dust and European pollution transport to America during the warm season: hidden links shown by a passive tracer simulation. J. Geophys. Res. 111, D10109.
García, I.M., Van Drooge, B., Rodríguez, S., Betancourt, S., Alastuey, A., 2017. Speciation of organic aerosols in the Saharan air layer and in the free troposphere westerlies.

Atmos. Chem. Phys. 17 (14), 8939–8958.
Garrison, V.H., Foreman, W.T., Genualdi, S., Griffin, D.W., Kellogg, C.A., Majewski, M.S., Mohammed, A., Ramsubhag, A., Shinn, E.A., Simonich, S.L., Smith, G.W., 2006. Saharan dust – a carrier of persistent organic pollutants, metals and microbes to the Caribbean? Revuista de Biología Tropical 54 (supp 3), 9–21. https://revistas.ucr.ac.cr/index.php/rbt/article/view/26867/27040.
Garrison, V.H., Majewski, M.S., Konde, L., Wolf, R., Otto, R.D., Tsuneoka, Y., 2014. Inhalable desert dust, urban emissions, and potentially biotoxic metals in urban Saharan-Sahelian air. Sci. Total Environ. 500-501C, 383–394.
Gill, T.E., 1996. Eolian sediments generated by anthropogenic disturbance of playas: human impacts on the geomorphic system and geomorphic impacts on the human system. Geomorphology 17, 207–228.
Gillette, D.A., 1999. A qualitative geophysical explanation for "hot spot" dust emitting source regions. Contrib. Atmos. Phys. 72, 67–77.
Gillies, J.A., Nickling, W.G., McTainsh, G.H., 1996. Dust concentrations and particle-size characteristics of an intense dust haze event: Inland Delta Region, Mali, West Africa. Atmos. Environ. 30, 1081–1090.
Ginoux, P., Garbuzov, D., Hsu, H.C., 2010. Identification of anthropogenic and natural dust sources using Moderate Resolution Imaging Spectroradiometer (MODIS) deep blue level 2 data. J. Geophys. Res. 115, D05204. https://doi.org/10.1029/2009JD012398.
Ginoux, P., Prospero, J.M., Gill, T.E., Hsu, N.C., Zhao, M., 2012. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS deep blue aerosol products. Rev. Geophys. 50, RG3005. https://doi.org/10.1029/2012RG000388.
Gobbi, P., Barnaba, F., Liberto, L.D., Bolignano, A., Lucarelli, F., Nava, S., Perrino, C., Pietrodangelod, A., Basart, S., Costabile, F., Dionisi, D., Rizza, U., Canepari, S., Sozz, R., Morelli, M., Manigrasso, M., Drewnick, F., Struckmeier, C., Wille, H., 2019. An inclusive view of Saharan dust advections to Italy and the Central Mediterranean. Atmos. Environ. 201, 242–256.
Gomes, L., 1990. Approche géochimique du soulèvement des aerosols à l'interface sol-atmosphere en zone désertique (Thesis). 251 pp.. Univ., Paris, pp. 7.
Goudie, A.S., 2014. Desert dust and human health disorders. Environ. Int. 63, 101–113.
Goudie, A.S., Middleton, N.J., 2006. Desert Dust in the Global System. Springer, Heidelberg978-3-540-32355-6 (288 pp).
Griffin, D.W., 2007. Atmospheric movement of microorganisms in clouds of desert dust and implications for human health. Clin.Microbiol. Rev. 20, 459–477.
Griffin, D.W., Kellogg, C.A., 2004. Dust storms and their impact on ocean and human health: dust in Earth's atmosphere. Ecohealth 1, 284–295.
Griffin, D.W., Kellogg, C.A., Garrison, V.H., Lisle, J.T., Borden, T.C., Shinn, E.A., 2003. African dust in the Caribbean atmosphere. Aerobiologia 19, 143–157.
Grineski, S.E., Staniswalis, J.G., Bulathsinhala, P., Peng, Y., Gill, T.E., 2011. Hospital admissions for asthma and acute bronchitis in El Paso, Texas: do age, sex, and insurance status modify the effects of dust and low wind events? Environ. Res. 111, 1148–1155.
Hashizume, M., Ueda, K., Nishiwaki, Y., Michikawa, T., Onozuka, D., 2010. Health effects of Asian dust events: a review of the literature. Japanese J. Hyg. 65 (3), 413–421 (in Japanese).
Ho, K.F., Wu, K.Ch, Niua, X., Wu, Y., Zhud, Ch.-S., Wu, F., Cao, J.J., Shen, Z.X., Hsiao, T.H., Chuang, K.J., Chuang, HCh., 2019. Contributions of local pollution emissions to particle bioreactivity in downwind cities in China during Asian dust periods. Environ. Pollut. 245, 675–683.
Hsu, N.C., Tsay, S.C., King, M.D., Herman, J.R., 2004. Aerosol properties over bright-refl ecting source regions. IEEE Trans. Geosci. Remote Sens. 42, 557–569.
Hsu, N.C., Tsay, S.-C., King, M., Herman, J.R., 2006. Deep blue retrievals of Asian aerosol properties during ACE-Asia. IEEE Trans. Geosci. Remote Sens. 44, 3180–3195.
Huang, X., Song, Y., Zhao, Ch., Li, M., Zhu, T., Zhang, Q., Zhang, X., 2009. Pathways of sulfate enhancement by natural and anthropogenic mineral aerosols in China. J. Geophys. Res. Atmos. 119, 14165–14179.
Huneeus, N., Schulz, M., Balkanski, Y., Griesfeller, J., Prospero, J., Kinne, S., Bauer, S., Boucher, O., Chin, M., Dentener, F., Diehl, T., Easter, R., Fillmore, D., Ghan, S., Ginoux, P., Grini, A., Horowitz, L., Koch, D., Krol, M.C., Landing, W., Liu, X., Mahowald, N., Miller, R., Morcrette, J.-J., Myhre, G., Penner, J., Perlwitz, J., Stier, P., Takemura, T., Zender, C.S., 2011. Global dust model intercomparison in AeroCom phase I. Atmos. Chem. Phys. 11, 7781–7816.
Hwang, H.J., Ro, C.-U., 2006. Direct observation of nitrate and sulfate formations from mineral dust and sea-salts using low-Z particle electron probe X-ray microanalysis. Atmos. Environ. 40, 3869–3880.
Ito, A., Wagai, R., 2015. Global distribution of clay-size minerals on land surface for biogeochemical and climatological studies. Scientific Data 4, 170103. https://doi.org/10.1038/sdata.2017.103.
Jaffe, D., Snow, J., Cooper, O., 2003. The 2001 Asian dust events: transport and impact on surface aerosol concentrations in the U.S. Eos Trans. AGU 84 (46), 501.
Jayaratne, E.R., Johnson, G.R., McGarry, P., Cheung, H.C., Morawska, L., 2011. Characteristics of airborne ultrafine and coarse particles during the Australian dust storm of 23 September 2009. Atmos. Environ. 45, 3996–4001.
Journet, E., Balkanski, Y., Harrison, S.P., 2014. A new data set of soil mineralogy for dust-cycle modeling. Atmos. Chem. Phys. 14 (8), 3801–3816.
Kallos, G., Kotroni, V., Lagouvardosa, K., Papadopoulos, A., 1998. On the long-range transport of air pollutants from Europe to Africa. Geophys. Res. Lett. 25, 619–622.
Kallos, G., Astitha, M., Katsafados, P., Spyrou, Ch., 2008. Long-range transport of anthropogenically and naturally produced particulate matter in the Mediterranean and North Atlantic: current state of knowledge. J. App. Meteo. Climat. 46, 1230–1251.
Kandler, K., Schütz, L., Deutscher, C., Ebert, M., Hofmann, H., Jäckel, S., Jaenicke, R., Knippertz, P., Lieke, K., Massling, A., Petzold, A., Schladitz, A., Weinzierl, B., Wiedensohler, A., Zorn, S., Weinbruch, S., 2009. Size distribution, mass concentrations, chemical and mineralogical composition, and derived optical parameters of the boundary layer at Tinfou, Morocco, during SAMUM 2006. Tellus Ser. B 61, 32–50.
Kang, D., Kim, J.-E., 2014. Fine, ultrafine, and yellow dust: emerging health problems in Korea. J. Korean Med. Sci. 29 (5), 621–622.
Karanasiou, A., Moreno, N., Moreno, T., Viana, M., de Leeuw, F., Querol, X., 2012. Health effects from Sahara dust episodes in Europe: literature review and research gaps. Environ. Int. 47, 107–114.
Kellogg, C.A., Griffin, D.W., 2006. Aerobiology and the global transport of desert dust. Trends Ecol. Evol. 2, 638–644.
Kellogg, C.A., Griffin, D.W., Garrison, V.H., Peak, K.K., Royall, N., Smith, R.R., et al., 2004. Characterization of aerosolized bacteria and fungi from desert dust events in Mali, West Africa. Aerobiologia 20, 99–110.
Kim, H.S., Kim, D.S., Kim, H., Yi, S.M., 2012. Relationship between mortality and fine particles during Asian dust, smog-Asian dust, and smog days in Korea. Int. J. Environ. Health Res. 22, 518–530.
Klein Goldewijk, K., 2001. Estimating global land use change over the past 300 years: the HYDE database. Glob. Biogeochem. Cycles 15, 417–433.
Knippertz, P., Stuut, J.-B.W. (Eds.), 2014. Mineral Dust: A Key Player in the Earth System. Springer, Dortdrecht, The Netherland (509 pp).
Kok, J.F., Ridley, D.A., Zhou, Q., Miller, R.L., Zhao, C., Heald, C.L., Ward, D.S., Albani, S., Haustein, K., 2017. Smaller desert dust cooling effect estimated from analysis of dust size and abundance. Nat. Geosci. 10 (4), 274–278.
Krasnov, H., Katra, I., Koutrakis, P., Friger, M.D., 2014. Contribution of dust storms to PM10 levels in an urban arid environment. J. Air Waste Manag. Assoc. 64 (1), 89–94.
Krueger, B.J., Grassian, V.H., Cowin, J.P., Laskin, A., 2004. Heterogeneous chemistry of individual mineral dust particles from different dust source regions: the importance of particle mineralogy. Atmos. Environ. 38, 6253–6261.
Kubilay, N., Saydam, A.C., 1995. Trace elements in atmospheric particulates over the eastern Mediterranean; concentrations, sources, and temporal variability. Atmos. Environ. 29, 2289–2300.
Labban, R., Veranth, M., Chow, J.C., Engelbrecht, J., Watson, J.G., 2004. Size and geographical variation in PM1, PM2.5, and PM10: source profiles from soils in the western United States. Water Air Soil Poll 157, 13–31.
Leathers, C.R., 1981. Plant components of desert dust in Arizona and their significance for man. Geol. Soc. Am. Spec. Pap. 186, 191–206.
Lee, J.A., Baddock, M.C., Mbuh, M.J., Gill, T.E., 2012. Geomorphic and land cover characteristics of aeolian dust sources in West Texas and eastern New Mexico, USA. Aeolian Res. 3 (4), 459–466.
Levin, Z., Ganor, E., Gladstein, V., 1996. The effects of desert particles coated with sulfate on rain formation in the eastern Mediterranean. J. Appl. Meteorol. 35, 1511–1523.
Li, J., Wang, Z., Zhuang, G., Luo, G., Sun, Y., Wang, Q., 2012. Mixing of Asian mineral dust with anthropogenic pollutants over East Asia: a model case study of a super-dust storm in March 2010. Atmos. Chem. Phys. 12, 7591–7607.
Lim, N., Munday, C.I., Allison, G.E., O'Loingsigh, T., De Deckker, P., Tapper, N.J., 2011. Microbiological and meteorological analysis of two Australian dust storms in April 2009. Sci. Total Environ. 412-413, 223–231.
Litvintseva, A.P., Marsden-Haug, N., Hurst, S., Hill, H., Gade, L., Driebe, E.M., Ralston, C., Roe, C., Barker, B.M., Goldoft, M., Keim, P., Wohrle, R., Thompson III, G.R., Engelthaler, D.M., Brandt, M.E., Chiller, T., 2015. Valley fever: finding new places for an old disease: Coccidioides immitis found in Washington state soil associated with recent human infection. Clin. Infect. Dis. 60 (1), e1–e3.
Ma, R., Duan, H., Hu, C., Feng, X., Li, A., Ju, W., Jiang, J., Yang, G., 2010. A half-century of changes in China's lakes: global warming or human influence? Geophys. Res. Lett. 37, L24106. https://doi.org/10.1029/2010GL045514.
Mahowald, N., Rivera, G., Luo, C., 2004. Comment on "Relative importance of climate and land use in determining present and future global soil dust emission" by I. Tegen et al. Geophys. Res. Lett. 31 (24), L24105. https://doi.org/10.1029/2004GL021272.
Mahowald, N., Albani, S., Kok, J.F., Engelstaeder, S., Scanza, R., Ward, D.S., Flanner, M.G., 2014. The size distribution of desert dust aerosols and its impact on the earth system. Aeolian Res. 15 (5–71).
Majbauddin, A., Onishi, K., Otani, S., Kurosaki, Y., Kurozawa, Y., 2016. Association between Asian dust-borne air pollutants and daily symptoms on healthy subjects: a web-based pilot study in Yonago, Japan. J. Environ. Public Health 2016, 1–6. https://doi.org/10.1155/2016/8280423. (ID 8280423).
Martigny, N., Chiapello, I., 2013. Assessments for the impact of mineral dust on the meningitis incidence in West Africa. Atmos. Environ. 70, 245–253.
Metcalf, J.S., Richer, R., Cox, P.A., Godd, G.A., 2012. Cyanotoxins in desert environments may present a risk to human health. Sci. Total Environ. 421-422, 118–123.
Middleton, N., Tozer, P., Tozer, B., 2019. Sand and dust storms: underrated natural hazards. Disasters 43 (2), 390–409.
Molesworth, A.M., Cuevas, L.E., Connor, S.J., Morse, A.P., Thomson, M.C., 2003. Environmental risk and meningitis epidemics in Africa. Emerg. Infect. Dis. 9, 287–1293.
Molinaroli, E., Guerzoni, S., Rampazzo, G., 1993. Contribution of Saharan dust to the central Mediterranean basin. Geol. Soc. Am. Spec. Pap. 284, 303–312.
Mona, L., Amodeo, A., Pandolfi, M., Pappalardo, G., 2006. Saharan dust intrusions in the Mediterranean area: three years of Raman lidar measurements. J. Geophys. Res. 111, D16203. https://doi.org/10.1029/2005JD006569.
Moreno, T., Querol, X., Castillo, S., Alastuey, A., Cuevas, E., Herrmann, L., Mounkaila, M., Elvira, J., Gibbons, W., 2006. Geochemical variations in aeolian mineral particles from the Sahara-Sahel Dust Corridor. Chemosphere 65 (2), 261–270.
Moreno, T., Pérez, N., Querol, X., Amato, F., Alastuey, A., Bhatia, R., Spiro, B., Hanvey, M., Gibbons, W., 2010. Physicochemical variations in atmospheric aerosols recorded at sea on board the Atlantic-Mediterranean 2008 scholar ship cruise (part II): natural versus anthropogenic influences revealed by PM10 trace element geochemistry.

Atmos. Environ. 44, 2563–2576.
Mori, I., Iwasaka, Y., Matsunaga, K., Hayashi, M., Nishikawa, M., 1999. Chemical characteristics of free tropospheric aerosols over the Japan Sea coast: aircraft-borne measurements. Atmos. Environ. 33 (4), 601–609.
Mori, I., Nishikawa, M., Tanimura, T., Quan, H., 2003. Change in size distribution and chemical composition of Kosa (Asian dust) aerosol during long-range transport. Atmos. Environ. 37, 4253–4263.
Neff, J.C., Ballantyne, A.P., Farmer, G.L., Mahowald, N.M., Conroy, J.L., Landry, C.C., Overpeck, J.T., Painter, T.H., Lawrence, C.R., Reynolds, R.L., 2008. Increasing eolian dust deposition in the western United States linked to human activity. Nat. Geosci. 1, 189–195.
Nguyen, C., Barker, B.M., Hoover, S., Nix, D., Ampel, N.M., Frelinger, J.A., Orbach, M.J., Galgiani, J.N., 2013. Recent advances in our understanding of the environmental, epidemiological, immunological, and clinical dimensions of Coccidioidomycosis. Clin.Microbiol. Rev. 26 (3), 505–525.
Nickovic, S., Vukovic, A., Vujadinovic, M., Djurdjevic, V., Pejanovic, G., 2012. Technical note: high-resolution mineralogical database of dust-productive soils for atmospheric dust modeling. Atmos. Chem. Phys. 12 (2), 845–855.
Nicolás, J., Chiari, M., Crespo, J., Garcia Orellana, I., Lucarelli, F., Nava, S., Pastor, C., Yubero, E., 2008. Quantification of Saharan and local dust impact in an arid Mediterranean area by the positive matrix factorization (PMF) technique. Atmos. Environ. 42 (39), 8872–8882.
Norris, G., Duvall, R., 2014. EPA Positive Matrix Factorization (PMF) 5.0 Fundamentals and User Guide. United States Environmental Protection Agency (EPA), Office of Research and Development, Washington; U.S. (EPA/600/R-14/2018).
Ogorodnikov, B.I., 2011. A dust storm over the Ukraine and Belarus territory contaminated by radionuclides after the Chernobyl accident. Russ. Meteorol.Hydrol. 36, 613–623.
O'Hara, S.L., Wiggs, G., Mamedov, B., Davidson, G., Hubbard, R.B., 2000. Exposure to airborne dust contaminated with pesticide in the Aral Sea region. Lancet 355, 627–628.
Onishi, K., Kurosaki, Y., Otani, S., Yoshida, A., Sugimoto, N., Kurozawa, Y., 2012. Atmospheric transport route determines components of Asian dust and health effects in Japan. Atmos. Environ. 49, 94–102.
Orlove, B., 2005. Human adaptation to climate change: a review of three historical cases and some general perspectives. Environ. Sci. Pol. 8, 589–600.
Paatero, P., Tapper, U., 1994. Positive matrix factorization: a non-negative factor model with optimal utilization of error estimates if data values. Environmetrics 5, 111–126.
Pandolfi, M., Tobias, A., Alastuey, A., Sunyer, J., Schwartz, J., Lorente, J., Pey, J., Querol, X., 2014. Effect of atmospheric mixing layer depth variations on urban air quality and daily mortality during Saharan dust outbreaks. Sci. Total Environ. 494, 283–289.
Papastefanou, C., Manolopoulou, M., Stoulos, S., Ioannidou, A., Gerasopoulos, E., 2001. Coloured rain dust from Sahara Desert is still radioactive. J. Environ. Radioact. 55, 109–112.
Papayannis, A., Balis, D., Amiridis, V., Chourdakis, G., Tsaknakis, G., Zerefos, C., Castanho, A.D.A., Nickovic, S., Kazadzis, S., Grabowski, J., 2005. Measurements of Saharan dust aerosols over the Eastern Mediterranean using elastic backscatter-Raman lidar, spectrophotometric and satellite observations in the frame of the EARLINET Project. Atmos. Chem. Phys. 5, 2065–2079.
Papayannis, A., Mona, L., Tsaknakis, G., Balis, D., Bösenberg, J., Chaikovski, A., De Tomasi, F., Grigorov, I., Mattis, I., Mitev, V., Müller, D., Nickovic, S., Pérez, C., et al., 2008. Systematic lidar observations of Saharan dust over Europe in the frame of EARLINET (2000–2002). J. Geophys. Res. 113, D10204. https://doi.org/10.1029/2007JD009028.
Pappagianis, D., Einstein, H., 1978. Tempest from Tehachapi takes toll or coccidioides conveyed aloft and afar. West J. Med. 129, 527–530.
Pérez García-Pando, C., Stanton, M.C., Diggle, P.J., Trzaska, S., Miller, R.L., Perlwitz, J.P., Baldasano, J.M., Cuevas, E., Ceccato, P., Yaka, P., Thomson, M.C., 2014. Soil dust aerosols and wind as predictors of seasonal meningitis incidence in Niger. Environ. Health Perspect. 122, 7679–7686.
Pérez, N., Moreno, T., Querol, X., Alastuey, A., Bhatia, R., Spiro, B., Hanvey, M., 2010. Physicochemical variations in atmospheric aerosols recorded at sea on board the Atlantic-Mediterranean 2008 scholar ship cruise (part I): particle mass concentrations, size ratios, and main chemical components. Atmos. Environ. 44, 2552–2562.
Pérez, L., Tobías, A., Pey, J., Pérez, N., Alastuey, A., Sunyer, J., Querol, X., 2012. Effects of local and Saharan particles on cardiovascular disease mortality. Epidemiology 23 (5), 768–769.
Pey, J., Querol, X., Alastuey, A., Forastiere, F., Stafoggia, M., 2013. African dust outbreaks over the Mediterranean Basin during 2001–2011: PM10 concentrations, phenomenology and trends, and its relation with synoptic and mesoscale meteorology. Atmos. Chem. Phys. 13, 1395–1410.
Polymenakou, P.N., Mandalakis, M., Stephanou, E.G., Tselepides, A., 2008. Particle size distribution of airborne microorganisms and pathogens during an intensive African dust event in the eastern Mediterranean. Environ. Health Perspect. 116, 292–296.
Prospero, J.M., 1999. Long-term measurements of the transport of African mineral dust to the southeastern United States: implications for regional air quality. J. Geophys. Res. 104 (D13), 15917–15927.
Prospero, J.M., Carlson, T.N., 1980/1981. Saharan air outbreaks over the tropical North Atlantic. Pure and Applied Physics 119, 667–691.
Prospero, J.M., Lamb, P.J., 2003. African droughts and dust transport to the Caribbean: climate change implications. Science 302, 1024–1027.
Prospero, J.M., Schmitt, R., Cuevas, E., Savoie, D.L., Graustein, W.C., Turekian, K.K., Volz-Thomas, A., Díaz, A., Oltmans, S.J., Levy, I.I.H., 1995. Temporal variability of summer-time ozone and aerosols in the free troposphere over the eastern North Atlantic. Geophys. Res. Lett. 22 (21), 292–2928.
Prospero, J.M., Olmez, I., Ames, M., 2001. Al and Fe in PM 2.5 and PM 10 suspended particles in south-central Florida: the impact of the long range transport of African mineral dust. Water Air Soil Pollut. 125, 291–317.
Prospero, J.M., Ginoux, P., Torres, O., Nicholson, S.E., Gill, T.E., 2002. Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. Rev. Geophys. 40 (1), 1002. https://doi.org/10.1029/2000RG000095.
Prospero, J.M., Blades, E., Mathison, G., Naidu, R., 2005. Interhemispheric transport of viable fungi and bacteria from Africa to the Caribbean with soil dust. Aerobiologica 21, 1–19.
Prospero, J.M., Bullard, J.E., Hodgkins, R., 2012. High-latitude dust over the North Atlantic: inputs from Icelandic proglacial dust storms. Science 335, 1078–1082.
Querol, X., Alastuey, A., Puicercus, J.A., Mantilla, E., Miro, J.V., Lopez-Soler, A., Plana, F., Artíñano, B., 1998a. Seasonal evolution of suspended particles around a large coal-fired power station: particulate levels and sources. Atmos. Environ. 32, 1963–1978.
Querol, X., Alastuey, A., Lopez-Soler, A., Plana, F., Puicercus, J.A., Ruiz, C.R., Mantilla, E., Juan, R., 1998b. Seasonal evolution of atmospheric suspended particles around a coal-fired power station: chemical characterization. Atmos. Environ. 32 (4), 719–731.
Querol, X., Alastuey, A., Rodríguez, S., Plana, F., Ruiz, C.R., Cots, N., Massagué, G., Puig, O., 2001. PM10 and PM2.5 source apportionment in the Barcelona Metropolitan Area, Catalonia, Spain. Atmos. Environ. 35 (36), 6407–6419.
Querol, X., Pey, J., Pandolfi, M., Alastuey, A., Cusack, M., Moreno, T., Viana, M., Mihalopoulos, N., Kallos, G., Kleanthous, S., 2009. African dust contributions to mean ambient PM10 levels across the Mediterranean Basin. Atmos. Environ. 43, 4266–4277.
Querol, X., Pérez, N., Reche, C., Ealo, M., Ripoll, A., Tur, J., Pandolfi, M., Pey, J., Salvador, P., Moreno, T., Alastuey, A., 2019. African dust and air quality over Spain: is it only dust that matters? The Science of Total Environment. https://doi.org/10.1016/j.scitotenv.2019.05.349. (In press).
Querol, X., Alastuey, A., Castillo, S., Alonso, Pérez S., Cuevas, E., Rodríguez, S., 2008. Impacto de las Emisiones Desérticas de Polvo Africano sobre la Calidad del Aire en España. The Impact of Desert-Windblowed Dust Particles on the Quality of Air in Spain. Macla 8, 22–27.
Ravelo-Pérez, L.M., Rodríguez, S., Galindo, L., García, M.I., Alastuey, A., López-Solano, J., 2016. Soluble iron dust export in the high altitude Saharan air layer. Atmos. Environ. 133, 49–59.
Reid, J.S., Jonsson, H.H., Maring, H.B., Smirnov, A., Savoie, D.L., Cliff, S.S., Reid, E.A., Livingston, J.M., Meier, M.M., Dubovik, O., Tsay, S.C., 2003. Comparison of size and morphological measurements of coarse mode dust particles from Africa. J. Geophys. Res. 108 (D19), 8593.
Richter, D., Gill, T., 2018. Challenges and opportunities in atmospheric dust emission, chemistry, and transport. Bull. American Meteorological Society 18, ES115–ES118. https://doi.org/10.1175/BAMS-D-18-0007.1.
Rittmeister, F., Ansmann, A., Engelmann, R., Skupin, A., Baars, H., Kanitz, T., Kinne, S., 2017. From the Caribbean to West Africa: four weeks of continuous dust and marine aerosol profiling with shipborne polarization/Raman Lidar - a contribution to SALTRACE. Atmos. Chem. Phys. Discuss. https://doi.org/10.5194/acp-2017-130. (2017).
Rivera Rivera, N.I., Gill, T.E., Bleiweiss, M.P., Hand, J.L., 2010. Source characteristics of hazardous Chihuahuan desert dust outbreaks. Atmos. Environ. 44, 2457–2468.
Rodríguez, S., Querol, X., Alastuey, A., Kallos, G., Kakaliagou, O., 2001. Saharan dust contributions to PM10 and TSP levels in southern and eastern Spain. Atmos. Environ. 35, 2433–2447.
Rodríguez, S., Alastuey, A., Alonso-Pérez, S., Querol, X., Cuevas, E., Abreu-Afonso, J., Viana, M., Pandolfi, M., De La Rosa, J., 2011. Transport of desert dust mixed with North African industrial pollutants in the subtropical Saharan air layer. Atmos. Chem. Phys. 11, 6663–6685.
Sabre, M., 1997. Etude dynamique du processus d'Émission de poussières désertiques: impact sur le fractionnement chimique entre sol et aèrosol (Thesis). 170 pp.. Univ., Paris, pp. 7.
Sánchez de la Campa, A., García-Salamanca, A., Solano, J., de la Rosa, J., Ramos, J.L., 2013. Chemical and microbiological characterization of atmospheric particulate matter during an intense African dust event in southern Spain. Environ. Sci. Technol. 47, 3630–3638.
Scanza, R.A., Mahowald, N., Ghan, S., Zender, C.S., Kok, J.F., Liu, X., Zhang, Y., Albani, S., 2015. Modeling dust as component minerals in the community atmosphere model: development of framework and impact on radiative forcing. Atmos. Chem. Phys. 15, 537–561.
Scheuvens, D., Schütz, L., Kandler, K., Ebert, M., Weinbruch, S., 2013. Bulk composition of northern African dust and its source sediments - a compilation. Earth-Science Rev 116 (1), 170–194.
Schuerger, A.C., Smith, D.J., Griffin, D.W., Jaffe, D.A., Wawrik, B., Burrows, S.M., Christner, B.C., Gonzalez-Martin, C., Lipp, E.K., Schmale III, D.G., Yu, H., 2018. Science questions and knowledge gaps to study microbial transport and survival in Asian and African dust plumes reaching North America. Aerobiologia 34 (4), 425–435.
Schütz, L., Sebert, M., 1987. Mineral aerosols and source identification. J. Aerosol Sci. 18 (1), 1–10.
Shen, Z., Caquineau, S., Cao, J., Zhang, X., Hana, Y., Gaudichet, A., Gomes, L., 2009. Mineralogical characteristics of soil dust from source regions in northern China. Particuology 7, 507–512.
Song, Y., Zhang, Y., Xiea, S., Zeng, L., Zheng, M., Salmon, L.G., Shao, M., Slanina, S., 2006. Source apportionment of PM2.5 in Beijing by positive matrix factorization. Atmos. Environ. 40 (8), 1526–1537.
Sotoudeheian, S., Salim, R., Arhami, M., 2016. Impact of Middle Eastern Dust Sources on PM 10 in Iran: Highlighting the Impact of Tigris-Euphrates Basin Sources and Lake Urmia desiccation: Impact of dust sources on Iranian cities. J. Geophys. Res. Atmos.

121 (23). https://doi.org/10.1002/2016JD025119.
Sprigg, W.A., 2016. Dust storms, human health and a global early warning system. In: Steinberg, S.L., Sprigg, W.A. (Eds.), Extreme Weather, Health and Communities: Interdisciplinary Engagement Strategies. Springer Press, pp. 59–87 Chapter: 4.
Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J.B., Cohen, M.D., Ngan, F., 2015. NOAA's HYSPLIT atmospheric transport and dispersion modeling system. Bull. Amer. Meteor. Soc. 96, 2059–2077.
Stohl, A., Forster, C., Frank, A., Seibert, P., Wotawa, G., 2005. Technical note: the Lagrangian particle dispersion model FLEXPART version 6.2. Atmos. Chem. Phys. 5, 2461–2474.
Stout, J.E., 2001. Dust and environment in the Southern High Plains of North America. J. Arid Environ. 47, 425–441.
Sullivan, R.C., Guazzotti, S.A., Sodeman, D.A., Tang, Y., Carmichael, G.R., Prather, K.A., 2007. Mineral dust is a sink for chlorine in the marine boundary layer. Atmos. Environ. 41, 7166–7179.
Sultan, B., Labadi, K., Guégan, J.-F., Janicot, S., 2005. Climate drives the meningitis epidemics onset in West Africa. PLoS Med. 2, 44–49.
Tegen, I., Lacis, A.A., Fung, I., 1996. The influence of mineral aerosols from disturbed soils on the global radiation budget. Nature 380, 419–422.
Tegen, I., Werner, M., Harrison, S.P., Kohfeld, K.E., 2004. Relative importance of climate and land use in determining present and future global soil dust emission. Geophys. Res. Lett. 31, L05105. https://doi.org/10.1029/2003GL019216.
Tesche, M., Groß, S., Ansmann, A., Müller, D., Althausen, D., Freudenthaler, V., Esselborn, M., 2011. Profiling of Saharan dust and biomass-burning smoke with multiwavelength polarization Raman Lidar at Cape Verde. Tellus B 63, 649–676.
Textor, C., Schulz, M., Guibert, S., Kinne, S., Balkanski, Y., Bauer, S., Berntsen, T., Berglen, T., Boucher, O., Chin, M., Dentener, F., Diehl, T., Easter, R., Feichter, H., Fillmore, D., Ghan, S., Ginoux, P., Gong, S., Grini, A., Hendricks, J., Horowitz, L., Huang, P., Isaksen, I., Iversen, I., Kloster, S., Koch, D., Kirkevåg, A., Kristjansson, J.E., Krol, M., Lauer, A., Lamarque, J.F., Liu, X., Montanaro, V., Myhre, G., Penner, J., Pitar, G., Reddy, S., Seland, Ø., Stier, P., Takemura, T., Tie, X., 2006. Analysis and quantification of the diversities of aerosol life cycles within AeroCom. Atmos. Chem. Phys. 6, 1777–1813.
Thomson, M.C., Molesworth, A.M., Djingarey, M.H., Yameogo, K.R., Belanger, F., Cuevas, L.E., 2006. Potential of environmental models to predict meningitis epidemics in Africa. Tropical Med. Int. Health 11, 781–788.
Thomson, M.C., Jeanne, I., Djingarey, M., 2009. Dust and epidemic meningitis in the Sahel: a public health and operational research perspective. IOP Conf. Ser.: Earth Environ. Sci. 7, 012017. https://doi.org/10.1088/1755-1307/7/1/012017.
Tobías, A., Karanasiou, A., Amato, F., Querol, X., 2019. WHO Global Air Quality Guidelines: Systematic Review of Health Effects of Dust and Sand Storms. A World Health Organization Report, Geneva. 92 pp. (submitted).
Tobo, Y., Zhang, D., Nakata, N., Yamada, M., Ogata, H., Hara, K., Iwasaka, Y., 2009. Hygroscopic mineral dust particles as influenced by chlorine chemistry in the marine atmosphere. Geophys. Res. Lett. 36, L05817.
Van Curen, R.A., Cahill, T.A., 2002. Asian aerosols in North America: frequency and concentration of fine dust. J. Geophys. Res. 107 (4804), D24.
Varga, G., 2012. Spatio-temporal distribution of dust storms—a global coverage using NASA TOMS aerosol measurements. Hung. Geog.r Bull. 61, 275–298.
Viana, M., Querol, X., Alastuey, A., Cuevas, E., Rodriguez, S., 2002. Influence of African dust on the levels of atmospheric particulates in the Canary Islands air quality network. Atmos. Environ. 36 (38), 5861–5875.
Walker, A.L., Liu, M., Miller, S.D., Richardson, K.A., Westphal, D.L., 2009. Development of a dust source database for mesoscale forecasting in southwest Asia. J. Geophys. Res. 114, D18207. https://doi.org/10.1029/2008JD011541.
Wang, Y., Zhuang, G., Sun, Y., An, Z., 2005. Water-soluble part of the aerosol in the dust storm season—evidence of the mixing between mineral and pollution aerosols. Atmos. Environ. 39 (37), 7020–7029.
Washington, R., Todd, M., Middleton, N., Goudie, A.S., 2003. Global dust storm source areas determined by the Total Ozone Monitoring Spectrometer and ground observations. Ann. Assoc. Am. Geogr. 93, 297–313.
Watanabe, M., Igishi, T., Burioka, N., Yamasaki, A., Kurai, J., Takeuchi, H., et al., 2011a. Pollen augments the influence of desert dust on symptoms of adult asthma patients. Allergol. Int. 60, 517–524.
Watanabe, M., Yamasaki, A., Burioka, N., Kurai, J., Yoneda, K., Yoshida, A., et al., 2011b. Correlation between Asian dust storms and worsening asthma in western Japan. Allergol. Int. 60, 267–275.
Wehner, B., Wiedensohler, A., Tuch, T.M., Wu, Z.J., Hu, M., Slanina, J., Kiang, C.S., 2004. Variability of the aerosol number size distribution in Beijing, China: new particle formation, dust storms, and high continental background. Geophys. Res. Lett. 31, L22108.
Weir-Brush, J.R., Garrison, V.H., Smith, G.W., Shinn, E.A., 2004. The relationship between gorgonian coral (Cnidaria: Gorgonacea) diseases and African dust storms. Aerobiologia 20, 11–126.
Wiggs, G.F.S., O'Hara, S., Wegerdt, J., Van der Meer, J., Small, I., Hubbard, R., 2003. The dynamics and characteristics of aeolian dust in dryland Central Asia: possible impacts on human exposure and respiratory health in Aral Sea basin. Geogr. J. 169, 142–157.
Williams, P.L., Sable, D.L., Mendez, P., Smyth, L.T., 1979. Symptomatic coccidioidomycosis following a severe natural dust storm.An outbreak at the Naval Air Station, Lemoore, Calif. Chest 76, 566–570.
Yu, Y., Kalashnikova, O.V., Garay, M.J., Notaro, M., 2019. Climatology of Asian dust activation and transport potential based on MISR satellite observations and trajectory analysis. Atmos. Chem. Phys. 19, 363–378.
Yuan, H., Zhuang, G., Li, J., Wang, Z., Li, J., 2008. Mixing of mineral with pollution aerosols in dust season in Beijing: revealed by source apportionment study. Atmos. Environ. 42 (9), 2141–2157.
Yumimoto, K., Eguchi, K., Uno, I., Takemura, T., Liu, Z., Shimizu, A., Sugimoto, N., 2009. An elevated large-scale dust veil from the Taklamakan Desert: intercontinental transport and three-dimensional structure as captured by CALIPSO and regional and global models. Atmos. Chem. Phys. 9, 8545–8558.
Zender, C.S., Talamantes, J., 2005. Climate controls on valley fever incidence in Kern County, California. Int. J. Biometeorol. 50 (3), 174–182.
Zhang, X.Y., Arimoto, T., An, Z.S., 1997. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. Journal of Geophysical Research: Atmosphere 102 (D23), 28041–28047.
Zhang, D., Iwasaka, Y., Shi, G., Zang, J., Matsuki, A., Trochkine, D., 2003. Mixture state and size of Asian dust particles collected at southwestern Japan in spring 2000. J. Geophys. Res. 108 (D24), 4760.
Zhang, X., Zhao, L., Tong, D., Wu, G., Dan, M., Teng, B., 2016. A systematic review of global desert dust and associated human health effects. Atmosphere 7 (12), 158. https://doi.org/10.3390/atmos7120158.
Zhao, W., Hopke, P.K., 2004. Source apportionment for ambient particles in the San Gorgonio wilderness. Atmos. Environ. 38 (35), 5901–5910.
Zhao, P., Feng, Y.-Ch., Zhu, T., Wu, J., 2006. Characterizations of resuspended dust in six cities of North China. Atmos. Environ. 40 (30), 5807–5814.
Zheng, M., Salmon, L.G., Schauer, J.J., Zeng, L., Kiang, C.S., Zhang, Y., Cass, G.R., 2005. Seasonal trends in PM2.5 source contributions in Beijing, China. Atmos. Environ. 39, 3967–3976.