# Desert dust and human health disorders

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Review

# Desert dust and human health disorders

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ABSTRACT

Dust storms may originate in many of the world's drylands and have an effect not only on human health in the drylands themselves but also in downwind environments, including some major urban centres, such as Phoenix, Kano, Athens, Madrid, Dubai, Jedda, Tehran, Jaipur, Beijing, Shanghai, Seoul, Taipei, Tokyo, Sydney, Brisbane and Melbourne. In some parts of the world dust storms occur frequently throughout the year. They can transport particulate material, pollutants, and potential allergens over thousands of km from source. The main sources include the Sahara, central and eastern Asia, the Middle East, and parts of the western USA. In some parts of the world, though not all, the frequency of dust storms is changing in response to land use and climatic changes, and in such locations the health implications may become more severe. Data on the $PM_{10}$ and $P_{2.5}$ loadings of dust events are discussed, as are various pollutants (heavy metals, pesticides, etc.) and biological components (spores, fungi, bacteria, etc.). Particulate loadings can far exceed healthy levels. Among the human health effects of dust storms are respiratory disorders (including asthma, tracheitis, pneumonia, allergic rhinitis and silicosis) cardiovascular disorders (including stroke), conjunctivitis, skin irritations, meningococcal meningitis, valley fever, diseases associated with toxic algal blooms and mortality and injuries related to transport accidents.


**Contents**



## 1. Introduction

The purpose of this paper is firstly to review recent studies on the nature of desert dust storms (e.g. their main sources areas, frequencies,

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changing frequencies, durations, and particulate contents), and secondly to consider some of the empirical evidence that is now accumulating to relate these characteristics of dust storms to various human health disorders. It does not seek to review in detail the underlying biological processes that lie behind such disorders.

## 2. Desert dust

Dust storms play an important role in the Earth system (Goudie and Middleton, 2006; Ravi et al., 2011; Shao et al., 2011). They are in most cases the result of turbulent winds, including fronts and convective *haboobs* (Miller et al., 2008), which raise large quantities of dust from desert surfaces and reduce visibility to less than 1 km. Dust reaches concentrations in excess of 6000 μg $m^{-3}$ in severe events (Song et al., 2007). It can be transported over thousands of kilometres and is deposited downwind by wet and dry processes, sometimes in appreciable quantities. Much of this load consists of silt. The silt comes finer with distance from source, and in the case of the Sahara, the coarsest dust (over 70 μm) occurs close to the Sahara itself, whereas dust that has travelled further tends to be finer silt, with a diameter of 5 to 30 μm or less. Saharan dust collected in the eastern USA may be finer than 1 μm (Perry et al., 1997). Aeolian dust is dominated by $SiO_2$ and $Al_2O_3$, but other significant components are $Fe_2O_3$, CaO and MgO. It may also have a large salt content, an organic content (Zaady et al., 2001), and, crucially from the health point of view can transport pathogens and anthropogenic pollutants.

### 2.1. Source areas

The health impact of dust storms will depend on where human populations are located with respect to the source areas of dust storms and the downwind direction of dust transport from them. Some areas are major generators of dust to the atmosphere. Other areas are, however, much less active. Analysis of Total Ozone Mapping Spectrometer (TOMS) data (Prospero et al., 2002; Varga, 2012; Washington et al., 2003) and other satellite borne sensors such as MODIS (Ginoux et al., 2012) has demonstrated the primacy of the Sahara, and the importance of large basins of internal drainage as dust sources (Bodélé, Taoudenni, Tarim, Seistan, Eyre, Etosha, Mkgadikgadi, Etosha, Uyuni, and the Great Salt Lake) (Engelstädter, 2001). Also, many sources are associated with alluvial deposits (Prospero et al., 2002) or piedmont alluvial fans (Tegen and Schepanski, 2009). Furthermore, TOMS data indicate that many of the world's major dust source areas, with high Aerosol Index (AI) values, are very arid (Table 1). Estimates of the relative strength of dust emissions for different parts of the world are variable but in general they demonstrate the importance, firstly of the Sahara (with over half of the global total), secondly of China and Central Asia (with about 20% of the global total), thirdly of Arabia and fourthly of Australia. Southern Africa and the Americas are relatively minor sources, together accounting for less than about 5% of the total (see, for example, Miller et al. (2004) and Tanaka and Chiba (2006) (Fig. 1)).

**Table 1**
Maximum mean aerosol index (AI) values for major global dust sources determined from TOMS (from Goudie and Middleton, 2006, Table 4.2).

| Location | AI value | Average annual rainfall (mm) |
|---|---|---|
| Bodélé Depression of south central Sahara | >30 | 17 |
| West Sahara in Mali and Mauritania | >24 | 5–100 |
| Arabia (southern Oman/Saudi border) | >21 | <100 |
| Eastern Sahara (Libya) | >15 | 22 |
| Southwest Asia (Makran coast) | >12 | 98 |
| Taklamakan/Tarim Basin (China) | >11 | <25 |
| Etosha Pan (Namibia) | >11 | 435–530 |
| Lake Eyre Basin (Australia) | >11 | 150–200 |
| Mkgadikgadi Basin (Botswana) | >8 | 460 |
| Salar de Uyuni (Bolivia) | >7 | 178 |
| Great Basin (USA) | >5 | 400 |

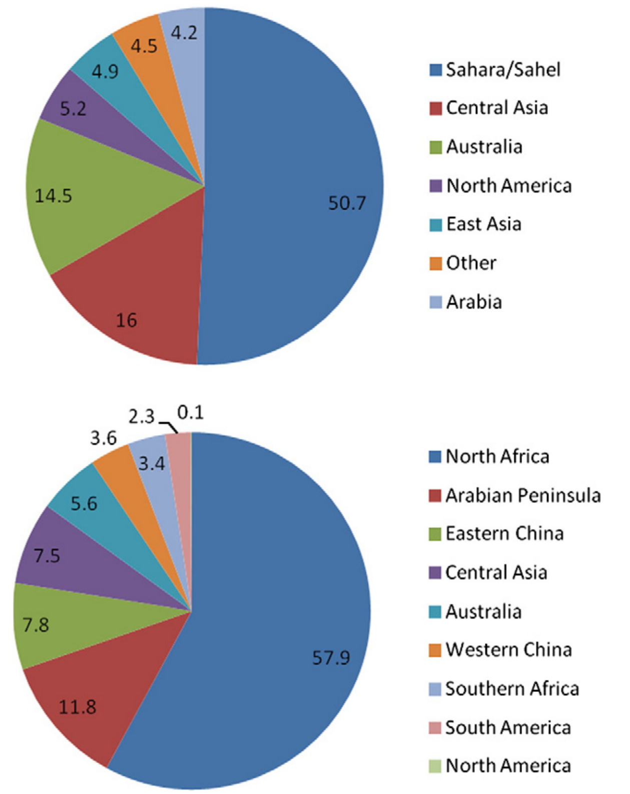


**Fig. 1.** Estimates of the relative strength of dust emissions for different parts of the world (from data in Miller et al. (2004) (top) and Tanaka and Chiba (2006) (bottom).

With regard to individual source regions, in the USA the greatest frequency of dust events occurs in the Great Plains and the Great Basin. These areas combine erodible materials with a dry climate and high wind energy (Gillette and Hanson, 1989). With regards to the arid south west, Bach et al. (1996) discuss the spatial and temporal variabilities of dust storms in the Mojave and Colorado Deserts and identify the Coachella Valley as being the dustiest region. Dust blown from the desiccated Owens Valley in California has been a cause of local health concerns. Dust has also been a major health issue in cities such as Phoenix in Arizona (Leathers, 1981), and pneumonia, called 'Haboob Lung Syndrome', has been reported after dust events in Lubbock, Texas (Panikkath et al., 2013).

The main source areas for Saharan dust (Goudie and Middleton, 2001) include: the Bodélé Depression (Bristow et al., 2009; Washington et al., 2006a, 2006b); an area that comprises southern Mauritania, northern Mali and central-southern Algeria (Knippertz and Todd, 2010); southern Morocco and western Algeria; the southern fringes of the Mediterranean Sea in Libya (O'Hara et al., 2006) and Egypt (Koren et al., 2003); and northern Sudan (Brooks et al., 2005). Much dust is moved by the north easterly trades over Nigeria and the Guinea zone to give the Harmattan haze (Breuning-Madsen and Awadzi, 2005) which may play a role in the timing and severity of meningococcal meningitis outbreaks. The Tokar delta of the Sudan, an arid, silty region across which high velocity winds are funnelled by a gap in the Red Sea Hills, is a frequent source of dust over the Red Sea (Hickey and Goudie, 2007) — dust which often moves into Arabia and may lead to air quality deterioration in cities like Jedda.

Dust storms in the Middle East itself (Middleton, 1986a) are frequent on the alluvial plains of southern Iraq and Kuwait, and concerns have been expressed about their possible health implications (Thalib and Al-Taiar, 2012). In Tehran the great bulk of particulates appear to be derived from the deserts of Iraq and Syria (Givehchi et al., 2013). The Wahiba Sands (Pease et al., 1998) of Oman and the Oman–Saudi Arabia border are other large dust generation areas (Middleton and

Goudie, 2001). Also important is the eastern part of Saudi Arabia to the north of the Rub'Al Khali sand sea. Some dust in the United Arab Emirates may be derived from Iran and central Asia (de Villiers and van Heerden, 2011). Another major region of dust storms occurs in Iraq and Iran (Middleton, 1986b) where much dust is lofted off the Tigris–Euphrates alluvial plain (Hamidi et al., 2013) and at the convergence of the common borders between Iran, Pakistan and Afghanistan. At Zabol, in Iranian Seistan, there are on average 81 dust storm days per year, making it one of Earth's dustiest locations. This is a closed basin fed by the silt-laden Helmand River and through which high velocity winds are channelled by the high mountains that bound it (Hickey and Goudie, 2007). The frequency of dust storms in that region varies greatly from year to year depending on whether or not the Helmand lakes are wet or dry (Miri et al., 2010). The Makran coast is also an area of significant dust storm occurrence, and plumes are often identifiable on satellite images, showing dust being blown off dry river beds.

Middleton (1986c) has mapped dust storm activity in the arid zones of the Indian sub-continent, and has demonstrated that the greatest number of dust storms occur in the Thar Desert, but eastward moving dust clouds move into the heavily populated areas of the North Indian Plains (Gharai et al., 2013).

In the southern former Soviet Union the number of dust storms exceeds 40 per year, and some locations have more than 80, one of the highest occurrences in the world (Groll et al., 2013; Indoitu et al., 2012; Orlovsky et al., 2005). Dust is blown off the desiccated bed of the Aral Sea, with various proposed health implications.

According to Kes and Fedorovich (1976), the Tarim Basin has more dust storms than any other location on Earth, with 100 to 174 per year. Studies of dust loadings and fluxes suggest that there are two main source areas in China: the Taklamakan (Gao and Washington, 2009) and the Badan Jarain (Shao and Wang, 2003). The Gobi of Mongolia is also significant (Natsagdorj et al., 2003). The dust storms can cover immense areas and may transport dust particles to the more humid parts of China (Zhao et al., 2010), Korea, Japan, and beyond. As a consequence some major urban centres, including Beijing, Shanghai, Seoul, Tokyo and Taipei are subjected to what are called 'Asian Dust Storms'.

In southern Africa, satellite images show plumes blowing off the Namib and the Kalahari towards the South Atlantic (Eckardt et al., 2002), often having their sources in ephemeral river channels (Eckardt and Kuring, 2005). However, TOMS analyses indicate that the Etosha Pan in northern Namibia (Bryant, 2003) and the Mkgadikgadi Depression in northern Botswana (Resane et al., 2004) are even bigger sources.

In South America to the west of Buenos Aires in Argentina there are more than 8 dust storms per year (Middleton, 1986b). Dust is also generated from Patagonia (Gassó and Stein, 2007). The presence of extensive areas of closed depressions and of wind fluted topography, combined with the probable importance of salt weathering in the generation of fine material for deflation (Goudie and Wells, 1995), suggest that the dry areas of the Puna and Altiplano should be major source areas for dust storms (Gaiero et al., 2013). TOMS identifies one area where aerosol values are relatively high: this is the Salar de Uyuni, a large closed basin in Bolivia. It is probable that the deflation of fine sediments from its desiccated floor is one of the reasons for the existence of high aerosol values in this region.

Australia, though not as dusty as some regions of the world (McTainsh, 1989), is the largest dust source in the Southern Hemisphere (McTainsh et al., 2010). Within the Lake Eyre basin, one of the main source areas, using MODIS data, Bullard et al. (2008) found that 37% of dust plumes originated in areas of aeolian deposits, 30% from alluvial deposits and flood plains, and 29% from ephemeral lakes. Such lakes make some dust rich in NaCl (Shiga et al., 2011). Dust from this region leaves Australia in two main plumes: one that crosses the Tasman Sea to New Zealand (Marx et al., 2005) and another that heads westwards out into the Indian Ocean (Hesse and McTainsh, 1999). Australian dust may lead to increased respiratory problems in New Zealand (Cowie et al., 2010).

### 2.2. Long distance transport

One of the reasons why dust emissions have impacts on human health at great distances from their source is because of the great lengths over which dust plumes can travel (Zhu et al., 2007). Thus dust from the Lake Eyre basin and other parts of the interior of Australia may accumulate in New Zealand, but it also impacts upon air quality in major Australian cities, including Brisbane, Sydney, Newcastle and Melbourne (Leys et al., 2011). Saharan dust is carried thousands of kilometres to the Americas (Ben-Ami et al., 2010), Europe (Varga et al., 2013) the Near East (Thevenon et al., 2011) and the Arctic (Barkan and Alpert, 2010). Large amounts of Saharan (Harmattan) dust are blown southwards across the West African states into the Gulf of Guinea (Resch et al., 2007) and across the Atlantic to the Americas. The Sahara is also a major source of dust deposition into the Mediterranean Sea and neighbouring countries (Pey et al., 2013; Santese et al., 2007), where its health implications have been explored in such cities as Madrid, Barcelona, Rome and Athens. Dust from the Sahara and Thar reaches Mount Everest and Hong Kong in substantial quantities (Lee et al., 2010). The Ukraine has recently delivered large quantities of dust to central Europe (Birmili et al., 2007). Middle Eastern dust reaches Tehran (Givehchi et al., 2013) and India (Badarinath et al., 2010) and Chinese dust may reach North America and Europe via the Pacific (Uno et al., 2009). Indeed in May 2007 a dust cloud from the Taklamakan made a complete circuit of the globe in just 13 days.

### 2.3. The changing frequency of dust storms

The frequency with which dust storms occur is probably of importance in health terms, and there is an indication that in some areas the incidence of dust storms has increased. Neff et al. (2008), for instance, used analyses of lake cores in the San Juan Mountains of south-western Colorado, USA, to show that dust levels increased by 500% above the late Holocene average following the increased western settlement and livestock grazing during the nineteenth and the early twentieth century. A dust core from the Antarctic Peninsula (McConnell et al., 2007) showed a doubling in dust deposition in the twentieth century, and this is explained by increasing temperatures, decreasing relative humidity, and widespread desertification in the source region — Patagonia and northern Argentina. Finally, analysis of a 3200 year marine core off West Africa shows a marked increase in dust activity at the beginning of the nineteenth century, which was a time that saw the advent of commercial agricultural activity (including the clearing of ground for groundnut production) in the Sahel region (Mulitza et al., 2010).

It remains to be established, however, whether analysis of meteorological data, which has enabled the changing frequency of dust events to be established for the last six decades or so, indicates whether or not increasing dust storm frequencies are the norm. Some areas have indeed shown increasing trends (e.g. the Sahel zone of Africa (Goudie and Middleton, 1992), the eastern Mediterranean (Ganor et al., 2010), the Gobi of Mongolia (Dement'eva et al., 2013), the western USA (Brahney et al., 2013) and Korea (Chun et al., 2001)). However, others have shown declining trends in the late twentieth century (e.g. China (Wang et al., 2004), the Canary Islands (Laken et al., 2013), Turkmenistan (Orlovsky et al., 2005), Central Asia (Indoitu et al., 2012), Pakistan (Hussain et al., 2005) and parts of the USA High Plains (Stout and Lee, 2003), and Utah (Steenburgh et al., 2012). In Australia (McTainsh et al., 2005)), the declining trend was followed by a spike of activity in the early years of the present century (e.g. Mitchell et al., 2010). Other areas (e.g. the Kalahari, southwestern Iran and Seistan) have shown marked fluctuations upwards and downwards in response to such factors as lake flooding and desiccation (Bryant et al., 2007; Ghasem et al., 2012; Miri et al., 2010; Rashki et al., 2013b) or climatic fluctuations such as sunspot cycles (Mohammed, 2010).

With respect to China, both natural and anthropogenic factors are implicated in the observed trends (Xu, 2006). There is certainly no clear upward trend in dust storm activity in China when the past 50 years are considered (Yao et al., 2010) though the early years of the present millennium saw some severe events (Kurosaki et al., 2011; Yang et al., 2008). Links have been established between dust emissions from the Tarim basin and the Arctic Oscillation (AO) Index, with dust activity being high during the negative phase of the AO (Gao and Washington, 2010). The general consensus is that natural climatic fluctuations have played a greater role in explaining the observed trends than have changes in human pressures on the land (Wang et al., 2007).

In the Kalahari of southern Africa fluctuations in the emission of dust from the Mkgadikgadi Pan over the period 1980–2000 suggest that dust loadings are intermittently influenced by the extent and frequency of lake inundation, sediment inflows, and surface wind speed variability. The variability of these is in turn influenced by the El Niño-Southern Oscillation and Indian Ocean sea surface temperature anomalies (Bryant et al., 2007).

In the West African Sahel, where drought has been persistent since the mid 1960s, analysis of wind, precipitation and visibility data by Ozer (2003) has shown that there have been remarkable changes in dust emissions since the late 1940s. He indicated that during the pre-drought conditions that existed from the late 1940s to the late 1960s yearly dust production was $126 \times 10^6$ tons. It rose to $317 \times 10^6$ tons during the 1970s and has been $1275 \times 10^6$ tons since 1980, a ten-fold increase. Variability in Sahel dust emissions may be related not only to droughts, but also to an increase in the threshold wind velocity for dust entrainment. It also seems to be related to changes in the North Atlantic Oscillation (NAO) (Engelstaedter et al., 2006), North Atlantic sea surface temperatures (Wong et al., 2008) and the Atlantic Multidecadal Oscillation (Jilbert et al., 2010). The steadily increasing trend of dust storms from Africa in the Eastern Mediterranean over the last five decades in association with changing synoptic conditions has been analysed by Ganor et al. (2010). The slope of the increase is 0.27 days per year. However, African dust incidence in the Mediterranean basin decreased between 2006/2007 and 2011 in parallel with a negative period of the NAO (Pey et al., 2013).

Using a variety of data sources, Mahowald et al. (2010) have tried to estimate the global picture of changes in dust storm activity for the twentieth century. They suggest a doubling of atmospheric desert dust loadings took place over much of the globe.

An important issue form the human health perspective is whether or not dust activity will become even more frequent in coming decades. This will depend on three main factors: anthropogenic modification of desert surfaces (Mahowald and Luo, 2003); natural climatic variability (e.g. in the El Niño Southern Oscillation or the North Atlantic Oscillation); and changes in climate brought about by global warming. With regard to the first of these, increasing human pressures include disturbance of desert surfaces by vehicular traffic, increasing wildfires, removal of vegetation cover for wood supply, grazing and crop production, and desiccation of lakes and soil surfaces by inter-basin water transfers and ground water depletion (see, for example, Pelletier, 2006; Field et al., 2010; Ravi et al., 2011). A good review of the importance of different anthropogenic pressures in different parts of the world is provided by Ginoux et al. (2012). An example of severe change to a major inland sea is that taking place is the Aral Sea. Between 1960 and 1990, largely because of diversions of river flow, it lost more than 40% of its area and about 60% of its volume, and its level fell by more than 14 m. By 2002 its level had fallen another 6 m. By 2008, the area of the Aral Sea was just 15.7% of that in 1961 (Kravtsova and Tarasenko, 2010). This has lowered the artesian water table over a band 80–170 km in width, has exposed extensive expanses of former lake bed to desiccation and deflation. In the USA, water transfers from the Mono and Owens Lake basins have led to exposure of salty flats and the generation of severe dust storms derived from them (see, for example, Oho et al. (2011)). Some of the highest coarse particulate ($PM_{10}$) values ever recorded have been associated with these two sources (see Table 2).

The impact and occurrence of dust storms will depend a great deal on land management practices. Recent decreases in dust storm activity in North Dakota and the High Plains have resulted from conservation measures (Todhunter and Cihacek, 1999), while in Utah they have been caused by controls on grazing densities (Steenburgh et al., 2012).

Natural climatic variability will doubtless continue as it has in the past, but global warming has the potential to cause major changes in dust emissions. The IPCC (2007) suggests that many dryland areas will suffer from lower rainfall levels and increased amounts of moisture deficits because of higher rates of evapotranspiration. Munson et al. (2011) have argued that with increased drought brought about by reduced precipitation and higher temperatures, there will be a reduction in perennial vegetation cover in the Colorado Plateau and thus an increase in aeolian activity. Modelling studies of southern Africa by Thomas et al. (2005) have suggested that during the course of the twenty-first century most of the currently stable dune systems of the mega-Kalahari will become reactivated and mobile. This could cause substantial winnowing of fines from the weathered dune surfaces and an increase in dust emissions in southern Africa (Bhattachan et al., 2013). In the Bodélé depression of the Central Sahara, in spite of the possibility of higher rainfall amounts predicted by some models, higher wind velocities may increase its dust activity in coming decades (Washington et al., 2009).

In contrast, however, in northern China, there is some evidence that dust storm activity has decreased in recent warming decades, partially in response to changes in the atmospheric circulation and associated wind conditions (Jiang et al., 2009) and might decrease therefore still further in a warming world (Zhu et al., 2008). Indeed, recent research in China has demonstrated that over the last five decades or so there have been changes in wind activity that have been related to warming trends. As warming has occurred wind velocities have fallen (e.g. Wang et al., 2007; Xu, 2006). Various modelling studies have suggested that more generally in low latitudes extreme wind events will become less frequent with global warming, and this has been confirmed for the USA (Breslow and Sailor, 2002). 'Atmospheric stilling' has been a widespread feature of recent warming decades in Australia and elsewhere (Vautard et al., 2010).

### 2.4. $PM_{10}$ and $PM_{2.5}$ levels in dust storms

A very important aspect of dust storms in relationship to health issues, particularly respiratory ones, is the amount of suspended material that they contain. This is normally expressed as $PM_{10}$ values (aerodynamic diameter less than 10 μm) and $PM_{2.5}$ (aerodynamic radius less than 2.5 μm). This review concentrates on these two parameters as they are the ones most usually monitored on an international basis. Table 2 presents data on $PM_{10}$ levels that have been recorded in dust storms, though in many cases these data have not been related to specific health outcomes but are presented to give an indication of the concentrations that have been recorded during recent dust monitoring programmes. Some storms are associated with very high dust concentrations. While this may be the case in proximity to source, it is notable that events at quite large distances downwind can also be elevated, as is evident for some of the data for big cities in East Asia (Wang et al., 2013) and Australia (Leys et al., 2011). Even in southern Europe African dust incursions can produce high particulate levels (Pey et al., 2013), though they show a decline northwards. Table 3 presents data on the concentrations of finer particles ($PM_{2.5}$) and also on the percentage they make of the total coarse and fine particulates. In general the finer particles form a bigger percentage of the total at lower particulate concentrations. In the USA the highest $PM_{10}$ concentrations are associated with thunderstorm downbursts (Lei and Wang, 2013).

**Table 2**
Maximum observed $PM_{10}$ levels in dust storms.

| Source | Location | Date | Concentration (μg $m^{-3}$) |
|---|---|---|---|
| *(1) Southern Europe* | | | |
| Masson et al. (2010) | South of France | 20/2/2004 | 150–443 |
| Mallone et al. (2011) | Rome | – | 182 |
| Neophytou et al. (2013) | Cyprus | – | >250 |
| Cabello et al. (2012) | S. Spain | October 2008 | 378 |
| Kaskaoutis et al. (2008) | Crete | 17/4/2005 | 2500 |
| Kaskaoutis et al. (2008) | Athens | 17/4/2005 | 250 |
| Polymenakou et al. (2008) | Crete | February 2006 | 2800 |
| Birmili et al. (2008) | Central Europe | March 2007 | 200–1400 |
| *(2) Eastern Asia* | | | |
| Chung et al. (2003) | Korea | 21–23/3/2002 | 3006 |
| Chung et al. (2003) | Korea | 7/4/2002 | 2942 |
| Lee et al. (2013) | Korea | 30–31/5/2008 | 1059 |
| Lee et al. (2013) | Korea | 25–26/12/2009 | 1041 |
| Yuan et al. (2004) | Pescadores (Taiwan) | – | 134 |
| Xie et al. (2005) | Beijing | 6/4/2000 | 798 |
| Xie et al. (2005) | Beijing | 25/4/2000 | 849 |
| Fu et al. (2010) | Shanghai | April 2007 | 648 |
| Wang et al. (2013) | Shanghai | 20–21/3/2010 | 1700 |
| Wang et al. (2013) | Shanghai | 26–27/4/2010 | 236 |
| Dement'eva et al. (2013) | Mongolia | – | 1930 |
| *(3) Australia* | | | |
| Merrifield et al. (2013) | Sydney | September 2009 | 11705 |
| Leys et al. (2011) | Randwick | 23/9/09 | 1734 |
| Leys et al. (2011) | Newcastle | 23/9/09 | 2426 |
| Leys et al. (2011) | Bringelly | 23/9/09 | 15,366 |
| Barnett et al. (2012) | Brisbane | 24/9/2009 | 894 |
| Chan et al. (2005) | Sydney | 23/10/2002 | 266 |
| Chan et al. (2005) | Brisbane | 23/10/2002 | 841 |
| Chan et al. (2005) | Gladstone | 23/10/2002 | 537 |
| Chan et al. (2005) | Mackay | 23/10/2002 | 899 |
| *(4) West Africa* | | | |
| Alastuey et al. (2005) | Canary Islands | July 2002 | 312 |
| Ozer (2006) | Mauritania | March 2004 | 2998 |
| Marticorena et al. (2010) | M'Bour (Senegal) | 8/3/2006 | 2500 |
| Marticorena et al. (2010) | Cinzana (Mali) | 8/3/2006 | 3500 |
| Marticorena et al. (2010) | Banizoumbo (Niger) | 8/3/2006 | 5000 |
| *(5) North America* | | | |
| Bennett et al. (2006) | Vancouver (Canada) | April 1998 | 123 |
| Claiborn et al. (2000) | Spokane (USA) | July 1994 | 1200 |
| Lei and Wang (2013) | Western USA | – | 3543 |
| Cahill et al. (1996) | Owens Lake (USA) | – | 40,620 |
| Oho et al. (2011) | Mono Lake (USA) | 20/11/2009 | 65,112 |
| Hahnenberger and Nicoll (2012) | Lindon, Utah (USA) | 30/3/2010 | 424 |
| *(6) Middle East* | | | |
| Rashki et al. (2012) | Iran | – | 3094 |
| Shahsavani et al. (2012) | Ahvaz (Iran) | 2010 | 5338 |
| Grishkan et al. (2012) | Haifa (Israel) | 23/1/2004 | 700 |
| Amanollahi et al., 2011 | Sanandaj (Iran) | 5/7/2009 | 5619 |
| Krasnov et al. (2013) | Beer-Sheva (Israel) | February 2012 | 5197 |

### 2.5. The durations of elevated particulate levels

In general dust storms have a short duration at any one location. In the western USA, Lei and Wang (2013) (Table 2) suggest that most storms last between 2 and 21 h. In Turkmenistan the frequency of dust storms with a duration of 12 h or more is only about 3%, though occasional examples lasting 3 days have been observed there (Orlovsky and Orlovsky, 2001). In Central Asia more generally, 40–60% of the dust events last on average 1.5–5.4 h (Indoitu et al., 2012). In the Gobi of Mongolia the average dust storm lasts from 1.6 to 6.0 h (Natsagdorj et al., 2003), while in China's Taklamakan the most serious dust storm conditions persist for 2 to 4 h (Yoshino, 1992). More generally in China, Wang et al. (2005) suggest that most dust storms last less than 2 h.

$PM_{10}$ values may, however, remain high for extended periods in dusty areas. In the Sistan region of Iran, for example, monthly mean values are high throughout the year, and were found to average 273 μg $m^{-3}$ in the winter, 289 in the spring, 683 in the summer and 484 in the autumn (Rashki et al., 2012). In Zabol over 30% of days in the year exceeded the US EPA hazardous value of 425 μg $m^{-3}$. In the Gobi of Mongolia the average annual $PM_{10}$ concentration at Zamyn-üüd is 81 μg $m^{-3}$ and the maximum mean monthly concentration in May reaches 139 μg $m^{-3}$ (Dement'eva et al., 2013). In Ahvaz, Iran, the average $PM_{10}$ values for the months of April to September range from 186 to 489 μg $m^{-3}$ (Shahsavani et al., 2012), while in Zahedan they range from 101 to 182 μg $m^{-3}$ (Rashki et al., 2013a, 2013b). In 1984, a particularly dry year, the average annual $PM_{10}$ concentration in Gouré, Niger, was 245 μg $m^{-3}$ (de Longueville et al., 2013). In Canyonlands National Park, Utah, Neff et al. (2013) found that in several cases, PM > 10 concentrations exceeded 300 μg $m^{-3}$ with the largest dust-deposition period, in 2010, having a two-week average concentration in excess of 700 μg $m^{-3}$.

Engelbrecht et al. (2009) presented annual average particulate concentrations for 15 locations in the Middle East (Table 4). This

**Table 3**
Maximum observed $PM_{2.5}$ levels ($\mu g\ m^{-3}$) in dust storms.

| Source | Location | Date | $PM_{2.5}$ | % of $PM_{10}$ |
|---|---|---|---|---|
| *(1) Southern Europe* | | | | |
| Mallone et al. (2011) | Rome | – | 86 | 47.3 |
| Jiménez et al. (2010) | Madrid | – | 71 | 47.3 |
| Vanderstraten et al. (2008) | Belgium | March, 2007 | 43 | 42.8 |
| *(2) Eastern Asia* | | | | |
| Dement'eva et al. (2013) | Mongolia | – | 700 | 36.3 |
| Yuan et al. (2004) | Pescadores (Taiwan) | – | 63 | 47.0 |
| Chung et al. (2003) | Korea | 23–24/3/2000 | 331 | 11.0 |
| Chung et al. (2003) | Korea | 7/4/2002 | 294 | 10.0 |
| Jugder et al. (2011) | Mongolia | – | 500 | 60.9 |
| Wang et al. (2013) | Shanghai | 20–21/3/2010 | 469 | 27.6 |
| Wang et al. (2013) | Shanghai | 26–27/4/2010 | 94 | 28.8 |
| *(3) Others* | | | | |
| Shahsavani et al. (2012) | Ahvaz, Iran | 2010 | 911 | 17.1 |
| Merrifield et al. (2013) | Sydney | 9/2009 | 1638 | 14.0 |
| Barnett et al. (2012) | Brisbane | 24/9/2009 | 138 | 15.4 |
| Chan et al. (2005) | Brisbane | 23/10/2002 | 42 | 26.1 |
| Claiborn et al. (2000) | Spokane (USA) | 07/1994 | 150 | 12.5 |
| Grishkan et al. (2012) | Haifa (Israel) | 23/1/2004 | 280 | 40.0 |
| Hahnenberger and Nicoll (2012) | Lindon, Utah (USA) | 30/3/2010 | 55.7 | 13.1 |

demonstrates very powerfully that over large parts of the region, citizens (and military personnel) are exposed to high levels of particulates, with $PM_{10}$ values ranging from 72 to 303 $\mu g\ m^{-3}$ and $PM_{2.5}$ values ranging from 35 to 111 $\mu g\ m^{-3}$. The WHO (http://www.who.int/phe/health_topics/outdoorair/databases/en/) (accessed 2nd July, 2013) has provided data on annual average $PM_{10}$ values for cities from all over the world, and while some of the cities with high values may be heavily polluted because of industrial and transport emissions, combined with atmospheric inversions that retain particulates in the lower atmosphere, it is noticeable that most of them occur in areas that are also subject to major dust storm incursions (Table 5a). Likewise, World Bank data (Table 5b) (http://data.worldbank.org/indicator/EN.ATM.PM10.MC.M3) (accessed 2nd July, 2013) indicates that most countries with high average $PM_{10}$ values are in the dusty countries of northern Africa and the Middle East.

### 2.6. Biomaterials

Dust storms pick up and transport biological materials which include bacteria, pollen spores, fungi and viruses (Table 6). These are capable of surviving long-range transport on a global scale. All of these have potential implications for disease incidence, including meningococcal meningitis and coccidiomycosis. This is an area that has been expertly reviewed by Griffin (2007) who notes that although we know that dust contains pathogens, in most cases the risk associated with them is still largely unknown. Dadvand et al. (2011), working in Barcelona, tested the possibility that infections associated with materials transported from North Africa might have an adverse effect on pregnancies, but found no evidence for a link. Desert dust may contain dangerous cyanotoxins but further research is required to assess their significance (Metcalf et al., 2012). Nonetheless, in Japan, Watanabe et al. (2011a, 2011b) found that asthma in adults was augmented on days when Asian Dust carried pollen in comparison with dusty days without pollen.

**Table 4**
Annual particulate concentrations in Middle East locations (derived from data in Engelbrecht et al., 2009).

| Location | $PM_{10}$ $\mu g\ m^{-3}$ | $PM_{2.5}$ $\mu g\ m^{-3}$ | Ratio |
|---|---|---|---|
| Djibouti | 72 | 35 | 0.49 |
| Bagram (Afghanistan) | 108 | 38 | 0.35 |
| Khowst (Afghanistan) | 127 | 75 | 0.59 |
| Qatar | 165 | 67 | 0.41 |
| UAE | 140 | 52 | 0.37 |
| Balad (Iraq) | 184 | 56 | 0.30 |
| Baghdad (Iraq) | 250 | 103 | 0.41 |
| Tallil (Iraq) | 303 | 65 | 0.21 |
| Tikrit (Iraq) | 298 | 111 | 0.37 |
| Taji (Iraq) | 213 | 81 | 0.38 |
| Al Asda (Iraq) | 95 | 37 | 0.39 |
| N. Kuwait | 211 | 67 | 0.32 |
| C. Kuwait | 298 | 87 | 0.29 |
| Coastal Kuwait | 175 | 60 | 0.34 |
| Southern Kuwait | 199 | 62 | 0.31 |
| Mean | 189 | 66 | 0.35 |

### 2.7. Miscellaneous pollutants

Dust storms can pick and transport anthropogenic material as a result of particulate/pollutant aerosolization and the absorption of such materials as pesticides, herbicides, heavy metals, dioxins, and radioactive isotopes (Table 7). Dust storms that have moved across heavily industrialized and polluted areas, such as northern China may therefore pose a greater risk than those storms that have tracked out of the Sahara to the Atlantic Ocean without passing over heavily developed areas (Almeida-Silva et al., 2013). In addition, dust storms may remove toxic or irritating materials from desiccated lake beds, including various types of salts and arsenic (Morman and Plumlee, 2013). There has been especial concern about the deflation of pesticides from the exposed bed of the shrinking Aral Sea (Ataniyazova et al., 2001; O'Hara et al., 2000). Because they are normally sparsely populated, deserts such as those of China (Lop Nor), Australia (Maralinga), Kazakhstan (Semipalatinsk) USA (Nevada), Algeria (Reggane) and north west India (Pokhran) were the sites of nuclear tests. Radionuclides may be blown from them in dust storms. Dust storms also used to occur in the Chernobyl area and transported cesium towards the Baltic states (Ogorodnikov, 2011). Tailings from uranium mines are another potential source of radionuclides in dust storms (Csavina et al., 2012), with major uranium mines occurring in a number of arid regions, including South Australia, Niger, Utah, Namibia and Kazakhstan.

## 3. Human disorders

There is not space in this paper to consider in detail the specific biological processes by which dust particles of different sizes have an impact on human health. However, as Sandstrom and Forsberg (2008) have pointed out, particle size is a main determinant of where in the respiratory tract the particle will come to rest when inhaled. Because of

**Table 5**
Particulate concentrations in world cities.

a. The world's cities with average annual PM10 values of 150 and above (μg $m^{-3}$), processed from WHO (http://www.who.int/phe/health_topics/outdoorair/databases/en/) (accessed 2nd July, 2013) by author.

| Average value | City | Country |
|---|---|---|
| 372 | Ahwaz | Iran |
| 279 | Ulanbaator | Mongolia |
| 254 | Sanandaj | Iran |
| 251 | Ludhiana | India |
| 251 | Quetta | Pakistan |
| 229 | Kermanshah | Iran |
| 219 | Peshawar | Pakistan |
| 216 | Gaborone | Botswana |
| 215 | Yasouj | Iran |
| 209 | Kanpur | India |
| 200 | Lahore | Pakistan |
| 198 | Delhi | India |
| 193 | Karachi | Pakistan |
| 189 | Islamabad | Pakistan |
| 185 | Rawalpindi | Pakistan |
| 183 | Uromiyeh | Iran |
| 176 | Qom | Iran |
| 174 | Indore | India |
| 168 | Khoramabad | Iran |
| 165 | Agra | India |
| 158 | Al Ain | United Arab Emirates |
| 157 | Riyadh | Saudi Arabia |
| 151 | Al Hafouf | Saudi Arabia |
| 150 | Lanzhou | China |

b) World Bank data on countries with average annual $PM_{10}$ values greater than 60 μg $m^{-3}$ in 2010 and relating to cities with >100,000 inhabitants (http://data.worldbank.org/indicator/EN.ATM.PM10.MC.M3) (accessed 2nd July, 2013).

| Average value | Country |
|---|---|
| 137 | Sudan |
| 115 | Bangladesh |
| 112 | Uruguay |
| 111 | Mali |
| 97 | Trinidad and Tobago |
| 96 | Mongolia |
| 96 | Niger |
| 96 | Saudi Arabia |
| 95 | Oman |
| 91 | Kuwait |
| 91 | Pakistan |
| 89 | United Arab Emirates |
| 88 | Iraq |
| 83 | Chad |
| 78 | Egypt |
| 77 | Senegal |
| 69 | Algeria |
| 68 | Mauritania |
| 65 | Burkina Faso |
| 65 | Libya |
| 65 | Sri Lanka |
| 64 | Botswana |
| 64 | Paraguay |
| 61 | Eritrea |

their small size, particles on the order of ~10 μm or less ($PM_{10}$) can penetrate the deepest part of the lungs such as the bronchioles or alveoli. Larger particles are generally filtered in the nose and throat via cilia and mucus, but particles smaller than about 10 μm, can settle in the bronchi and lungs and cause health problems. Particles which are smaller than 2.5 μm, tend to penetrate into the gas exchange regions of the lung, and ultra-fine particles (<100 nm) may pass through the lungs to affect other organs, with possible cardiovascular consequences (Brook et al., 2010; Martinelli et al., 2013).

According to WHO (http://www.who.int/mediacentre/factsheets/fs313/en/) (accessed 29th June, 2013) the acceptable annual mean value of $PM_{10}$ is 20 μg $m^{-3}$ and the acceptable 24 h mean value is 50 μg $m^{-3}$ (de Longueville et al., 2013). The EU (http://ec.europa.eu/environment/air/quality/standards.htm) (accessed 29th June 2013) has 1 year mean $PM_{2.5}$ values of 25 μg $m^{-3}$, 1 year $PM_{10}$ mean values of 40 and 24 h mean $PM_{10}$ values of 50. Such values are regularly exceeded in areas downwind of dust sources (Ozer, 2006). On Dec. 14, 2012 the U.S. Environmental Protection Agency (EPA) strengthened the nation's air quality standards for fine particle pollution to improve public health protection by revising the primary annual $PM_{2.5}$ standard to 12 micrograms per cubic meter (μg $m^{-3}$). The EPA also has a 24-h $PM_{2.5}$ standard of 35 μg $m^{-3}$ and a 24-h standard of 150 μg $m^{-3}$ for $PM_{10}$ (http://www.epa.gov/airquality/particlepollution/2012/decfsstandards.pdf) (accessed 29th June, 2013). The EPA regards 24 h $PM_{2.5}$ levels between 35.5 and 55.4 μg $m^{-3}$ as being unhealthy for sensitive groups, 55.5–150.4 as being unhealthy, 150.5–250.4 as being very unhealthy, and 250.4–500 as hazardous.

**Table 6**
Examples of biological materials carried in dust storms.

| Source | Location | Material |
|---|---|---|
| Leski et al. (2011) | Kuwait & Iraq | *Mycobacterium*, *Brucella*, *Coxiella Burnetii*, *Clostridium perfingens*, *Bacillus* |
| Thomson et al. (2009) | West Africa | *Neissera meningitides* |
| Chen et al. (2010) | Taiwan | Influenza virus |
| Watanabe et al. (2011a) | Japan | Pollen spores |
| Polymenakou et al. (2008) | Crete | Bacteria |
| Jeon et al. (2011) | Korea | Bacteria |
| Grishkan et al. (2012) | Israel | Fungal communities |
| Soleimani et al. (2013) | Iran | Fungi: *Cladosporium*, *Alternaria*, *Aspergillus*, *Penicillium* and *Rhizophus* |
| Perfumo and Marchant (2010) | Turkey | Thermophilic bacteria (*Geobacillus*) |
| Schlesinger et al. (2006) | Israel | Bacteria and fungi |
| Najafi et al. (2013) | Iran | Bacteria and fungi |

### *3.1. Respiratory disorders*

The pathogenic effect of dust inhalation on respiratory tissues can be attributed to the direct physical action of dust particles on the epithelium of the human airways and may be exacerbated by the toxic effects of both trace elements (including arsenic, etc.) and of biologically active compounds (bacteria, fungi, pollen, and viruses) (Leski et al., 2011). It is likely that the population most susceptible to suffering from the short-term effects of suspended particulates are (Jiménez et al., 2010) (a) the elderly, due to their lower immunological capacity and the deterioration in their general health due to the ageing process, (b) subjects affected by chronic cardiopulmonary disorders, and (c) the very young, whose lungs and airways have yet to develop fully (Yu et al., 2012). In Japan, Kanatani et al. (2010) found that Asian dust exacerbated asthma in children and caused increased hospitalisation, while Chien et al. (2012) working in Taipei (Taiwan) found that there was a significant relationship between dust storms and clinic visits for respiratory disease in children.

Questions have been asked in the Americas as to whether or not dust from Asia, notwithstanding the distance over which it has travelled and the relatively low particulate content it displays, has an effect on asthma (Prospero et al., 2008). Gyan et al. (2005) found that there was an association between increased asthma admissions in Trinidad and African dust clouds. On the other hand, Bennett et al. (2006), working in Vancouver (Canada) found that a Gobi desert dust event was not associated with a significant risk to public health.

There are a range of studies in East Asia that have sought to relate Asian Dust events to respiratory problems such as asthma, pneumonia and tracheitis (Yang, 2013). Tao et al. (2012), working in Lanzhou, China, found that dust storms led to increased respiratory hospitalizations, particularly for those aged over 65. Tam et al. (2012), working in Hong Kong, found significant increases in emergency hospital admissions due to respiratory problems, with a 1.05 increase per 10 μg $m^{-3}$.

**Table 7**
The nature of pollutant materials carried in dust storms.

| Source | Location | Nature of substance(s) |
|---|---|---|
| Masson et al. (2010) | France | Radioactive cesium ($^{137}Cs$) from Sahara |
| Akata et al. (2007) and Fukuyama and Fujiwara (2008) | Japan | Radioactive cesium ($^{137}Cs$) from China and Mongolia |
| Kikawada et al. (2012) | Japan | Enriched uranium from Central Asia |
| Gabrieli et al. (2013) | European Alps | Plutonium from Saharan atomic tests |
| Lee et al. (2013) and Park and Dam (2010) | Korea | Heavy metals from China |
| Onishi et al. (2011, 2012) | Japan | Heavy metals from China |
| Liu et al. (2011), and Li et al., 2013 | China | Heavy metals |
| Li et al. (2012) | China | Sulphates and nitrates |
| Kwon et al. (2013) | Korea | Polycyclic aromatic hydrocarbons |
| Hou et al. (2006) | China | Polycyclic aromatic hydrocarbons and fatty acids |
| O'Hara et al. (2000) | Aral Sea | Phosalone from Aral Sea |
| Ataniyazova et al. (2001) | Aral Sea | Heavy metals, organochlorine pesticides, Dioxins from Aral Sea |
| Gill et al. (2002) | Owens Lake, USA | Arsenic |
| Chi et al. (2008) and Wu et al. (2010) | Taiwan | Dioxins and PCBs from China |

Chien et al. (2012), working in Taipei found that compared with weeks before Asian dust events respiratory clinic visits during the weeks after an event increased by 2.54% for children younger than 6, and by 5.03% for children aged 7–14 years. Studies in Seoul, Korea, by Lee and Lee (2013) showed that Asian dust events led to a 22% increase in the rate of asthma treatments with a 6 day lag. Pneumonia is another respiratory complaint that appears to be influenced by Asian dust events. Cheng et al. (2008) and Kang et al. (2012), working in Taipei (Taiwan), found significantly elevated pneumonia admissions. Allergic rhinitis incidence in Taiwan has also been related to Asian dust (Chang et al., 2006).

In Australia, various studies have been undertaken to see the effects of dust storms moving eastwards from the interior. Rutherford et al. (1999), who studied Brisbane, found that dust events were significantly associated with asthma severity. A 15%increase in non-accidental mortality at a lag of 3 days from a dust event was found for Sydney (Johnston et al., 2011), where Merrifield et al. (2013) also found large increases in asthma emergency department visits. In Brisbane, there was a 39% increase in emergency admissions associated with a dust storm in 2009.

The effects of African dust outbreaks on asthma and other respiratory and cardiac afflictions in southern Europe has been the subject of considerable attention (Karanasiou et al., 2012). In Athens, Samoli et al. (2011) found that a 10 μg $m^{-3}$ $PM_{10}$ level was associated with a 0.71% increase in all deaths, with those over 75 years or older being especially affected. Likewise, in Madrid Jiménez et al. (2010) found a significant statistical association between $PM_{10}$ levels and mortality for the elderly on Saharan Dust days. Also in Madrid, Reyes et al. (2013) found that periods with Saharan dust intrusions saw a significant increase in respiratory-caused admissions which could be related to $PM_{10}$ levels. In Barcelona, Perez et al. (2008) found that during Saharan Dust days a daily increase of 10 μg $m^{-3}$ of $PM_{10-2.5}$ increased daily mortality by 8.4%. In Rome, Mallone et al. (2011) found that such events were associated with an increase in cardiac and respiratory mortality. Similarly in Emilia–Romagna Sajani et al. (2011) found an increased risk of respiratory mortality for people aged 75 or over.

Military personnel stationed in Afghanistan and Iraq have also suffered from dust related pulmonary problems (Furlow, 2013). Other locations where a link between dust events and respiratory problems has been established include Seistan, Iran (Miri et al., 2007). There are also high levels of asthma in the Arabian Gulf region, with, for example, 24% of the population of Saudi Arabia being asthmatic, and dust storms are one possible factor (along with lifestyle, smoking and indoor dust levels) for this (Al-Ghazawy, 2013). On the other hand, a significant association between dust levels and respiratory mortality has not always been found, as demonstrated by the work of Schwartz et al. (1999) in the Spokane area of Washington, USA, by Wiggs et al. (2003) and Bennion et al. (2007) in the Aral Sea region, and by Al-Taiar and Thalib (2013) in Kuwait.

Much dust storm material is silt-sized quartz, and it has been argued that this can, if inhaled over a sustained period, cause non-occupational silicosis (also called desert lung syndrome) to develop in human lungs. This appears to be an issue, especially among the elderly, in some areas of High Asia (Derbyshire, 2007) including north west China and Ladakh (India) (Norboo et al., 1991; Saiyed et al., 1991). High incidences of silicosis and pneumoconiosis have been reported in Bedouins in the Negev (Bar-Ziv and Goldberg, 1974). Silicosis may be an important factor in the higher prevalence of tuberculosis in some deserts, including the Thar of India (Mathur and Choudhary, 1997).

Recently, a modelling study has suggested that in the 'dust belt' of North Africa and the Middle East, a substantial proportion of lung cancers may be caused by exposure to desert dust (Giannadaki et al., 2013), especially in countries like Mauritania and Mali.

### 3.2. Cardiovascular disorders

There is an increasing body of epidemiological evidence that high particulate levels in the air cause cardiovascular disease (Brook et al., 2010), including myocardial infarction, stroke, heart failure, arrhythmias, and venous thromboembolism (Martinelli et al., 2013). Schulz et al. (2005) have suggested that the possible biological mechanisms associated with exposure to particulates include '(i) pulmonary and/or systemic inflammatory responses triggering endothelial dysfunction and a pro-coagulatory state with thrombus formation and promotion of atherosclerotic lesions, (ii) dysfunction of the autonomic nervous system in response to direct reflexes from receptors in the lungs and/or to local or systemic inflammatory stimuli, and (iii) cardiac malfunction due to ischemic responses in the myocardium and/or altered ion-channel functions in myocardial cells'.

There is increasing evidence of cardiovascular problems associated with dust events. Yang et al. (2005) and Kang et al. (2013), working in Taiwan, found that Asian Dust Storms were associated with an acute increase in stroke hospitalisation. However, also working in Taiwan, Yang et al. (2009) were unable to find a statistically significant association with congestive heart failure. On the other hand, Meng and Lu (2007), working in Minqin, China, found an association between dust events and hypertension in males. In Nagasaki, Japan, Ueda et al. (2012) reported that heavy Asian dust events caused emergency ambulance dispatches for cardiovascular diseases to rise by 20.8%. Likewise, in Cyprus, Middleton et al. (2008) found that cardiovascular admissions increased after dust episodes, and Neophytou et al. (2013) found there was a 2.43% increase in daily cardiovascular associated with each 10 μg $m^{-3}$ increase in $PM_{10}$ concentrations on African Dust days. In Spain, Perez et al. (2012) found an increased cardiovascular mortality associated with $PM_{10-2.5}$ levels, as did Alessandrini et al. (2013) in Rome, Italy.

### 3.3. Miscellaneous other diseases and health issues

#### 3.3.1. Coccidiomycosis

Coccidiomycosis is an infection caused by the inhalation of airborne spores of *Coccidioides immitis*, a soil dwelling fungus found in the south west USA and parts of Mexico and central and South America. It affects the lungs, can cause extreme disfigurement, and can be fatal. In the USA it is often known as Valley Fever (Zender and Talamantes, 2006) and around 150,000 cases are reported each year (Anderson, 2013). The association between dust storms and the disease in California and Arizona has been known for a long time (see, for example, Pappagianis and Einstein, 1978; Leathers, 1981), and more recently Comrie (2005) has demonstrated that there is a strong bimodal seasonality of the disease in Pima County, Arizona, with peaks in June–July and August–November, which are the drier and dustier months.

#### 3.3.2. Meningococcal meningitis

Meningococcal meningitis is a serious health problem in West Africa (Thomson et al., 2009) and the incidence of epidemics appears to be related to the timing and severity of Saharan dust intrusions (the Harmattan). Fears have also been expressed about possible transport of the bacteria *Neisseria meningitides*, to southern Europe (Tobias et al., 2011a, 2011b). During the 1980s there were between 25,000 and 200,000 cases in the Sahel per year (Sultan et al., 2005), and levels continued to be high between 2004 and 2009 (Martigny and Chiapello, 2013), especially in Nigeria, Burkina Faso, the Congo Democratic Republic and Niger. One theory is that dust, combined with the extremely dry air, damages the pharyngeal mucosa, thereby easing bacterial invasion (Agier et al., 2013). There is a clear temporal correlation between times of great atmospheric dust contents and cases of meningitis (i.e. in January to April) (Deroubaix et al., 2013; Martigny and Chiapello, 2013).

#### 3.3.3. Conjunctivitis

Prolonged exposure to dusty air can lead to conjunctivitis. Dust blown by the Irifi wind of the Western (formerly Spanish) Sahara is responsible for the conjunctivitis that is common among the nomads of that country (Morales, 1946). In Taiwan, Yang (2006) found some evidence for an association between Asian Dust Events and clinic visits for conjunctivitis, but the association was not statistically significant. However, in a subsequent study Lien et al. (2013) did find elevated conjunctivitis clinic visits during dust storm periods. An epidemic of conjunctivitis in Lagos, Nigeria has also been related to Saharan dust outbreaks (McMoli et al., 1984).

#### 3.3.4. Dermatological disorders

The presence of heavy metals such as nickel in dust may cause skin irritation (Onishi et al., 2011; Otani et al., 2012). In addition, it has been suggested that Asian dust storm particles can 'exert toxicological effects on human skin through the activation of the cellular detoxification system, the production of pro-inflammatory and immunomodulatory cytokines and changes in the expression of proteins essential in normal epidermal differentiation' (Choi et al., 2011, p. 92).

#### 3.3.5. Algal blooms and red tides

There is increasing evidence that the nutrients carried in dust storms, including iron (Mahowald et al., 2009), can indirectly impact human health by stimulating toxic algal blooms in coastal environments (Griffin and Kellogg, 2004). This is true for the Arabian Gulf (Al-Shehhi et al., 2012), the Arabian Sea (Kayetha et al., 2007), the Yellow Sea off China (Shi et al., in press; Tan et al., 2011), the south east Mediterranean (Herut et al., 1999) but also for Florida, where red tides associated with blooms of *Karenia brevis* and *Trichodesmium* appear to result from inputs of Saharan dust (Lenes et al., 2008; Walsh and Steidinger, 2001; Walsh et al., 2006) and have a range of effects including neurotoxic shellfish poisoning (NSP) and respiratory complaints (Fleming et al., 2011).

#### 3.3.6. Deaths and injuries resulting from transport accidents

Dust storms can cause death through their role in causing accidents on the road and in the air (Baddock et al., 2013). In November 1991, a series of collisions involving 164 vehicles and causing 17 deaths occurred on Interstate 5 in the San Joaquin Valley in California, USA (Pauley et al., 1996), while in Oregon a dust storm in September 1999 set off a chain reaction of 50 car crashes that killed eight people and injured more than twenty. The loss of visibility may be very sudden when caused by the arrival of a dust wall associated with a dry thunderstorm. Such Haboob dust walls were responsible for 32 multiple accidents between 1968 and 1975 on Interstate 10 in Arizona (Brazel and Hsu, 1981). Between 2001 and 2005 there were 44 deaths in 2323 traffic accidents in New Mexico and 15 deaths in 614 accidents in Arizona (http://www.azcentral.com/arizonarepublic/news/articles/20120726arizona-researcher-explores-dangers-living-dust.html?nclick_check=1) (accessed 6th September, 2013). In the USA in 2012/3 a survey of newspaper headlines available online indicates that dust storm related multiple traffic incidents occurred in Idaho, California, Texas, Arizona, Nevada and Oklahoma.

Some fatal commercial air crashes have also been attributed to visibility reduction or to the adverse mechanical effects of dust storms (Goudie and Middleton, 2006, p. 51). On 7th May 2002, for example, an EgyptAir aircraft crashed near Tunis killing 18 of 60 people on board (http://airsafe.com/events/airlines/egyptair.htm) (accessed 6th September, 2013). On 30th January 2000, a Kenya Airways Airbus crashed in the Ivory Coast with the loss of 179 lives (http://www.nrlmry.navy.mil/aerosol_web/Case_studies/20000130_ivorycoast/) (accessed 6th September, 2013). On 19th August 2012 31 people died in an air crash at Talodi in Sudan (http://www.ainonline.com/aviation-news/aviation-international-news/2012-10-05/accidents-october-2012) (accessed 6th September, 2013) while on 25th May, 2011, 10 people died in a crash in Faridabad, India. (http://dgca.nic.in/accident/reports/VT-ACF.pdf) (accessed 6th September, 2013).

## 4. Conclusions

Dust storms are events of considerable extent and of frequent occurrence in deserts and on their margins, and transport large amounts of particulates, pollutants and biological materials for long distances downwind. In some parts of the world, though not all, they appear to be occurring with greater frequency and some forecasts suggest that this will continue in response to increasing land use pressures and lower soil moisture contents resulting from climate change. An increasing corpus of studies, particularly in east Asia, show associations between dust events and a range of human health issues, including respiratory problems, cardiovascular complaints, meningococcal meningitis, conjunctivitis, skin irritation, and deaths and injuries associated with transport accidents. There are, however, some parts of the world, including the Gulf States of the Middle East, and countries in northern and western Africa (De Longueville et al., 2010), where relatively little epidemiological research has been published on the relationship between dust events and health. Nevertheless, the increasing availability of information about dust storm frequencies, trajectories, and particulate contents as a result of the availability of large amounts of data from various satellite-borne sensors, means that there is now a greater potential for their health effects to be explored in greater detail by collaboration between medical and environmental scientists.

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