

Desert dust hazards: A global review

Highlights

- Discusses distribution and frequency of dust storms across the world.
- Discusses long-distance transport pathways.
- Examines the effects of desert dust storms on human society.
- Reviews economic assessments of desert dust hazards.

Abstract

Dust storms originate in many of the world's drylands and frequently present hazards to human society, both within the drylands themselves but also outside drylands due to long-range transport of aeolian sediments. Major sources of desert dust include the Sahara, the Middle East, central and eastern Asia, and parts of Australia, but dust-raising occurs all across the global drylands and, on occasion, beyond. Dust storms occur throughout the year and they vary in frequency and intensity over a number of timescales. Long-range transport of desert dust typically takes place along seasonal transport paths. Desert dust hazards are here reviewed according to the three phases of the wind erosion system: where dust is entrained, during the transport phase, and on deposition. This paper presents a synthesis of these hazards. It draws on empirical examples in physical geography, medical geology and geomorphology to discuss case studies from all over the world and in various fields. These include accelerated soil erosion in agricultural zones – where dust storms represent a severe form of accelerated soil erosion – the health effects of air pollution caused by desert aerosols via their physical, chemical and biological properties, transport accidents caused by poor visibility during desert dust events, and impacts on electricity generation and distribution. Given the importance of desert dust as a hazard to human societies, it is surprising to note that there have been relatively few attempts to assess their impact in economic terms. Existing studies in this regard are also reviewed, but the wide range of impacts discussed in this paper indicates that desert dust storms deserve more attention in this respect.

Keywords: Desert dust; Mineral aerosols; Particulate matter; Drylands; Climate hazards; Wind erosion

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34 **1. Introduction**

35 Dust storms, most of which originate in the world’s deserts and semi-deserts – commonly
36 referred to as drylands – play an integral role in the Earth system (Goudie and Middleton, 2006; Shao
37 et al., 2011). Their impacts are numerous and wide-ranging, including effects on climate processes
38 and air chemistry, nutrient dynamics and biogeochemical cycling in both oceanic and terrestrial
39 environments, soil characteristics and geomorphology. All of these impacts have repercussions for
40 human society, of course, but people are also influenced more directly by a number of desert dust
41 hazards, such as atmospheric pollution. Given that drylands cover about 40% of the world's land
42 surface and are home to more than 2 billion people (Safriel et al., 2005), these hazards are of
43 considerable importance, but their significance is further magnified because desert dust events
44 frequently involve long-range transport over thousands of kilometres, often taking dust far beyond
45 dryland environments.

46 Our understanding of desert dust and our appreciation of its significance in the Earth system has
47 increased markedly in recent years. In large part, this has been driven by self-interest due to the direct
48 and indirect effects dust can have on human society. Indeed, over the last 100 years or so pulses of
49 aeolian research output have occurred in response to major ecological disasters that have focused
50 attention on wind erosion and blowing dust (Stout et al., 2009). We know that dust emissions vary in
51 frequency and intensity seasonally and over longer timescales (Goudie and Middleton, 1992),
52 responding to droughts (Middleton, 1985) and large-scale standing atmospheric pressure oscillations
53 such as the North Atlantic Oscillation (Moulin et al., 1997), but the recent increase in dust storms in
54 some areas (e.g. Kim, 2008; Ganor et al., 2010; Ghasem et al., 2012; Hsu et al., 2012; Notaro et al.,
55 2015) prompted the United Nations General Assembly (UNGA) to adopt a resolution in 2015 entitled
56 “Combatting sand and dust storms” (A/RES/70/195). This was followed in 2016 by the second UN
57 Environment Assembly (UNEA-2) adopting a resolution that requests countries to address the
58 challenges of sand and dust storms through relevant policy measures.

59 The purpose of this paper is to review the ways in which desert dust is related to hazardous
60 conditions experienced by human populations both within drylands and beyond their margins. This
61 synthesis of hazards research follows a brief resumé of our knowledge on the nature of desert dust
62 storms, particularly their main sources areas, frequencies and long-distance transport pathways.

63
64 **2. Desert dust**

65 There are numerous sources of tropospheric aerosols, including sea salt, volcanic dust, cosmic
66 dust and industrial pollutants, but this paper refers to mineral dust that originates from land surfaces.
67 Most of this material comes from desert and semi-desert areas and is therefore commonly referred to
68 as desert dust. Dust storms are atmospheric events typically associated with drylands because of the
69 preponderance of desiccated, unconsolidated substrates with little vegetation cover. Strong, turbulent
70 winds blowing over desert surfaces raise fine-grained material, much of it consisting of silt-sized (4-
71 62.5µm) and clay-sized (<4µm) particles, to reduce visibility to less than 1 km (Figure 1).
72 Atmospheric PM₁₀ dust concentrations exceed 15,000 µg/m³ in severe events (Leys et al., 2011),
73 although concentrations naturally diminish with distance from source areas as material in suspension
74 is deposited downwind by wet and dry processes. Desert dust is dominated by SiO₂ and Al₂O₃, but
75 may also contain significant proportions of Fe₂O₃, CaO and MgO. Many desert dust source areas also
76 contribute a large salt content, organics content, pathogens and anthropogenic pollutants.

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Figure 1. Sydney harbour bridge obscured by thick dust during the notorious Red Dawn event in Australia in September 2009 (Photo: Mrcricket48)

84 **2.1. Source areas**

85 Not all drylands are equally active from a dust storm perspective. Analyses of data from terrestrial
86 meteorological stations and a number of satellite borne sensors has provided us with a decent, though not
87 perfect, understanding of where the planet’s major contemporary desert dust sources are located (Ginoux
88 et al., 2012; Washington et al., 2003), although these surveys omit most high-latitude sources (Bullard, et
89 al. 2016). The Sahara is undoubtedly the largest source of atmospheric desert dust, contributing perhaps
90 50% of the global total, followed by China and Central Asia (about 20% of the global total), Arabia and
91 Australia. Drylands in Southern Africa and the Americas are relatively minor sources, together
92 accounting for probably less than 5% of the global total. These regional proportions are by necessity
93 tentative because quantifying the global mineral dust mass budget is not a straightforward matter. Since
94 actual measurements are geographically sparse and temporally sporadic, the majority of estimates are
95 produced using models. Most estimates of total mineral dust emissions to the global atmosphere range
96 between one billion and three billion tonnes per annum (e.g. Mahowald et al., 1999; Miller et al., 2004).
97 The lack of agreement between models is largely a reflection of the fact that there remains much to learn
98 about dust emission and transport processes (Cakmur et al., 2006; Evan et al., 2014).

99 Within dryland regions, certain types of geomorphology are typically richer in dust-sized material
100 than others (Bullard et al., 2011). Water plays a particularly important role in providing dust-producing
101 desert surfaces such as large basins of internal drainage (e.g. Bodélé, Taoudenni, Seistan, Eyre), alluvial
102 deposits, playas and piedmont alluvial fans. These and a number of other typically abundant sources of
103 desert dust are shown with regional examples in Table 1. Dust is deflated from these sources with a
104 marked seasonality. The Bodélé Depression produces most of its dust during a season lasting from
105 October to April, affecting much of West Africa with the Harmattan dust haze. In the Middle East,
106 southern Iraq, Kuwait, southern Iran and the eastern coast of the Arabian Peninsula are affected by the
107 Shamal, a northwesterly dust-bearing wind that typically prevails between February and October.

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Table 1. Geomorphological units from which substantial dust deflation occurs

Geomorphological unit	Regional example	Reference
Floodplain	Lower Mesopotamia, Iraq	Al-Dousari and Al-Awadhi (2012)
Dry river bed (wadi)	Patagonia, Argentina	Johnson et al. (2010)
Alluvial fan	Hexi Corridor, China	Derbyshire et al. (1998)
Salt pan	Mojave Desert, USA	Reynolds et al. (2007)
Palaeolake bed	Bodélé Depression, Chad	Bristow et al. (2009)
Ephemeral lake bed	Hamoun Basin, Iran/Afghanistan	Rashki et al. (2013)
Active dunes	Erg in Koussamene, Mali	Coudé-Gaussen (1989)
Devegetated fossil dunes	Lake Eyre Basin, Australia	Bullard et al. (2008)
Glacial outwash plain	Sandar plains, southern Iceland	Prospero et al. (2012)
Loess	Loess Plateau, China	Park and In (2003)

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Many dust sources are naturally active (e.g. the world’s largest source of desert dust – the Sahara’s Bodélé Depression) but elsewhere dust is entrained from environments that have become susceptible to wind action through human influence. These situations include lake beds that have been desiccated due to society’s use of water, as in the Aral Sea in Central Asia (Issanova et al., 2015), and agricultural fields left bare after harvests and/or ploughing, as during the notorious Dust Bowl years on the Great Plains of the USA (McLeman et al., 2014). The mismanagement of rangeland is another frequently cited cause (Hoffmann et al., 2008), but the issue of overgrazing is controversial and there are many uncertainties in our understanding of how grasslands may act as dust sources (Shinoda et al., 2011; Middleton, 2016).

Anthropogenic activities may also affect dust emissions indirectly, by changing climate and the hydrological cycle. Climate change is an important potential driver of future wind erosion and dust storm occurrence, especially via the occurrence of more extreme wind events, greater drought frequency and greater aridity in some areas (Dai, 2010; IPCC 2012). The relative contribution to global dust emissions of sources significantly influenced by human action is a subject for debate with estimates varying from 50% (Tegen et al., 1996) to insignificant (Prospero et al., 2002). This high degree of uncertainty can be attributed in large part to the relative lack of detailed characterization of global dust sources.

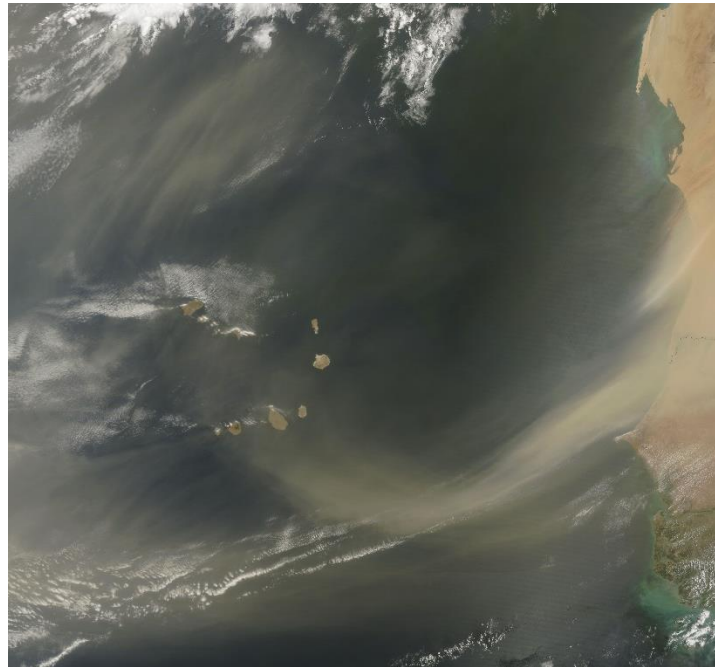
2.2. Long-distance transport

Numerous studies have demonstrated that desert dust is commonly transported over thousands of kilometres through the troposphere and hence affects geochemical conditions at great distances from dust sources (Figure 2). Saharan dust, for instance, has influenced the nature of soils in the Canary Islands (Menéndez et al., 2007) and on Mount Cameroon (Dia et al., 2006), but its contribution of micro-nutrients to ecosystems has also been detected much further afield: in northern Europe (Franzen et al., 1994), the Caucasus Mountains (Kutuzov et al., 2013), the southwestern USA (Prospero, 1999), on Caribbean islands (Muhs et al., 2007), in the Amazon (Swap et al., 1992) and the Andes (Boy and Wilcke, 2008). Dust from northeast Asian deserts is also frequently transported great distances. In and around the Gobi Desert, much attention has been devoted to hazards associated with long-distance dust transport to major regional cities, including Beijing (Liu et al. 2014), Seoul and Tokyo (Kashima et al. 2016). Material from the Taklamakan Desert is also frequently carried across the Pacific Ocean to the North American continent (McKendry et al., 2001), Greenland (Bory et al., 2003), Europe (Grousset et al., 2003) and on occasion even further (Uno et al., 2009).

The transboundary nature of many dust events represents a considerable challenge to policy-makers, although regional cooperation has yielded progress in some parts of the world. Notable examples include the Regional Master Plan for prevention and control of dust and sand storms in northeast Asia, involving the governments of China, Japan, Mongolia and South Korea (UNCCD,

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150 2005), and the creation in Barcelona of a regional dust forecasting centre for Northern Africa, the Middle
 151 East and Europe (Terradellas, 2015). There are plans to introduce a Global Dust-Health Early Warning
 152 System (Sprigg, 2016).



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 155 **Figure 2. Long-range transport of Saharan dust blowing off the coasts of Mauritania and Senegal**
 156 **over the Atlantic towards Cape Verde (Image: NASA MODIS)**

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 158 **3. Desert dust hazards**

159 Dust storms create hazards for human society in numerous ways (Goudie and Middleton, 2006;
 160 Middleton and Sternberg, 2013). An attempt to categorise these hazards by the three processes of the
 161 wind erosion system is shown in Table 2. Further discussion of some important empirical examples
 162 follows from places where dust has been hazardous on entrainment, during the transport phase, and on
 163 deposition.

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 165 **Table 2. Some environmental hazards to human populations caused by wind erosion and**
 166 **dust storms**

Entrainment	Transport	Deposition
Soil loss	Sand-blasting of crops	Salt deposition and groundwater salinization
Nutrient, seed and fertilizer loss	Radio communication problems	Reduction of reservoir storage capacity
Crop root exposure	Microwave attenuation	Drinking-water contamination
Undermining structures	Transport disruption	Burial of structures
	Local climatic effects	Crop growth problems
	Air pollution	Machinery problems
	Respiratory problems and eye infections	Reduction of solar power potential
	Disease transmission (human)	Electrical insulator failure
	Disease transmission (plants & animals)	Disruption to power supplies

167 **3.1. Entrainment phase**

168 When material is entrained from agricultural fields, a dust storm represents a severe form of accelerated
169 soil erosion (Nordstrom and Hotta, 2004). Wind erosion reduces soil productivity in a variety of ways.
170 Soil particles, nutrients, fertilizers and seeds are lost and the eroded particles may also cause serious
171 damage to crops by abrasion, a problem that is particularly critical for young shoots. Deflation of soils
172 removes the finest particles, which are some of the most important soil constituents: clay, silt and organic
173 matter. Since the ratio of sand, silt and clay sized particles is of primary importance to a soil's stability
174 (Chepil and Woodruff, 1963), the preferential removal of fines is detrimental to soil structure. These
175 particles also have an important influence on a soil's water retention capacity, so their removal reduces
176 soil moisture storage. A soil's nutrients also tend to be attached to the smallest and lightest particles, so
177 that the loss of fines reduces fertility (Zobeck et al., 1989). Overall, the loss of topsoil due to wind erosion
178 readily translates into a measureable effect on crop yields (Larney et al., 1998).

179 Other effects of deflation include the scouring and undermining of structures such as telegraph
180 poles, fencing, walls, railway sleepers and roads. On occasion such impacts may result in the collapse
181 of structures. In the Afghan region of Seistan, the dust-laden northerly *Wind of 120 days* is so
182 destructive that local houses are built with dead walls facing the wind (Middleton, 1986).

183 One of the best-known examples of large-scale wind erosion and dust storm activity anywhere in
184 the world occurred on the Great Plains of the USA during the 1930s. The most severe dust storms
185 ('black blizzards') occurred in the Dust Bowl between 1933 and 1938, with activity being at a
186 maximum during the spring of those years. At Amarillo, Texas, at the height of the period, one
187 month had 23 days with at least ten hours of airborne dust, and one in five storms had zero visibility
188 (Choun, 1936). For comparison, the long-term average for this part of Texas is just six dust storms a
189 year (Changery, 1983).

190 The drivers of this ecological disaster have been widely discussed, and blame has largely been
191 laid at the feet of pioneering farmers who ploughed up the plains for cultivation. The waves of
192 settlers that arrived in the area from 1914 to 1930, in conjunction with the increasing use of
193 mechanised agriculture, catalysed by high wheat prices, led to exceptionally large-scale wind erosion
194 when drought hit the plains in 1931. In 1937 the US Soil Conservation Service estimated that 43% of
195 a 6.5 million ha area in the heart of the Dust Bowl had been seriously damaged by wind erosion
196 (Worster, 1979).

197 Recent studies indicate that the degree of aridity over the Great Plains during the 1930s was
198 unusual. Cook et al. (2014) suggest that in the summer of 1934 over 70% of western North America
199 experienced extreme drought, making 1934 the single worst drought year of the last millennium.
200 However, this is not to exonerate the human impact, since analysis using general circulation models
201 (GCMs) indicates that human-induced land degradation (reduced vegetation cover and large-scale
202 emissions of soil dust, both consequences of crop failure) are likely to have suppressed precipitation
203 during the Dust Bowl and may have amplified the drying in 1934 (Cook et al., 2009). Irrespective of
204 the relative importance of anthropogenic and natural drivers, the Dust Bowl disaster was undoubtedly
205 exacerbated by the severe economic problems that affected North America during the 1930s (Lee and
206 Gill, 2015), which made it very difficult for farmers adequately to deal with this environmental
207 catastrophe.

208 Similar widespread deflation of soils resulted from analogous expansion of cultivation into
209 grasslands in the Argentine Pampas during the 1930s and 1940s (Viglizzo and Frank, 2006) and after
210 the 1950s Virgin Lands Scheme in the former USSR (Indoitu et al., 2012). In southeastern Australia,
211 Cattle (2016) makes a strong case for an episodic version of a Dust Bowl that continued for 50 years
212 (1895–1945), a period of depressed rainfall when marginal lands were actively cropped and grazed,
213 and rabbits were a burgeoning grazing pest.

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215 **3.2. Transport phase**

216 Dust suspended in the atmosphere has implications for human health due to its physical,
217 chemical and biological properties and this is one of the best studied aspects of desert dust hazards

218 (Griffin, 2007; Sandstrom and Forsberg, 2008; Goudie, 2014; Sprigg, 2016). Exposure to dust in the
 219 atmosphere can result in conjunctivitis and dermatological disorders while inhalation can cause
 220 respiratory illnesses such as silicosis (also known as desert lung syndrome) and act as a trigger for many
 221 others, including asthma, bronchitis, emphysema and chronic obstructive pulmonary disease. Some
 222 storms are associated with very high atmospheric dust concentrations that frequently exceed
 223 recommended health levels for particulate matter. In extreme cases, people and animals caught in a severe
 224 storm may lose their lives due to suffocation. A major dust storm in April 1895 in the US state of
 225 Colorado was reported to have caused the loss of 20% of the cattle in the east of the state (Idso, 1976).

226 Particle size is the main determinant of where dust comes to rest in the respiratory tract once inhaled.
 227 A distinction is commonly highlighted between particles $<10\ \mu\text{m}$ (PM_{10}) in diameter, which can penetrate
 228 into the lungs, and those with diameter $<2.5\ \mu\text{m}$ ($\text{PM}_{2.5}$) which penetrate into deep lung tissue. Various
 229 health authorities have issued air quality guidelines with two components (Table 3): acceptable
 230 atmospheric concentrations at the chronic level (annual mean) and acute level (24-hour mean), although
 231 the World Health Organization (WHO) points out that “The risk for various outcomes has been shown to
 232 increase with exposure and there is little evidence to suggest a threshold below which no adverse health
 233 effects would be anticipated.” (WHO, 2006, p9).
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235 **Table 3. Air quality guidelines for particulate matter**

Body	$\text{PM}_{2.5}$ annual mean ($\mu\text{g}/\text{m}^3$)	$\text{PM}_{2.5}$ 24-hour mean ($\mu\text{g}/\text{m}^3$)	PM_{10} annual mean ($\mu\text{g}/\text{m}^3$)	PM_{10} 24-hour mean ($\mu\text{g}/\text{m}^3$)
World Health Organization	10	25	20	50
European Commission	25	N/A	40	50
Australian National Environment Protection Council	8	25	N/A	50
Chinese Ministry of Environmental Protection (Class II level)	35	75	70	150
Pollution Control Board of India	40	60	60	100
US Environmental Protection Agency	12	35	N/A	150

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 237 Even so, such guideline values are regularly exceeded in, and downwind of, dust source areas. Desert
 238 dust is by no means the only source of atmospheric particulates, of course. Other common sources include
 239 volcanoes and sea salt aerosols, as well as the internal combustion engine and a variety of industries – and
 240 these sources are frequently combined – but Goudie (2014, Table 5a) shows a large number of desert
 241 cities where annual mean PM_{10} values are an order of magnitude higher than the WHO guideline.
 242 Atmospheric concentrations in individual dust events are characteristically much higher still. PM_{10} levels
 243 of $1,000\ \mu\text{g}/\text{m}^3$ and more have been recorded in dust storms in many desert areas and extreme values
 244 exceed $10,000\ \mu\text{g}/\text{m}^3$ (e.g. Leys et al., 2011; Kaly et al., 2015).

245 Annual average $\text{PM}_{2.5}$ particulate concentrations for 15 locations in the Middle East presented by
 246 Engelbrecht et al. (2009) range from 35 to $111\ \mu\text{g}/\text{m}^3$ and are, therefore, all higher than the air quality
 247 guidelines shown in Table 3. Very high $\text{PM}_{2.5}$ levels have been recorded in intense dust storms. Raman et
 248 al. (2014) measured a peak hourly $\text{PM}_{2.5}$ concentration of $907\ \mu\text{g}/\text{m}^3$ in a dry thunderstorm (‘haboob’)
 249 dust wall in the southwestern USA, but an hourly maximum $\text{PM}_{2.5}$ concentration reached $2899\ \mu\text{g}/\text{m}^3$ at
 250 Dalanzadgad during a dust storm in the Mongolian Gobi Desert (Jugder et al., 2011). The maximum daily

251 average concentration measured during a dust storm in western Saudi Arabia was 594 $\mu\text{g}/\text{m}^3$
 252 (Alghamdi et al., 2015).

253 The very large quantities of desert dust moved during some long-distance transport events means
 254 that high atmospheric concentrations can be experienced at considerable distances from dust source
 255 areas. Table 4 shows some of the PM_{10} levels recorded after dust has been carried between 500 km
 256 and 16,000 km from major sources, events that frequently take several days. Long-range transport of
 257 desert dust from China and Mongolia across the Korean peninsula is so common that the Korea
 258 Meteorological Administration has established a public information system to warn its citizens of
 259 possible health effects (Korea Meteorological Administration, 2016). There are two levels of notice:

- 260 • Advisory, issued when the hourly mean PM_{10} concentration is expected to exceed 400 $\mu\text{g m}^{-3}$
 261 for over 2 hours.
- 262 • Warning, issued when the hourly mean PM_{10} concentration is expected to exceed 800 $\mu\text{g m}^{-3}$
 263 for over 2 hours.

264 **Table 4. Maximum observed PM_{10} levels in long-distance dust transport events**

Location	Concentration ($\mu\text{g m}^{-3}$)	Date	Dust source	Distance transported (km)	Reference
<i>Saharan dust</i>					
Mbour, Senegal	1600 (daily mean)	9 March 2006	Mauritania-Mali-Algeria	>1,000	Skonieczny et al. (2011)
Praia, Cape Verde	500 (5-min mean)	18 January 2011	Western Sahara	>1,000	Pio et al. (2014)
Cayenne, French Guiana	100 (daily mean)	30 April 2009	Sahel and Sahara	>5,000	Prospero et al. (2014)
Athens, Greece	200 (daily mean)	17 April 2005	Libya	>500	Kaskaoutis et al. (2008)
La Seyne sur Mer, France	214 (peak)	21 February 2004	Southern Morocco and Algeria	>2,000	Masson et al. (2010)
Brussels, Belgium	150 (peak)	29 March 2007	Northern Sahara	>4,000	Vanderstraeten et al. (2008)
<i>Northeast Asian dust</i>					
Chongwon, Korea	1,779 (daily mean)	21 March 2002	Gobi Desert in Mongolia and Inner Mongolia	>1,900	Chung et al. (2003)
Seoul, Korea	880 (max hourly mean)	30 May 2008	Inner Mongolia, Man-Ju, and Ordos areas, China	>1,000	Kim et al. (2010)
Banryu, Japan	800 (peak)	2 April 2007	Gobi Desert, Mongolia	>2,500	Yumimoto et al. (2008)
Yasuhara, Japan	230	16 March 2009	Gobi Desert, Mongolia/China border	>2,000	Sugimoto et al. (2013)
Northern Taiwan	400	28 April 2000	Mongolia and Inner Mongolia	3,000	Lin (2001)
West coast, USA	>100	29 April 1998	Gobi desert	>16,000	Husar et al. (2001)
<i>Middle Eastern dust</i>					
Limassol, Cyprus	7,600 (peak)	8 September 2015	Northern Syria and Iraq	>500	Mamouri et al. (2016)
Sanandaj, Iran	5,616 (peak)	5 July 2009	Northern Saudi Arabia, Western Iraq and Eastern Syria	1,000	Amanollahi et al. (2011)

Delhi, India	990 (8-hour mean)	21 March 2012	Arabian Peninsula	>1,500	Yarragunta & Srivastava (2016)
<i>Australian dust</i>					
Newcastle, Australia	2,426 (daily mean)	23 September 2009	Lake Eyre Basin	>700	Leys et al. (2011)

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266 Many epidemiological studies show possible associations of dust exposure with increases in mortality and
267 hospital visits and admissions due to respiratory and cardiovascular diseases. The effects of desert dust
268 outbreaks on asthma incidence has attracted considerable research effort in numerous parts of the world,
269 both in desert areas such as Australia (Rutherford et al., 1999) and the Middle East (Thalib and Al-Taïar,
270 2012), but also in areas affected by frequent long-range transport, including northeast Asia (Lee and Lee,
271 2013) and southern Europe (Karanasiou et al., 2012). However, desert dust is just one of a host of factors
272 – including genetics, environmental exposure to allergens, and non-specific adjuvant factors such as air
273 pollution, tobacco smoke and infections – that may influence the development and expression of a
274 respiratory allergic disease such as asthma. In a review of how air pollution may be associated with
275 allergies and asthma, Kim et al. (2013) found that exposure to atmospheric particulate matter – including
276 desert dust, soot, smoke and other aerosols – can exacerbate symptoms in asthmatics, as can a number of
277 other pollutants, including nitrogen dioxide, ozone, sulfur dioxide, volatile organic compounds (VOCs),
278 dust mites, pet allergens and mould. Evaluating the impact of individual components is, they conclude,
279 “no easy task”.

280 Respiratory disease may be a chronic condition amongst farmers who are exposed to soil dust on a
281 regular basis during field activities such as ploughing and harvesting (Smith and Lee, 2003). Agricultural
282 workers are typically exposed to a range of hazardous respiratory agents, and it is difficult to identify
283 specific individual causes of specific ailments, but acute and chronic bronchitis, chronic obstructive
284 airways disease, and interstitial lung disease are thought to be predominantly linked to mineral dust
285 exposure, particularly in dryland farming areas (Schenker, 2000).

286 A range of cardiovascular disorders – including stroke, heart failure, myocardial infarction,
287 arrhythmias and venous thromboembolism – has been linked to short- and long-term exposure to high
288 atmospheric particulate levels, and PM_{2.5} in particular (Martinelli et al., 2013) although, as in the case of
289 asthma, attributing the individual effects of a variety of factors remains a significant challenge and
290 questions of causality are yet to be completely answered. Nevertheless, Lary et al. (2014) suggest that the
291 widest variety of health impacts are associated with PM_{2.5} when compared to PM₁₀ or ultra-fine particles
292 (<100 nm), although they also highlight the uneven spread of studies on the various health outcomes as
293 related to particulate matter (see their Table 1). One global study that modelled the effects of airborne
294 desert dust on air quality and premature mortality concluded that the global fraction of cardiopulmonary
295 deaths caused by PM_{2.5} desert dust particles was about 1.8 %. This proportion was much higher, at about
296 15–50 %, for the 20 countries most affected by desert dust: those located in the broad swath of desert
297 terrain stretching from North Africa across the Middle East and into Asia (Giannadaki et al., 2014).

298 While there is widespread agreement that airborne particulate matter is responsible for globally
299 important influences on premature human mortality, our understanding of the relative importance of the
300 different chemical components of this material for these effects is less well understood (Fuzzi et al.,
301 2015). The main component of desert dust is silica and mineralogical studies indicate that the great bulk
302 of this silica is made up of quartz. Reviewing a range of samples from various world deserts, Al₂O₃,
303 Fe₂O₃, CaO, MgO and K₂O were found to be typically present (Goudie and Middleton, 2006). Depending
304 on the nature of source sediments, a range of other toxic or irritating materials may occur, including
305 heavy metals and pesticide residues (e.g. Ataniyazova et al., 2001), polychlorinated biphenyls or PCBs
306 (e.g. Garrison et al., 2006), radionuclides (e.g. Csaveina et al., 2012) and arsenic (e.g. Soukup et al. 2012).
307 Where plumes are blown across heavily industrialized and polluted regions, desert dust is commonly
308 mixed with other atmospheric pollutants (Chin et al., 2007).

309 Microbiological studies have established that desert dust can contain a wide variety of
 310 microorganisms – including fungi, bacteria and viruses – capable of causing disease in a range of
 311 organisms, such as trees, crop plants and animals as well as people (Kellogg and Griffin, 2006). A
 312 thorough review of pathogenic microorganisms dispersed in desert dust and their implications for
 313 agriculture is given by Gonzalez-Martin et al. (2014). In human populations, a number of diseases are
 314 linked to desert aerosols. Exposure to desert dust may explain part of the variability in the incidence
 315 of Kawasaki disease, which causes an inflammation of the blood vessels that can lead to heart
 316 disease. Cases of Kawasaki disease diagnosed in Japan and Hawaii have been linked to dust
 317 transported from Asian deserts and cases in Chile have been associated with dust transport from the
 318 Atacama Desert (Jorquera et al., 2015). Rodo et al. (2014) suggest that a fungus of the *Candida*
 319 species could be the wind-borne infectious agent that spreads the disease. *Coccidioidomycosis*, a
 320 sometimes deadly fungal disease occurring only in the Americas, is caused by two species of fungus
 321 entrained from dryland soils in the US southwest, northern Mexico and northeastern Brazil. An
 322 estimated 100,000 primary coccidioidal infections occur in humans each year in the endemic areas of
 323 the USA but Mexico has the largest number of reported cases (Hector and Laniado-Laborin, 2005).

324 There have been relatively few studies about desert dust impacts on air quality and human health
 325 in West Africa (de Longueville et al., 2013), despite the proximity of the Sahara, and the dearth of
 326 data is a major constraint on our understanding of the health impacts in this region. One serious
 327 health problem that has been related to West Africa’s high atmospheric dust loads is meningococcal
 328 meningitis. The incidence of epidemics in the Sahelian zone, otherwise known as the Meningitis Belt,
 329 appears to be related to Saharan dust intrusions brought by the Harmattan (Thomson et al., 2009), and
 330 there are several possible explanations of how dust may be linked causally to the epidemics (Table
 331 5). The seriousness of the issue is highlighted by Jusot et al. (2016) who emphasise that the Sahel has
 332 the world’s highest attack rate (10 per 100,000) and case fatality rates (15%) for bacterial meningitis:
 333 350 million people being at risk across 21 countries. Many of these people are subsistence farmers
 334 and herders, for whom the debilitating effects of disease are particularly critical. In a survey of
 335 farmers’ views about the relative importance of constraints to agricultural production in Niger, 80%
 336 of villagers (n = 892) reported severe health symptoms during the Harmattan season. Interestingly,
 337 these health problems related to dust storms were of more concern than crop damage or loss of
 338 topsoil to wind erosion (Biielders et al., 2001).

340 **Table 5. Possible explanations for the impact of desert dust on meningitis epidemics in West Africa**
 341

Hypothesis	Reference
Increase in invasion rate (i.e. shift from carrier to infected status) due to high dust loads and persistent low humidity damaging immune defences in the mouth and easing bacterial invasion	Moore (1992)
Higher transmission levels due to changes in living habits, such as proximity of individuals taking refuge from dusty winds	Remy (1990)
Co-occurrence of viral respiratory infections weakening the immune system and easing transmission and invasion by bacteria	Mueller et al. (2008)
<i>Neisseria</i> bacteria, responsible for meningitis, require iron-rich dust to grow and become virulent	Noinaj et al., (2012)

342 Desert dust in suspension presents problems for several forms of communication, including radio
 343 waves and microwaves which pass through the atmosphere. The operations of terrestrial and satellite
 344 communications are hampered by attenuation induced by absorption and scattering by dust and sand
 345 particles in the atmosphere (Saleh and Abuhdima, 2011). Generally, the issue is greater for shorter
 346 wavelengths. Electric fields, some larger than 200 kV/m, have been measured in dust storms and
 347

348 might play an important role in saltation and dust emission processes (Kok and Renno, 2006). Such
349 electric forces also present hazards in themselves.

350 Dust storms can result in dangers for modes of transport and an increase in accidents in the air and on
351 the ground. Poor visibility is a frequent cause, sometimes in combination with the adverse mechanical
352 effects of dust. Holyoak et al. (2011) reported that a particularly severe dust event in Australia in 2009
353 resulted in the grounding of a large portion of the air medical retrieval fleet in the state of Queensland.
354 Several reasons were cited, including breaching of the minimum visibility level for instrument landing
355 systems, severe atmospheric turbulence, and the risk of damage to moving parts, windscreens, engine
356 intakes and air filtration systems. For these reasons airports, and on occasion seaports and roads, are
357 frequently closed during intense dust events.

358 Aircraft that do fly in dusty conditions require higher maintenance and replacement costs for
359 mechanical equipment. Helicopter engines are especially susceptible to large amounts of dust and sand
360 ingestion during hover, take-off, and landing. The loss in power and surge margins as a result of
361 compressor blade erosion during the first Gulf War resulted in some military helicopter units being
362 withdrawn after fewer than 20 hours of field operations (Hamed et al., 2006).

363 Although often mentioned in the literature as a transport hazard, this is a relatively under-studied
364 aspect of desert dust. Indeed, the hazards to aviation presented by volcanic ash clouds have attracted
365 much greater attention, despite being much less frequent and less widespread (Weinzierl et al., 2012). In a
366 rare national study using air traffic incident reports in Australia over the period 1969-2010, Baddock et al.
367 (2013) concluded that atmospheric dust in Australia represents at worst an inconvenience and economic
368 cost since nearly two thirds of the dust-caused air safety issues identified related to navigational problems.
369 There were no reported deaths over the 42-year period studied and these authors noted that improvements
370 in aviation technology were at least partly responsible for a reduction in incidents in more recent decades.
371 However, in other parts of the world, where equipment is often older and safety standards may be lower,
372 dust storms have been implicated in a number of aircraft accidents involving fatalities as shown in Table
373 6 which has been compiled using media reports. Attribution of cause in such crashes is seldom
374 straightforward, and often involves a combination of factors, but all the accidents shown in Table 6
375 involved dust storms to some extent. Similarly, an intense dust storm played a critical part in a collision
376 between a helicopter and fixed-wing aircraft in the Lut Desert, Iran during an attempt by the US military
377 to rescue hostages held in the US embassy in Tehran in 1980 (Thomas, 1987). Eight men died in the
378 crash, which also had considerable political repercussions.

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Table 6. Some fatal commercial aircraft crashes attributed to dust storms

Location	Date	Airline	Fatalities
Côte d'Ivoire	30th January 2000	Kenya Airways	179 dead
Tunis, Tunisia	7th May 2002	EgyptAir	18 dead
Faridabad, India	25th May 2011	Air Chartered Services	10 dead
Talodi, Sudan	19th August 2012	Sudan Airways	31 dead

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383

384 The change in atmospheric conditions to near-zero visibility may be very sudden when caused by the
385 arrival of a dust wall associated with a haboob. These dust walls were responsible for 32 multiple
386 accidents between 1968 and 1975 on Interstate 10 in Arizona, USA (Brazel and Hsu, 1981), a stretch of
387 highway that remains susceptible to multiple pile-ups caused by dust storms (Reid et al., 2016). When
388 conditions are appropriate, this sort of road traffic disaster can occur even outside the drylands, as in
389 northern Germany in April 2011 when dust blown from nearby potato fields led to a massive pile-up on
390 the adjacent autobahn A19 in which 8 people died (Deetz et al., 2016). However, there are very few
391 studies of such road traffic accidents outside the USA, where some 62 deaths nationally were related to
392 dust storms affecting road vehicles between 1980 and 2005 (Ashley and Black, 2008).

393 Strong, erosive winds also have impacts on rail communications. Cheng et al. (2015) report that
394 direct destructive effects on railways in northwestern China result from copious airborne particles
395 that can break windows, damage carriages and even blow over the train, as well as reduced visibility
396 that results in trains being stopped for safety reasons.

397
398 **3.3. Deposition phase**

399 Desert dust deposition rates can be considerable, with annual amounts frequently exceeding 100
400 t/km² close to major sources (e.g. McTainsh and Walker, 1982; Singer et al., 2003; Al-Awadhi and
401 AlShuaibi, 2013) and declining with distance transported. The deposition of dust has implications for
402 residents both within and beyond desert areas. Although some of the issues are difficult to separate
403 from those associated with dust in transport, dust deposition can lead to the contamination of
404 drinking-water with microorganisms mentioned above and/or with anthropogenic materials picked up
405 and transported in dust events. These include pesticides, herbicides, heavy metals, dioxins, and
406 radioactive isotopes.

407 The chemical effect of desert dust on water quality has been established in the Negev Desert by
408 Nativ et al. (1997). The high salinity typical of most groundwater in arid zones is often attributed
409 primarily to high evaporation rates and limited recharge, but the high levels of NaCl in precipitation,
410 surface water, vadose water and groundwater in the Negev are intimately linked to abundant dust that
411 provides a steady flux of minerals to the atmosphere which are dissolved by the scant precipitation.
412 Similar contamination can occur when dusts laden with salts are deposited on soils. Soil salinization
413 is a particular issue in the zone surrounding the desiccated former lakebed of the Aral Sea (Figure 3),
414 endangering the productivity of nearby rangeland and agricultural areas. Prevailing winds from the
415 north and north-east mean the most serious impacts occur on the Usturt Plateau to the west of the
416 Aral Sea and the Amudarya delta to the south (Issanova et al., 2015).

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Figure 3. Dust storm approaching the village of Qulandy, near the Aral Sea in Kazakhstan (Photo: NM)

423 Dust deposited on plants can have a range of physical and chemical impacts. In a review of the
424 effects, Farmer (1993) concluded that dust may affect photosynthesis, respiration, transpiration and allow
425 allow the penetration of phytotoxic gaseous pollutants. Overall, the result is usually decreased
426 productivity, an important outcome for cropland, although the level of deposition is critical, as is the grain
427 size of the dust. Excessive amounts may bury a plant, or physically smother the leaves. Dust can
428 physically block stomata, typically 8-12 μm for a range of crops, impairing their function, and could also
429 act as a desiccant reducing the drought tolerance of plants (Burkhardt, 2010). Conversely, some suggest
430 that dust provides a significant source of nutrients on the leaves of some graminaceous plants such as rice
431 and wheat (Das, 1988). In the same vein, it is also important to note that desert dust deposition has played
432 a role in soil formation in many parts of the world (Simonson, 1995) and is critical to the formation of
433 loess, an important soil parent material (Kapp et al., 2015).

434 Dust deposition in households and commercial buildings requires major efforts and economic costs
435 for interior cleaning and domestic landscaping clean-ups (Huszar and Piper, 1986). Such deposits also
436 reduce reservoir storage capacity, and clog streams and drainage channels. Dust deposition can have
437 serious repercussions for the operating potential of solar power plants (Sarver et al., 2013), adversely
438 affecting the two main technologies used to convert the sun's abundant radiation into electricity:
439 photovoltaic (PV) and concentrating solar-thermal power (CSP) systems. Although deserts offer the best
440 solar conditions, they are frequently combined with high atmospheric dust concentrations and an allied
441 relative lack of water that could be used to clean solar-power generation technology (both PV modules
442 and the highly reflective mirrors used in CSP systems to redirect light onto a central focal point). Dust
443 degrades the energy delivery of both types of system by reducing the solar intensity which in turn leads to
444 reductions in power output. For PV systems, power reduction is typically from 15% to 30% in moderate
445 dust conditions, but it can reach 100% when cementation by water-soluble salts occurs due to the
446 combination of dew, very light rain, or humidity with dust. CSP systems tend to be even more sensitive to
447 dust accumulation and require greater maintenance to mitigate dust deposition problems.

448 The reliability of power distribution grids in desert areas can also be adversely affected by excessive
449 amounts of dust (Maliszewski et al., 2012). Dust and sand particles that carry an electrical charge
450 interfere with porcelain insulators on high-voltage transmission lines, reducing effective distribution
451 potentially resulting in flashover outages.
452

453 ***4. Economic assessments of the desert dust hazard***

454 Individual events of course result in multiple impacts. The effects of a severe dust storm in eastern
455 Mongolia on 26–27 May 2008 are documented by Jugder et al. (2011): 52 people were killed, among
456 them 14 children, and about 242,000 head of livestock. There was also damage to 110 buildings, 221
457 homes and 668 telegraph poles. The total economic cost of this single event in rural Mongolia was
458 estimated to be some 640.2 million Tugrig (US\$457,000). Such large-scale dust events frequently cause
459 disruption internationally. A regional dust haze that affected many countries in the Middle East in early
460 April 2015 resulted in flights being diverted, cancelled or delayed at international airports in Bahrain,
461 Dubai and Muscat. Local media reported that all schools were closed in Qatar and eastern Saudi Arabia
462 and that high atmospheric dust loads had caused a spike in patient numbers at hospitals in the United
463 Arab Emirates. Bus services between Dubai and Abu Dhabi were cancelled as visibility was reduced to
464 zero, and the extreme weather conditions were blamed for causing 82 accidents on the roads in Sharjah.

465 Given the importance of desert dust as a hazard to human societies, as detailed in this paper, it is
466 surprising to note that there have been relatively few attempts to assess their impacts in economic terms.
467 One early estimate of the economic cost of a specific dust-related disease, an epidemic of Valley Fever
468 (*coccidioidomycosis*) in the US southwest over the period 1991–94, was reported by Kirkland and Fierer
469 (1996). The outbreak was considered to have cost more than US\$66 million in direct medical expenses
470 and time lost from work in Kern County, California. A more recent estimate, for the entire US state of
471 Arizona for the year 2007, put the charges for 1735 hospital visits for Valley Fever at US\$86 million
472 (Sprigg et al., 2014). Costs to a branch of the transport sector, the aviation industry, were estimated for

473 the year 2002 in South Korea by Kang et al. (2004). They calculated that the total cost of 102 flights
 474 being cancelled that year due to desert dust in the atmosphere was US\$578,000.

475 Total cost estimates for some individual dust events are shown in Table 7, reflecting a wide
 476 range of economic impacts. Both on-site and off-site costs associated with a single large storm that
 477 affected the Australian state of New South Wales in 2009 were estimated at Aus\$299 million
 478 (US\$219m), with most of that accounted for by household cleaning and disruption to commercial
 479 activities (retail and service industries), air transport and construction (Tozer and Leys, 2013). The
 480 large difference in estimated costs between the two events shown in Table 7 is in part due to different
 481 assessment methods, as well as the contrast between a rural event in a developing country (Mongolia)
 482 and an event that impacted several major cities in a more prosperous economy (Australia).

483
 484
 485 **Table 7. Economic cost estimates of individual dust events**
 486

Item	Location	Cost (US\$)	Reference
Total local cost, dust storm 26–27 May 2008	Eastern Mongolia	0.46m	Jugder et al. (2011)
On- and off-site costs Red Dawn dust storm 23 September 2009	New South Wales, Australia	219m	Tozer & Leys (2013)

487
 488
 489 Similar assessments of the economic burden on an annual basis have been made in a slightly
 490 larger number of cases, as shown in Table 8. The work of three separate South Korean studies, using
 491 different methodologies to establish the socio-economic cost to the country of yellow dust
 492 transported from Northeast Asian deserts in the year 2002, is compared by Jeong (2008). Estimates
 493 range from a low of US\$ 3,900 million to a maximum of US\$ 7,300 million. Jeong points out that the
 494 average of the two, US\$5,600 million, is equivalent to US\$ 117.00 per South Korean inhabitant or
 495 0.8% of GDP. Meibodi et al. (2015) took three main sectors (health, transport and agriculture) into
 496 account when calculating their 2013 costs of dust storms in Iran and Iraq, each in the region of
 497 US\$1,000 million. An earlier estimate by Pimentel et al. (1995) for wind erosion in the USA assessed
 498 just the off-site costs to reach a total of US\$9,600 million.

499
 500 **Table 8. Annual economic cost estimates of desert dust events**
 501

Item	Location	Cost (US\$)	Reference
Total costs	South Korea	5.6bn	Jeong (2008)
Total costs	Iran	1.0bn	Meibodi et al. (2015)
Total costs	Iraq	1.4bn	Meibodi et al. (2015)
Off-site costs	USA	9.6bn	Pimentel et al. (1995)
Total costs	Beijing, China	265m	Ai and Polenske (2008)
Total costs	Yazd plain, Iran	6.8m	Ekhtesasi & Sepehr (2009)
Off-site costs	Seistan Region, Iran	25m	Miri et al. (2009)
Off-site costs	South Australia	17m	Williams & Young (1999)

502
 503
 504 An assessment of the total off-site costs of the dust storm hazard in the state of South Australia
 505 put it at Aus\$23 million (US\$17m) a year on average (Williams and Young, 1999). Miri et al. (2009)

506 made a similar assessment of the Seistan region in Iran using questionnaires and estimated a total
507 economic cost due to physical damage and loss of productive man-hours of US\$125 million over a five-
508 five-year period. An attempt to assess the total cost of atmospheric soil dust to the city of Beijing in China
509 in the year 2000 identified a considerable decrease in output from urban agriculture, manufacturing,
510 construction, transportation, trade and catering services (Ai and Polenske, 2008). In total, the cost of these
511 direct impacts came to US\$265 million.

512 A number of agricultural studies have estimated the on-site costs of soil erosion by wind on farmers'
513 fields. One such assessment in the 1980s established that the on-site crop and soil damage in the US state
514 of New Mexico totalled US\$10 million per year (Davis & Condra, 1989), although this was dwarfed by
515 the annual off-site wind erosion costs in New Mexico of US\$466 million (Huszar & Piper, 1986). An EU
516 research project, Wind Erosion on European Light Soils (WEELS), analysed the effects of cultivating a
517 range of crop types (Riksen and De Graaff, 2001). The damage assessed consisted mainly of crop losses
518 and additional inputs in the case of re-sowing. Depending on the crop the average annual on-site costs in
519 high-risk areas amounted to about €60 (US\$55) per hectare, but for sugar beet and oilseed rape the costs
520 could be as much as €500 (US\$450) per hectare once in five years.

521

522 **5. Conclusions**

523 Drylands present a range of hazards to their human occupants, of which dust storms are one of the
524 most serious, but the significance of desert dust hazards also affects many people far beyond the dryland
525 realm due to long-distance dust transport. Living in drylands and on their margins frequently involves
526 society coping with high levels of risk, often stemming from natural hazards such as dust storms. Coping
527 with these risks, through prediction, adaptation and mitigation measures, depends on a thorough
528 understanding of the hazards and their impacts. The important implications that dust storms have for the
529 environment and their many impacts within the Earth system have been an impetus for a considerable
530 increase in desert dust research in recent years, but research into the hazard implications of dust has
531 lagged somewhat. As the wide range of direct and costly impacts indicates, desert dust storms warrant
532 greater attention in this respect.

533 There are several areas that deserve more research effort. Our knowledge and understanding of desert
534 dust source regions, processes of emission and transport, remain incomplete, which feeds into our
535 attempts to model desert dust movement and its impacts. Studies of some forms of dust storm hazard,
536 such as wind erosion in agricultural areas, are relatively mature, but others remain under-studied. The
537 latter group includes the impacts on transport, making causal associations between exposure to desert dust
538 particles and adverse human health effects, and the effects of dust deposition on plants. Better
539 understanding of such subjects will also improve another facet of desert dust research that remains in its
540 infancy: the economic impact assessment of dust events.

541 All aspects of desert dust hazards have received more research attention in some parts of the world
542 than others. West Africa, which lies in the pathway of the world's largest desert dust flows, is notably
543 under-studied in most regards. Improved knowledge of desert dust hazards, in all affected areas, is needed
544 for a satisfactory response to the United Nations call for countries to address the challenges of dust storms
545 cost-effectively through appropriate policy measures.

546

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