Annals of Arid Zone 40(3): 303-315, 2001

The Global Distribution of Dust Storms: Patterns and Controls

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Abstract: Dust storms have important environmental consequences that include climate change, nutrient additions to ocean and terrestrial ecosystems, ocean sedimentation, soil formation and loess deposition. The use of meteorological observations and various satellite-borne sensors (including the Total Ozone Mapping Spectrometer) has enabled the global and regional patterns of dust source areas to be determined. Dust source regions are especially important in the Northern Hemisphere, with the Sahara being predominant. Many of the most important sources are very dry areas, which are, or have been, basins of interior sedimentation.

Key words: Dust storms, dust sources, deserts.

Dust storms, in which visibility is reduced to less than 1 km, are climatic events that are being recognized as of increasing environmental significance. Dust loadings are significant for climate. They affect air temperatures through the absorption and scattering of solar radiation (Li *et al.*, 1996; Moulin *et al.*, 1997; Alpert *et al.*, 1998; Miller and Tegen, 1998; Arimoto, 2001). Dust modifies short-wave solar radiation transmitted through atmosphere to the earth surface and long-wave infrared radiation emitted to space. However, the balance between these two tendencies determines whether this creates cooling or warming. This in turn depends in part upon such variables as the grain-size distribution of the dust and its chemical composition (Fouquart *et al.* 1987). Other important factors in this equation are cloud cover and land surface albedo (Nicholson, 2000). In the case of clouds, their altitude and optical depth are important determinants of the dust's direct radiative impact (Quijano *et al.*, 2000).

Dust may affect climate through its influence on marine primary productivity (Jickells *et al.*, 1998), and there is some evidence that it may cause ocean cooling (Schollaert and Merrill, 1998). Changes in atmospheric temperatures and in concentrations of potential condensation nuclei may affect convectional activity and cloud formation, thereby modifying rainfall (Bryson and Barreis, 1967; Maley, 1982). Dust particles in storms reaching Israel from the Hoggar (Central Sahara), for example, are typically coated with sea salts after their long journey across the eastern Mediterranean, as well as anthropogenic sulphates (Levin *et al.*, 1996). These particles are thought to act as condensation nuclei, hence playing a role in the formation of rain.

It is probable that dust loadings in the atmosphere were both affected by past climatic changes and had an effect on such changes through complex feedback processes (Harrison *et al.*, 2001).

Secondly, dust deposition provides considerable quantities of nutrients to ocean surface waters and the sea bed (Talbot *et al.*, 1986; Swap *et al.*, 1996). Aeolian dust contains appreciable quantities of iron (Zhu *et al.*, 1997), the addition of which to ocean waters may increase plankton productivity. Dust aerosols derived from the Sahara influence the nutrient dynamics and biogeochemical cycling of both terrestrial and oceanic ecosystems. Moreover, because of the thousands of km over which the dust is transported its influence extends as far afield as Northern Europe (Franzen *et al.*, 1994), Amazonia (Swap *et al.*, 1992), and the coral reefs of the Caribbean. Saharan dust has been suggested by Shinn *et al.* (2000) to be an efficient medium for transporting disease-spreading spores which on occasion can cause epidemics that diminish coral reef vitality, a good match having been found between times of coral-reef die-off and peak dust deposition.

Thirdly, dust loadings may change substantially in response to climatic changes, such as the North Atlantic Oscillation and to drought phases (Moulin *et al.*, 1997; Middleton, 1985; Littmann, 1991a) and in response to land cover changes (Tegen and Fung, 1995).

Fourthly, additions of dust to land surfaces may affect soil formation. This has been proposed in the context of West Africa by Vine (1987) and for the formation of *terra rossa* soils in southern Europe and the Levant (Yaalon and Ganor, 1973; McLeod, 1980; Rapp, 1984). It may also contribute to the character of soils on Caribbean and West Atlantic Islands (Muhs *et al.*, 1990). Dust that has a high carbonate content (e.g., Champollon, 1963) may be a factor in the formation of calcretes.

Fifthly, dust additions play a major role in the delivery of sediments to the oceans. For example, Guerzoni *et al.* (1999, p. 147) have suggested that "Both the magnitude and the mineralogical composition of atmospheric dust inputs indicate that eolian deposition is an important (50%) or even dominant (80%) contribution to sediments in the offshore waters of the entire Mediterranean basin."

Dust storms also have many direct implications for humans. They can, for example, transport allergens and pathogens, and disrupt communications. They may be a manifestation of desertification.

USA

In the USA the greatest frequency of dust events occurs in the panhandles of Texas and Oklahoma, Nebraska, western Kansas, eastern Colorado, the Red River Valley of North Dakota, and northern Montana. These areas combine erodible materials with a dry climate and high values for wind energy (Gillettte and Hanson, 1989). The spring months are the time of maximum dust activity (Orgill and Sehmel, 1976; Stout, 2001). In Late Pleistocene times dust storm activity may have been even greater, leading to loess deposition (Muhs *et al.*, 1999).

Large amounts of dust are also blown off the bed of the former Owens Lake following its anthropogenically caused desiccation (Reheis, 1997). On the other hand, land management techniques are probably important in determining the variablility of dust storm occurrence. Lee *et al.* (1993) and Todhunter and Cihacelik (1999) have documented a decline in dust storm occurrence in Texas and North Dakota, which they attribute to the adoption of improved land-use practices. A discussion of the spatial and temporal variability of dust storms in the Mojave and Colorado Deserts is provided by Bach *et al.* (1996), who identify the Coachella Valley as being the dustiest region. A detailed study of dust deposition in Nevada and California is provided by Reheis and Kihl (1995).

The Sahara

The study of Saharan dust dates from the observations made by Darwin (1846) and Ehrenberg (1862) whose works were largely based on records taken from ships of west Africa. In the middle of the last century some pioneer works were produced on land, particularly by Dubief (1953, 1959) who was concerned with the spatial distribution of sand and dust storms and their relationship to the climate of the region.

The Sahara is the world's largest source of dust in the atmosphere, with an annual production of 400 to 700 Tg y^{-1} .(Swap *et al.*, 1996), perhaps contributing as much as 50% of the global total (Middleton, 1986a). Reviews are provided in Morales (1979), Coudé-Gaussen (1991), Goudie and Middleton (2001) and Middleton and Goudie (2001).

The main source areas for the dust are still far from clear (Herrmann *et al.*, 1999), but they include the Bodélé Depression in Niger and Chad (which supplies the dusty Harmattan wind of West Africa); an area that comprises southern Mauritania, northern Mali and central-southern Algeria; southern Morocco and western Algeria; the southern fringes of the Mediterranean Sea in Libya and Egypt; and northern Sudan (Brooks and Legrand, 2000).

Some of the dust from the Sahara is carried over thousands of kilometres, reaching the Americas, Europe and the Near East. Much is also moved by the north easterly trades over Nigeria and the Guinea zone of west Africa to give the Harmattan haze (McTainsh and Walker, 1982).

The frequency of dust storms appears to have increased in recent decades. As a result of a combination of low-rainfall quantities and increasing land-use pressures, the frequency of events increased after the mid-1960s by four to six times in the Sahel and Sudan zones (Middleton, 1985). Prospero (1999) demonstrated the increasing trend of Saharan dust concentrations in Barbados between 1965 and 1992, while Sala *et al.* (1996), using observatory data from southern Spain for 1948-1992, showed that there had been a marked increase in the number of dust-rain days since the 1970s. A discussion of the relationship between rainfall conditions and dust storm frequencies is provided for the Sahel by Littmann (1991a).

Analyses of sediments from ocean cores off the Sahara gives a long-term picture of dust storm power. Dust transport accelerated after 2.8 Ma in response to low sea surface temperatures associated with the start of northern hemisphere glaciation, and further increases occurred at 1.7 and 1.0 Ma (deMenocal, 1995). Analyses of the quartz contents of cores show a great increase in dust inputs at the time of the

Late Glacial Maximum (c. 18,000 years BP) in comparison with the Holocene. There were particularly low dust fluxes during the 'African Humid Period' from 14.8 to 5.5 ka ago (deMenocal *et al*., 2000).

The Middle East

The Middle East has a number of locally named dust-bearing winds (e.g., *shamal*, *belat*, *simoon*, *khamsin*, *sharav*, *shlour* and *shargi*), and the distribution and frequency of dust storms in the region has been analyzed by Middleton (1986b). It is one of the most important dust-generating areas in the world. Dust haze is common over the Arabian Sea, and aeolian silts have contributed to sedimentation in the Gulf of Oman, Arabian Gulf (Sugden, 1963), Red Sea and Arabian Sea (Stewart *et al*., 1965; Prins *et al*., 2000).

Dust storms, which reduce visibility to less than 1 km, reach a high frequency on the alluvial plains of southern Iraq and Kuwait. Nasiriyah has 33 dust storms per year and experiences blowing dust (when visibility is reduced to less than 1 km) on 208 days per year. The greatest concentration of dust storms occurs from March to July, though there are differences across the region. On the basis of the study of aerosol geochemistry over the Arabian Sea, Pease *et al*. (1998) have suggested that the Wahiba Sands of Oman is also a major source region. Analysis of Total Ozone Mapping Spectrometer data indicates that the Oman-Saudi Arabia border is a large source area that has not been picked up from ground meteorological observations. Also important is the eastern part of Saudi Arabia to the north of the Rub Al Khali sand sea. Overall, dust storms in the Arabian peninsula appear to be most prevalent where the mean annual precipitation is less than 100 mm.

Another major region of dust storms occurs in Iraq and Iran (Middleton, 1986c) and at the convergence of the common borders between Iran, Pakistan and Afghanistan. Zabol, in Iranian Seistan, averages 80.7 dust storm days per year, making it one of the World's dustiest locations.

The frequency of dust storms varies considerably from year to year and no very clear trends in incidence are evident even though the dust storm observation record extends back, in the case of Iraq, to the 1930s. Over the period from 1962 to 1984, Kuwait averaged 27 dust storms per year, but had as many as 40 in 1982 and only 8 in 1974 (Safar, 1985).

From time to time dust storms may be so vigorous that visibility is reduced to far below 1 km and the amount of sediment carried in suspension in the air can be huge. Goossens (1996) describes an event in the Negev in November, 1994, where sediment concentrations were at least 200 000 g m^{-3}. It set in motion around 100 000 tons of sediment in the Negev alone.

Dust storms generated within the Middle East and dust storms coming into the region from North Africa (Krom *et al*., 1999) have contributed to the development of some of the characteristics of Middle Eastern soils (Yaalon and Ganor, 1973). They have also caused the accumulation of loess deposits in suitable topographic situations. The deposits in the Negev are perhaps the best-developed (Yaalon and Dan, 1974), but deposits in Arabia itself are much more widespread than has generally been believed

(Goudie *et al.*, 2000). The presence of abundant silts can have a major impact on soil infiltration characteristics and thus on the flood response of desert surfaces to rainstorm events. Silty surfaces generate run-off from quite low rainfall intensities, and this was appreciated by Nabattean farmers who harvested runoff from silty areas of the Negev and elsewhere (Evenari *et al.*, 1983).

Indian Sub-continent

The arid zones of the Indian sub-continent are zones of dust mobilization and loess deposition. The loess - deposits are particularly extensive in Kashmir and on the Potwar Plateau (Rendell, 1993), but also occur in late Pleistocene river terrace deposits in Gujarat and Uttar Pradesh (Williams and Clarke, 1984). High aeolian dust loadings are present in late Pleistocene ocean core sections in the Indian Ocean (Kolla and Biscaye, 1977), and indicate formerly more intense wind activity.

Middleton (1986c) has mapped dust storm activity and has demonstrated that the greatest number of dust storms (on average 17-19 per year) occur at Ganganagar (north-west India) and at Jhelum and Fort Abbas (Pakistan). The Makran coast is also an area of significant dust storm occurrence. Analysis of aerosol levels by means of the Total Ozone Mapping Spectrometer (TOMS) shows a similar picture. May and June are the months with greatest dust activity and it is at that time that dust is raised in the Ganges plain as well as in the Indus Valley. This is the period before the south-west monsoon sets in, so that surfaces are still dry, wind velocities high, and thunderstorms and other types of instability of frequent occurrence (Littmann, 1991b). Conversely, only a limited amount of dust storm activity occurs between November and February.

Central Asia

One of the most striking features of this area, and one it shares with China, is the development of very thick (up to 200 m) and complex loess deposits dating back to the Pliocene. They are well displayed in both the Tajik and Uzbek Republics, where rates of deposition were very high in the late Pleistocene (Lazarenko, 1984). The nature of the soils and pollen grains preserved in the loess profiles suggest a progressive trend towards greater aridity through the Quaternary, and this may be related to the ongoing uplift of the Ghissar and Tien Shan Mountains (see Davis *et al.*, 1980). A thermoluminescence chronology for the Middle and Upper Pleistocene loess deposits of Tajikistan is provided by Frechen and Dodonov (1998), and section and granulometric details are provided by Goudie *et al.* (1984). As in China, the loess profiles contain a large number of palaeosols that formed during the periods of relatively moist and warm climate. Rates of loess deposition have been relatively modest in the Holocene, whereas in the Last Glacial rates of accumulation were as high as 1.20 m per 1000 years (Frechen and Dodonov, 1998).

In the southern parts of the former Soviet Union there is a large zone where the number of dust storms exceeds 40 per year, and some locations experience more than 80, one of the highest occurrences in the world. Human activities have caused dust storm frequencies to be raised, both by the extension of cultivation, as during the ploughing up associated with the Virgin Lands Scheme of the 1950s, and as a result of the desiccation of the Aral Sea. The dust from the Aral Region is heavily polluted with pesticides (O'Hara *et al.*, 2000).

Dust storms take on a particular importance in the Chinese deserts because of their significance for the formation of the world's greatest loess deposits (Derbyshire *et al.*, 1998). Moreover, according to Kes and Fedorovich (1976), the Tarim Basin seems to have 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: the Taklamakan and the Badan Juran (Zhang *et al.*, 1998; Xuan, 1999; Xuan, *et al*, 2000; Jinhuan and Liquan, 2000). In all about 800 Tg of Chinese desert dust is injected into the atmosphere annually, which may be as much as half of the global production of dust (Zhang *et al.*, 1997). There are certainly stations to the north west of the 750 mm isohyet that have dust storms on more than 30 days in a year (Goudie, 1983). The dust storms can cover immense areas and may transport dust particles to Korea, Japan (Willis *et al.,* 1980), Hong Kong (Fang *et al.,* 1999), and beyond.

Dust storms are particularly prevalent during the spring dry season (Littmann, 1991b) and are mainly associated with cyclonic cold fronts during surges of cold continental air masses. Most of the area is then under the influence of the powerful Siberian-Mongolia anticyclone (Middleton, 1991), most notably in the southern region of the Gobi Desert, where Zamiin Und has over 34 dust storm days in a year.

Dust Storms in Southern Africa

Southern Africa is not a major area of dust production from a global perspective even though it has a large area of arid terrain both in the coastal Namib and in the interior (Kalahari and Karoo). There are extensive areas of pans (Goudie and Wells, 1995), many of which are, at least in part, the result of deflation, and there are many windstreaks and yardangs known from the Namib. Examination of satellite images has shown the presence of dust plumes blowing westwards off the Namib and the Kalahari towards the South Atlantic. In addition, sedimentological studies have shown the presence of loess and loess-like deposits in parts of Namibia (Eitel *et al.*, 2001).

TOMS analyses indicate that there are two relatively small, but clearly developed dust source areas in southern Africa. The most intense of these is centered over the Etosha Pan in northern Namibia. The other center is over the Mgkadikgadi Depression in northern Botswana.

The Etosha Pan, which covers an area of about 6000 km^2, is comprised of a salt lake that occupies the sump of a much larger fault-controlled basin. The salt lake often floods in the summer months, but is for the most part dry enough in the winter for deflation to occur, as is made evident by the presence of extensive lunette dunes on its lee (western) side (Buch and Zoller, 1992). It is fed by an extensive system of ephemeral flood channels – *oshanas* – that have laid down large tracts of susceptible fine-grained alluvial and lacustrine sediments. In the past, it is possible that it has also received large inputs of material from the highlands of Angola via the Cunene river (Wellington, 1938).

The Mkgadikdadi depression of northern Botswana is another major structural feature, the floor of which is now occupied by a series of saline sumps. In dry years these present surfaces from which deflation can and does occur. The pans are, however, shrivelled remnants of a former pluvial lake, lake Palaeo-Mkgadikgadi, which at its greatest extent covered 120,000 km^2 (Thomas and Shaw, 1991). It was second in Africa only to lake Chad at its Pleistocene maximum. It was fed with water and sediment from the Okavango and, perhaps, Zambezi system, and by more locally derived rivers (*mekgacha*) flowing from the south.

Dust Storms in South America

Information on the occurrence of dust storms in South America is sparse. However, Johnson (1976) suggests that dust storms are frequent in the Altiplano of Peru, Bolivia and Chile. Middleton (1986a) noted their importance on the Puna de Atacama where salt basins – *salars* – appear to be important sources. The presence of extensive areas of closed depressions and of wind fluted topography, combined with the probable importance of salt weathering in the preparation of fine material for deflation (Goudie and Wells, 1995), suggest that the dry areas of the Altiplano should indeed be major source areas for dust storms. TOMS identifies one area in South America where aerosol values are relatively high. This is the Salar de Uyuni, a closed basin in the Altiplano of Bolivia which is located in an area with 200 to 400 mm of annual rainfall. This salar, the largest within the Andes, is possibly the world's largest salt flat, though in the Late Pleistocene it was the site of a huge lake, pluvial Lake Tauca (Lavenu *et al.*, 1984). The pluvial lake was more than 600 km long, and it is possible that the fine sediments from its desiccated floor are one of the reasons for the existence of high aerosol values in this region. It is of the same order of size as some of the other major basins that are major dust sources (e.g., Bodélé/Chad, Eyre, Taklamakan and Mkgadikgadi).

In addition, as Middleton (1986a) has shown, there is a tract to the west of Buenos Aires where dust storm activity is substantial, with extensive areas experiencing more than 8 dust storms per year. Dust trapped in the West Antarctic glaciers may have a Patagonian origin (Iriondo, 2000). In addition, this arid zone has the most extensive spread of loess in the southern hemisphere (Teruggi, 1957; Kröhling, 1999; Sayago *et al.*, 2001).

Australia

Like other parts of the Southern Hemisphere, Australia is not an especially dusty continent. However, both at the present and in the past dust activity has been appreciable and has contributed to sedimentation on and off shore (McTainsh and Pitbaldo, 1989). It is today the largest dust source in the Southern Hemisphere and in the Late Glacial Maximum contributed three times more dust to the South West Pacific than now (Hesse and McTainsh, 1999). Notable dust events of the twentieth century included the great 'dust-up' of November 1902, the series of storms that darkened the mid-day sky in Adelaide in the summer of 1944 to 45, and the huge pall of Mallee-derived dust that swept across Melbourne in February, 1983.

The distribution of dust storm activity has been plotted from meteorological data by McTainsh and Pitblado (1987), and shows six areas of above-average activity: Central Australia, Central Queensland, the Mallee, the Eastern and Western Nullarbor plains, and coastal Western Australia, with an excess of five storms per year.

Substantial quantities of dust leave Australia in two main plumes: one that runs across the Tasman Sea towards New Zealand and another that heads westwards out into the Indian Ocean (Hesse and McTainsh, 1999). The former plume was more active during the last Glacial Maximum and is an important contributor to Tasman Sea sediments. The Channel Country north of Lake Eyre and the Simpson Desert have probably been major sources of dust in arid phases. Much dust may also be derived from around Lake Eyre and the Murray-Darling plains. Some dust has accumulated on land, contributing to the formation of 'parna', a clay-rich sediment.

There is considerable variation in dust storm activity from year to year, and agricultural degradation of land surfaces in areas like the Mallee may have had an impact on dust storm frequencies. However, a recent study of changing dust storm frequencies has indicated a downward rather than an upward trend in recent years. The reasons for this are obscure, but they could include a reduction in rabbit numbers, the adoption of minimum tillage techniques, and an increase in land cover as a result of the invasion of woody weeds (State of the Environment Advisory Council, 1996).

Conclusion

The analysis of ground meteorological observations and of aerosol indices derived from the Total Ozone Mapping Spectrometer have enabled a picture to emerge of the importance and extent of dust storm activity at a global scale. The Northern Hemisphere surpasses the Southern as a source of dust and the Sahara is the most important global source. There are, however, other significant source areas, including the Great Basin and High Plains of the USA, the Middle East, the Makran and Thar, parts of central Asia, and the Taklamakan. In the Southern Hemisphere the three prime sources appear to be the Salars of the South American Altiplano, the Etosha and Mkgadikgadi basins of Southern Africa, and the Lake Eyre basin of Australia. Two prime features of major source regions is that they are often basins of internal sedimentation and that they occur in regions of considerable aridity. Dust storm frequencies vary from year to year and decade to decade in response to climatic fluctuations (e.g., the North Atlantic Oscillation and the Sahel Drought) and in response to land use changes. Some areas have experienced lower dust storm activity in recent years (e.g., parts of the USA High Plains and Australia) while others have seen a substantial increase (e.g., the Sahel of West Africa). In the Pleistocene period, arid phases associated with possibly higher wind velocities may have seen even greater dust storm activity than today, as is made evident by enhanced dust sedimentation in the oceans and in ice caps and loess accumulation downwind from major dust source regions.

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