13.9 Climate Change and Aeolian Processes

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Glossary

Drift potential (DP) The amount of potential sand transport by winds from different directions, calculated using wind data following Fryberger (1979).

Dust Mineral matter of a size range less than 63 μm (silt and clay size).

Global circulation model (GCM) Also known as a general climate model, it describes climate behavior by integrating a variety of fluid-dynamical, chemical, or even biological equations.

Palmer drought severity index (PDSI) A measurement of dryness based on recent precipitation and temperature.

Abstract

Aeolian processes are widespread in the Earth system, especially in low- and mid-latitude dryland environments, and also affect other environments through transport and deposition of dust. Because water is an important limiting factor in most dryland environments, these processes are strongly affected by climate changes that affect the amount, type, and temporal and spatial distribution of precipitation, which affect the supply, availability, and mobility of sediment. Dust emissions, sand transport, and dune mobility are all strongly influenced by antecedent precipitation, which affects soil moisture and vegetation cover, although specific responses are generally complex and nonlinear. Models for the response of aeolian processes to climate change on annual to decadal scales can be developed on the basis of studies of modern short-term changes in climate (e.g., drought cycles), validated by reference to late Holocene and historical climate change.

13.9.1 Introduction

Aeolian processes, involving the erosion, transport, and deposition of material of sand and dust size, are widespread throughout the Earth system, although their occurrence is concentrated in dryland (arid, semi-arid, and sub-humid) regions of the Earth (about 50% of the global land surface) (Thomas and Wiggs, 2008). Sand-transport systems, including major low-latitude desert sand seas, cover about 20% of drylands (areas in which annual evapotranspiration exceeds precipitation). Reactivation of vegetation-stabilized dunes is a major component of the desertification process. Dust transport from drylands has a regional or global significance and contributes material to soil formation in desert margins (McFadden et al., 1987), provides nutrients to distant ecosystems (McTainsh and Strong, 2007), and contributes to ocean biogeochemical cycles and thus to productivity of marine ecosystems (Jickelis et al., 2005). Mineral aerosols may influence atmospheric radiative properties and affect the distribution and amount of precipitation in adjacent areas (Solmon et al., 2008). The human health impacts of dust-laden air are well documented (Vedal, 1997). A full discussion of the nature and operation of aeolian processes and the resulting landforms and sediments can be found in Volume 11 of this treatise.

Aspects of the response of aeolian processes to climate change have been discussed by a number of authors (Muhs

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and Zárate, 2001; Lancaster, 2008; Singhvi and Porat, 2008). Most of these have concentrated on the response to Quaternary climate change on millennial timescales (*see* Chapter 11.18) and indicate the sensitivity of sand- and dust-transport systems to climate change. The focus of this chapter, however, is on the response of aeolian processes in drylands to climate change and climate variability on annual to decadal timescales during the period of climate observations, particularly in the past few centuries, with a look toward the response of these systems to future climate change.

13.9.2 Conceptual Framework

The response of aeolian sediment-transport systems and landforms to climate change is governed by the supply of sediment of a size suitable for transport by the wind, the existence of wind energy to erode and transport this material (erosivity or mobility), and the susceptibility of a sediment surface to entrainment of material by wind (erodibility or availability). The interactions between these variables in space and time (**Figure 1**) determine the state of the aeolian system (Kocurek and Lancaster, 1999).

On all timescales, sediment supply, availability, and mobility are determined in large part by regional and local climate and vegetation cover. Sediment supply may be affected by variations in flood magnitude and frequency, river sediment load, lake and sea levels, and rates of bedrock weathering that affect sediment source areas. Climatic changes impact sediment availability and mobility (transport rates) via changes in the magnitude and frequency of winds capable of transporting sediment, vegetation cover, and soil moisture (Kocurek and Lancaster, 1999). The aeolian system therefore does not operate in isolation. Most sediment transported by the wind has been eroded, transported, and deposited by other agents, most notably by fluvial processes. There are thus close links between the fluvial domain, even in drylands, and sand and dust transport (Bullard and McTainsh, 2003).

Understanding of the response of aeolian processes to climate change on annual to decadal timescales has been based primarily on studies of the response of geomorphic systems to modern, short-term climatic changes, such as El Niño events and extended regional droughts (Lancaster, 1997). Observational data enable threshold conditions to be identified and well-constrained process–response models (**Figure 2**) to be developed from these scales of natural climate variability (Muhs and Holliday, 1995). Such responses can also be validated against climate change over the historic or pre-instrumental record (e.g., Little Ice Age and Medieval Warm Period) and, in some cases, by reference to the late Holocene record (e.g., Forman et al., 2005).

13.9.3 Dust Events and Climate Variability

Dust storms are defined as severe weather conditions in which visibility is reduced to 1 km or less by blowing dust. Major dust source areas (**Figure 3**) or dust hot spots (Gillette, 1999) include the Bodélé Depression in Tchad, the desiccated surface of the Aral Sea, southeast Iran and adjacent areas of Afghanistan, and parts of the deserts of China (Takla Makan, Inner Mongolia) (Washington et al., 2003). These areas

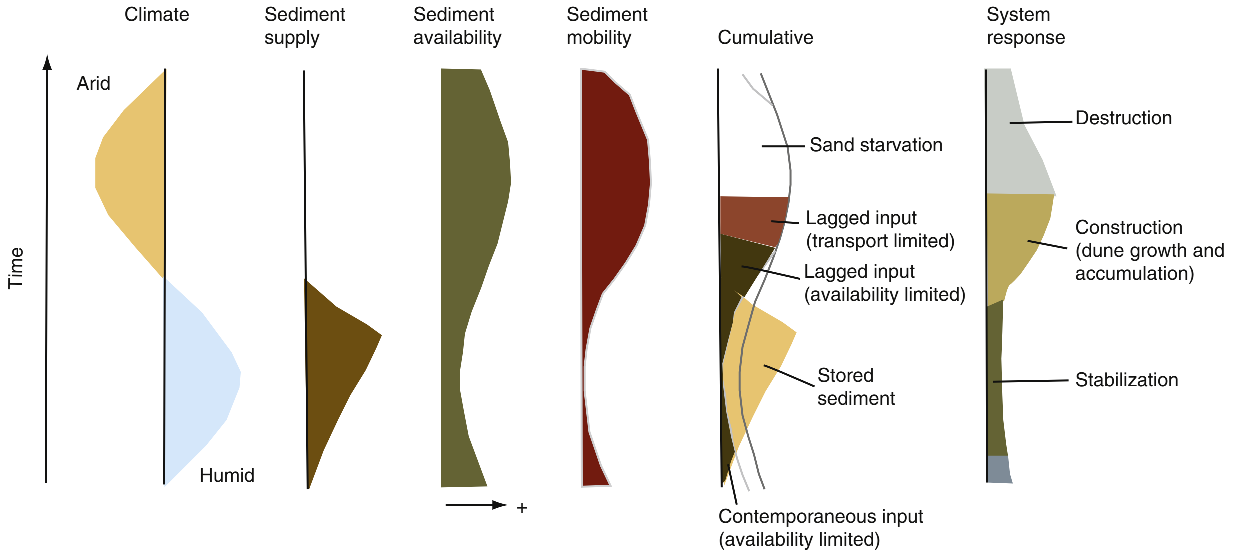

Figure 1 Changes in state of aeolian sand systems with climate change. In the example given, climate changes from wetter to drier, leading to a decrease in sediment supply, but an increase in its availability for transport as well as its mobility (transport capacity). The cumulative effect of these changes is to release the sediment produced and stored in the period of wetter climates in which the system was stabilized by increased vegetation cover, leading to aeolian construction. As the supply of stored sediment is exhausted, the system transitions to a sediment-starved state and may experience erosion and destruction of previously created landforms and deposits. Figure redrawn and colored from original in Kocurek, G., 1998. Aeolian system response to external forcing factors – a sequence stratigraphic view of the Saharan region. In: Alsharan, A.S., Glennie, K.W., Whittle, G.L., Kendall, C.G.S.C. (Eds.), Quaternary Deserts and Climatic Change. Balkema, Rotterdam/Brookfield, pp. 327–338.

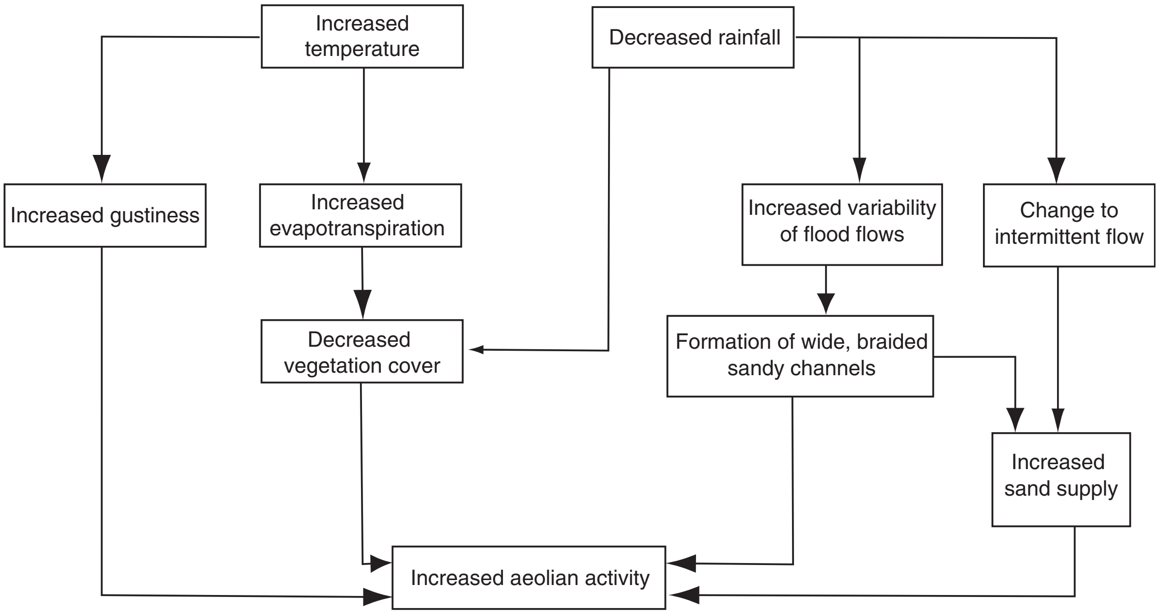

Figure 2 Conceptual model for response of aeolian systems to climate change and sediment supply. Redrawn from Figure 6 in Muhs, D.R., Holliday, V.T., 1995. Active dune sand on the Great Plains in the 19th century: evidence from accounts of early explorers. Quaternary Research 43, 118–124, with permission from Springer.

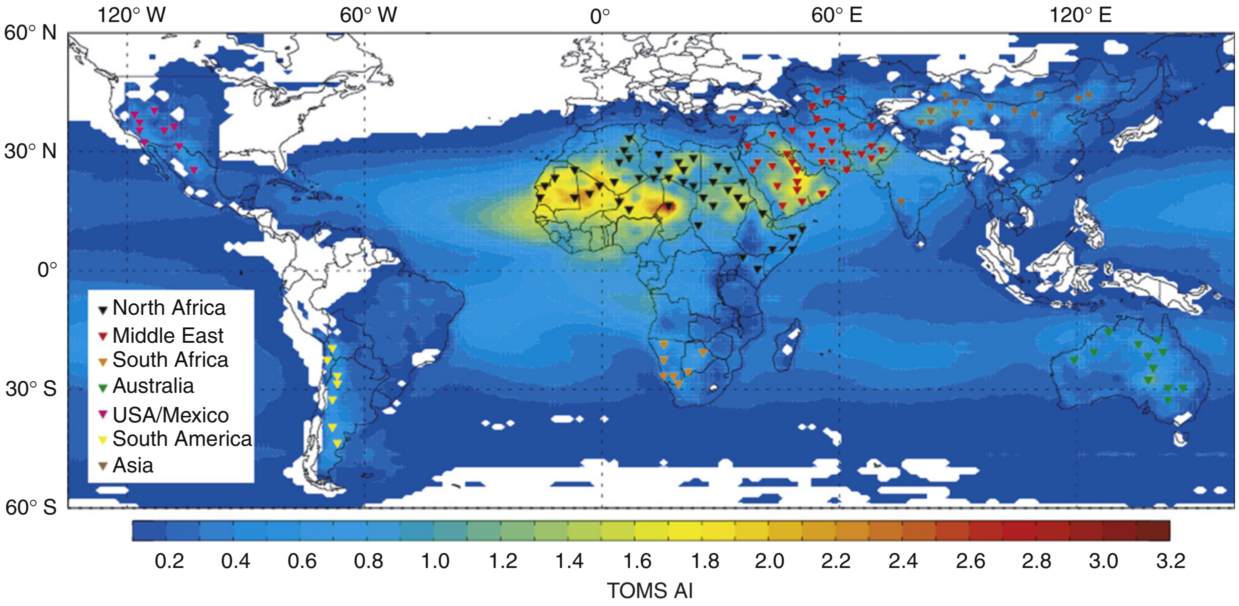

Figure 3 Major global dust source areas (hot spots) shown by inverted triangles. Dust hot spots are identified from high values of the total ozone mapping spectrometer (TOMS) aerosol index. Reproduced from Figure 1 in Engelstaedter, S., Washington, R., 2007. Temporal controls on global dust emissions: the role of surface gustiness. Geophysical Research Letters 34, L15805, with permission from AGU.

are characterized by seasonally strong winds and areas of fine-grained sediment (including distal fluvial deposits, playas, and lake basins, or previously deposited aeolian materials) (Washington et al., 2003). The majority of the global dust is derived from natural surfaces, but the relative magnitude of contributions from natural (e.g., playas and distal fluvial environments) or anthropogenic (e.g., agricultural wind erosion) sources of dust is uncertain – estimates range between 40% and 10% (Prospero et al., 2002; Tegen et al., 2004). In both cases, dust sources are highly sensitive to variations in climate, but the nature of the response is dependent on the character of the source.

Climate change and climate variability may affect dust storm frequency through changes in surface properties such as soil moisture, crusting and cohesion, or vegetation cover that affect the erodibility of the surface and the availability of fine-grained materials for erosion and transport. Similarly, changes in climate may give rise to changes in the magnitude and frequency of winds capable of eroding and transporting material (erosivity).

Temporal variations in the magnitude and frequency of dust storms have been studied in most of the major dust source areas, as well as in locations downwind (Goudie and Middleton, 2006). Observations of dust events in meteorological observations are complemented by satellite remote-sensing data, as well as by measurements of dust concentration and deposition at near-source and remote locations. In many areas, it is difficult to precisely identify the causes of temporal changes in the frequency of dust events because of complex interactions between land use, climate, and dust storm frequency. Use of high-resolution records of dust deposition during the late Holocene may help to identify the relative contributions of climate variability and land use to dust emissions. For example, it appears that prior to 1700, dust flux from the Sahel region was mainly determined by changes in precipitation, whereas from 1700 to the present, dust flux increases exponentially, in parallel to the spread of commercial agriculture in the region (Mulitza et al., 2010).

In many areas, the interannual frequency of dust storms is inversely related to antecedent precipitation, although generally in a complex, nonlinear manner that reflects changes in soil moisture and vegetation cover as well as human disturbance. In most areas, changes in vegetation cover lag changes in precipitation by months or years. In the Sahara and Sahel, increases in dust storm frequency during and following drought conditions in the 1970s have been noted by several workers (e.g., Prospero and Lamb, 2003; Engelstaedter et al., 2006). For example, at Nouakchott, Mauritania (**Figure 4**), dust storm frequency is strongly negatively correlated with rainfall over the previous 3 years (Middleton, 1989). Likewise, in the Sahel, dust flux is closely linked to rainfall in the previous year (Chiapello et al., 2005). The long instrumental record of far-traveled dust from the Sahara and Sahel reaching the Caribbean (**Figure 5**) shows considerable interannual

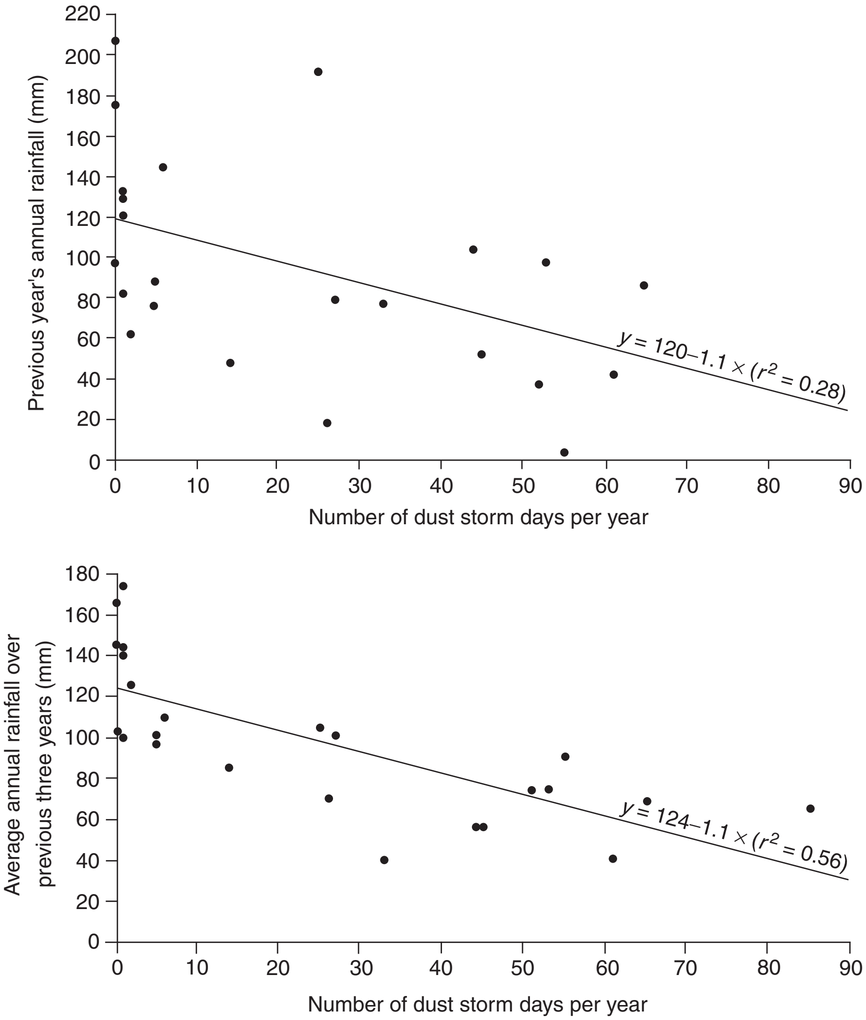

Figure 4 Relations between number of dust storms and antecedent rainfall, Nouakchott, Mauritania. Redrawn from Figure 11 in Middleton, N.J., 1989. Climatic controls on the frequency, magnitude and distribution of dust storms: examples from India/Pakistan, Mauritania and Mongolia. In: Leinen, M., Sarnthein, M. (Eds.), Palaeoclimatology and Palaeometeorology: modern and past patterns of global atmospheric transport. Kluwer, Dordrecht/Boston/London, pp. 97–132.

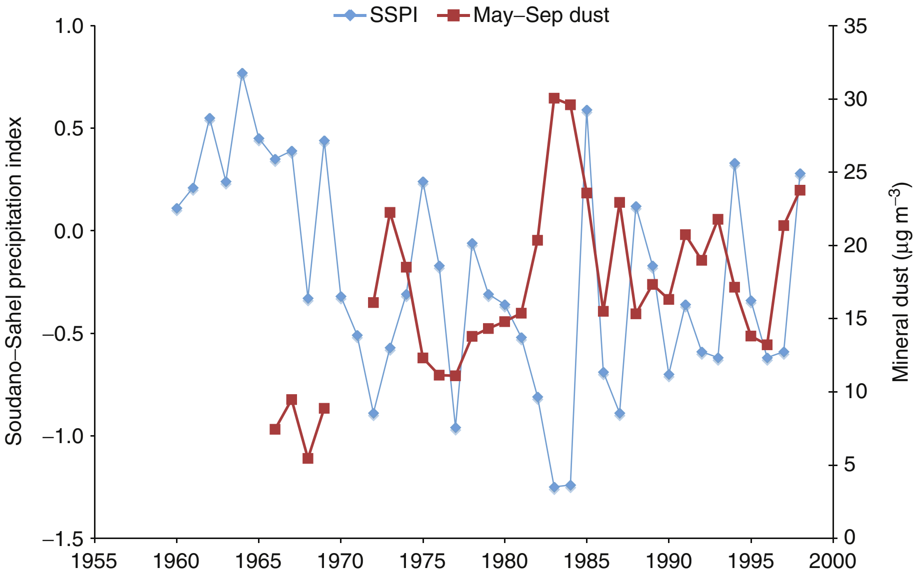

Figure 5 Relationships between Sahara and Sahel rainfall and dust flux to the Caribbean. Replotted from supplementary data in Prospero, J.M., Lamb, P.J., 2003. African droughts and dust transport to the Caribbean: climate change implications. Science 302, 1024–1027, with permission from AAAS.

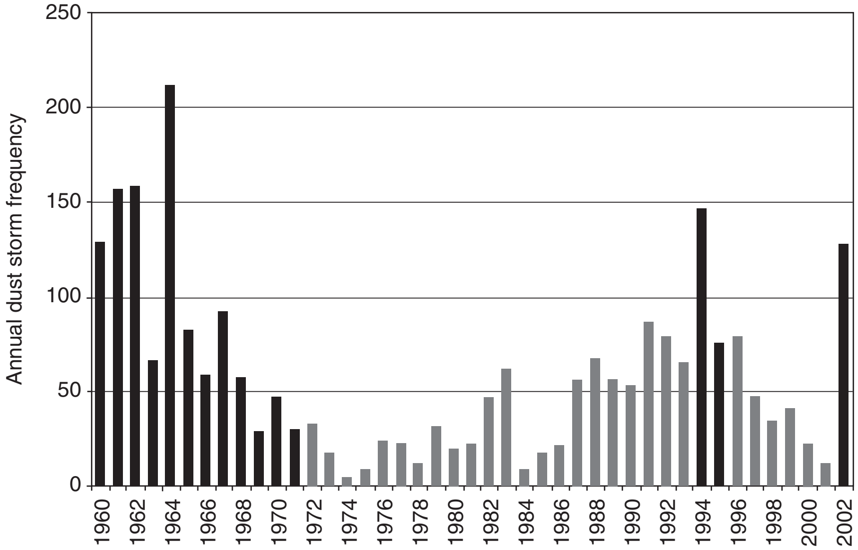

Figure 6 Time series of Australian dust storm annual frequency. Dark bars are drought years. Reproduced from Figure 5 in McTainsh, G.H., Chan, Y., McGowan, H., Leys, J.F., Tews, K., 2005. The 23rd October 2002 dust storm in eastern Australia: characteristics and meteorolgical conditions. Atmospheric Environment 39, 1227–1236.

variability that is highly anticorrelated with source region rainfall in the prior year (Prospero and Lamb, 2003). In addition, years of very high dust concentrations also commonly coincide with El Niño events. The data show that dust concentrations were low in the 1960s but increased sharply in the 1970s, coincident with the onset of regional drought in the Sahel. There seems to have been an overall increase in dustiness since the 1980s accompanied by a change in the seasonal distribution of dust (with a large increase in dust concentrations during April–May) and a breakdown in the relationship between dust and rainfall in recent years. Satellite and surface observations of dust from the Sahara appear to show general relationships to the North Atlantic Oscillation, indicating an overall control of dust emission and transport by large-scale atmospheric circulation patterns (Moulin et al., 1997; Engelstaedter et al., 2006).

In Australia, the dust record (**Figure 6**) is likewise related to the occurrence of droughts in the interior of the continent (McTainsh et al., 2005), with a strong decline in dust events noted in the 1970s, possibly as a result of circulation changes related to the Pacific Decadal Oscillation (Goudie and Middleton, 2006). For southern Africa, the major dust sources are the area of the ephemerally flooded Makgadikgadi Pans in Botswana and Etosha Pan in Namibia (Bryant et al., 2007).

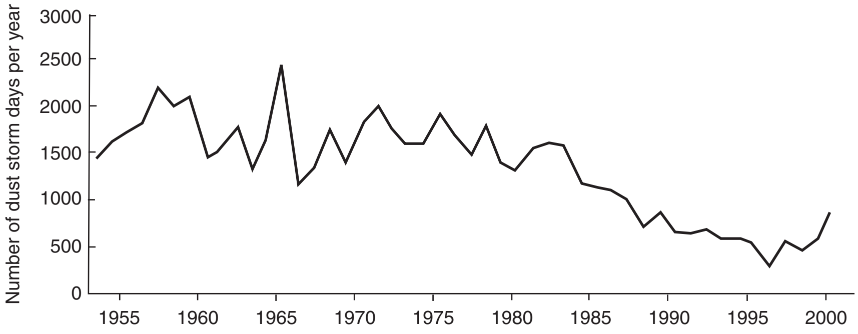

Figure 7 Time series of dust storm events in China. Redrawn from last graph of Figure 6 in Wang, X., Dong, Z., Zhang, J., Liu, L., 2004b. Modern dust storms in China: an overview. Journal of Arid Environments 58, 559–574, with permission from Journal of Arid Environments.

Dust emissions from the Makgadikgadi Pans during the period 1980–2005 appear to be related to the frequency and extent of flood events, which supply sediment for deflation, and also to the occurrence of strong winds during the dry seasons. In turn, flooding is related to heavy regional rainfall, which is influenced by Indian Ocean sea-surface temperatures. Much of the variability in this dust system can be attributed to El Niño Southern Oscillation (ENSO) as well as to extreme events (landfall of tropical cyclones) (Bryant et al., 2007).

In China, the record of dust events shows considerable interannual and spatial variability, but the regional aggregate (**Figure 7**) indicates that their frequency was highest in the 1950s and the 1960s–70s, with relatively low frequencies from the 1980s to the 1990s (Wang et al., 2004b). The general decline in dust events on a regional scale however masks important regional variations, with a marked increase in dust events in Xinghai Province in the 1980s, suggesting the role of human impact in these areas. Zhang et al. (2003) attributed most of these variations to climate change on the basis that the areas most affected by land degradation are not major dust source areas. The nature of the climate changes is debated, but changes in atmospheric circulations resulting in reduced frequency of dust-raising winds, as well as some increase in precipitation, were identified as possible causes by Ding and Li (2005).

In the deserts of the southwest USA, the generation and accumulation of dust are affected by the amount and seasonal distribution of rainfall (Brazel et al., 1986). There is some evidence that dust emissions appear to correlate with ENSO cycles in this region, because of the strong influence of such cycles on regional precipitation (Okin and Reheis, 2002). Regionally, blowing dust was at a low level or absent for the periods 1979–83 (1982, El Niño), 1987–89, and 1992–94 (1992–93, El Niño). The mid-1980s were moderately dusty and 1990–91 experienced a high level of dust activity, partly as a result of continued low levels of (mostly winter) rainfall (Bach et al., 1996), which resulted in a low cover of annual and ephemeral plants. For the period 1973–94, there is a weak, but statistically significant, correlation between dust activity and antecedent precipitation in the previous 2 years (Bach et al., 1996).

In the Mojave Desert, different source types (alluvium, dry playas, and wet playas) respond in different ways to precipitation variability (Reheis, 2006). A major factor determining dust generation from playas in the Mojave Desert is the moisture content of surface sediments, which is often related to the groundwater level (Reynolds et al., 2007). For example, the flux of silt and clay and soluble salt increased following the El Niño events of 1987–88 and 1997–98 at sites close to playas with a shallow depth to groundwater. In this case, evaporative concentration of salts disrupted surface crusts and this increased the susceptibility of surface sediment to wind erosion. The silt and clay flux increased during drought periods at sites downwind of alluvial sources and playas with deeper groundwater as a result of reduced vegetation cover on alluvial sediments and sand sheet areas (Urban et al., 2009), as well as local runoff events that delivered fresh sediment to playa margins and the distal portions of alluvial fans (Reheis, 2006). Reheis (2006) also noted geographical differences in the response of dust sources to precipitation variability, with a greater range of dust fluxes noted in southern (mostly Mojave Desert) sites (**Figure 8**).

13.9.4 Dune Systems

Dune systems and sand sheets occupy up to a third of the area of low- and mid-latitude arid areas and form important landscapes and ecosystems (Lancaster, 1995). They are dynamic geomorphic and sedimentary environments that respond to climate change and variability on a variety of temporal and spatial scales.

Because sand transport is not measured as part of normal meteorological observations, nor monitored by satellite platforms, there are no comparable data sets to those used to examine relationships between dust events and climate variables. However, there are several complementary sources of information that can be used to assess the response of dunes and sand-transport systems to climate change and variability. Most relevant to understanding the response of dune systems to future climate changes are those that have occurred during the past 2000 years, when atmospheric circulation patterns resemble those of today.

The conventional view of dune systems is that their formation or reactivation indicates periods of aridity, and therefore increases in aridity will result in enhanced sediment availability and/or mobility, leading to increased dune activity (larger areas of mobile sand and increased rates of dune migration or extension). Recent work however suggests that this is an oversimplification of the complex and generally

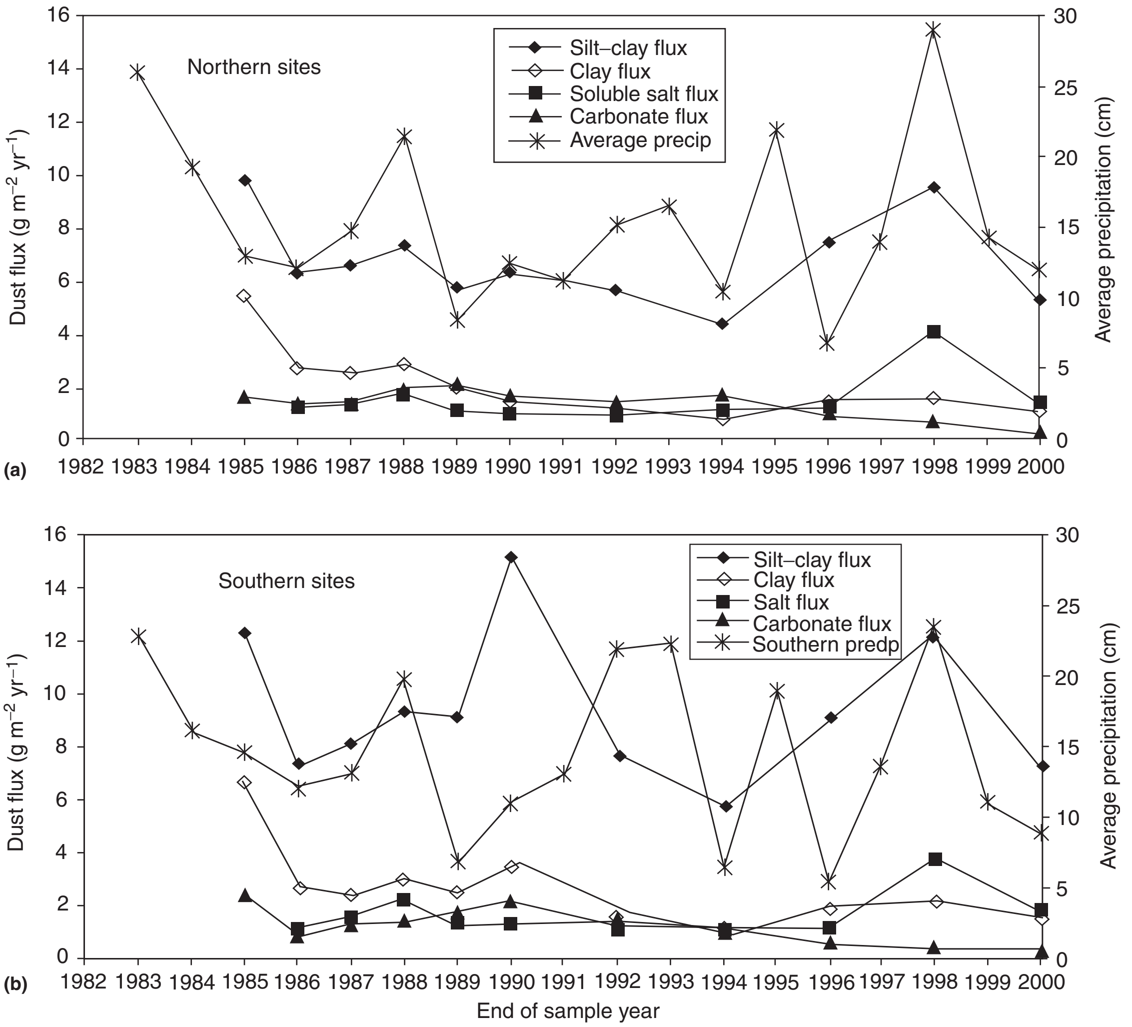

Figure 8 Variations in dust flux and precipitation in the Mojave Desert. (a) Sites in Great Basin and adjacent areas of the Mojave Desert. (b) Sites in the Mojave Desert. Reproduced from Figure 4, parts B and C in Reheis, M.C., 2006. A 16-year record of aeolian dust in Southern Nevada and California, USA: controls on dust generation and accumulation. Journal of Arid Environments 67, 488–520, with permission from Journal of Arid Environments.

nonlinear relationships that exist between desert dune activity and climate (Muhs and Holliday, 1995; Clarke and Rendell, 1998; Hugenholtz and Wolfe, 2005; Yizhaq et al., 2008; Chase, 2009), as discussed below.

13.9.4.1 Late Holocene and Historical Record of Dune Movement and Deposition

Dune systems in semi-arid, desert margin areas appear to be particularly sensitive to climate change and variability. On the Great Plains of the USA and Canada, many of these dunes are partially or completely stabilized by vegetation in current climatic conditions (Muhs and Wolfe, 1999). Reports from early explorers and surveys of the Great Plains of the USA indicate, however, much more widespread dune activity, probably as a result of drought conditions, in the nineteenth century (Muhs and Holliday, 1995). In the late 1700s, a decade-long drought on the southern Prairies of Canada resulted in an estimated 10–20% increase in the area of active dunes and the formation of barchanoid dunes in the Great Sand Hills, Saskatchewan (Wolfe et al., 2001; Hugenholtz and Wolfe, 2005; Wolfe and Hugenholtz, 2009). These dunes are now largely stabilized in warmer and less arid conditions. Stabilization was accompanied by a change in dune morphology from barchanoid to parabolic over a period of 70 years between 1810 and 1880 (Wolfe and Hugenholtz, 2009). The dune activity initiated by the late 1700s' drought was one of a series of periods of dune activity that occurred in the past 2000 years on the Great Plains (Forman et al., 2001; Miao et al., 2007). For example, six periods of dune activity (around 1390, 670, 470, 240, 140, and 70 years ago) have been recognized in the area of the Nebraska Sand Hills during the past 1500 years and have been correlated with evidence of drought episodes elsewhere in the region (Forman et al., 2005; Sridhar et al., 2006). The most significant of these periods of activity were coincident with a widespread and extended drought (mega-drought) that occurred in the sixteenth century. In addition, sand

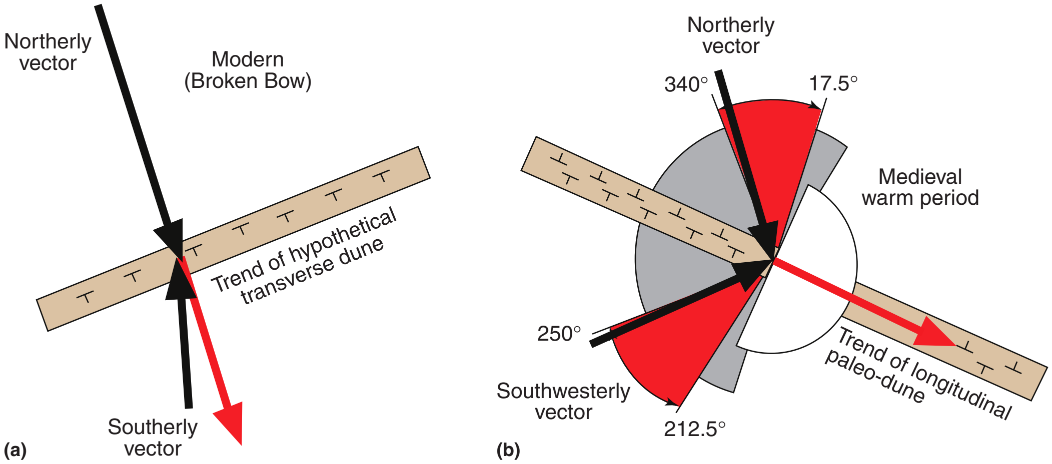

Figure 9 Changes in sand-moving wind regime on the Great Plains inferred from dune trends. Potential sand-transport directions indicated by black arrows; red arrows indicate resultant (vector sum) direction. (a) Modern potential sand transport vectors at Broken Bow, Nebraska. (b) Sand-transport vectors inferred from trends of Medieval Warm Period linear dunes. Winds from the two red sectors are required to produce a linear dune; sand transport from gray sectors would have produced transverse dunes. Reproduced from Figure 2 in Sridhar, V., Loope, D.B., Swinehart, J.B., Mason, J.A., Oglesby, R.J., Rowe, C.M., 2006. Large wind shift on the Great Plains during the medieval warm period. Science 313, 345–347, with permission from AAAS.

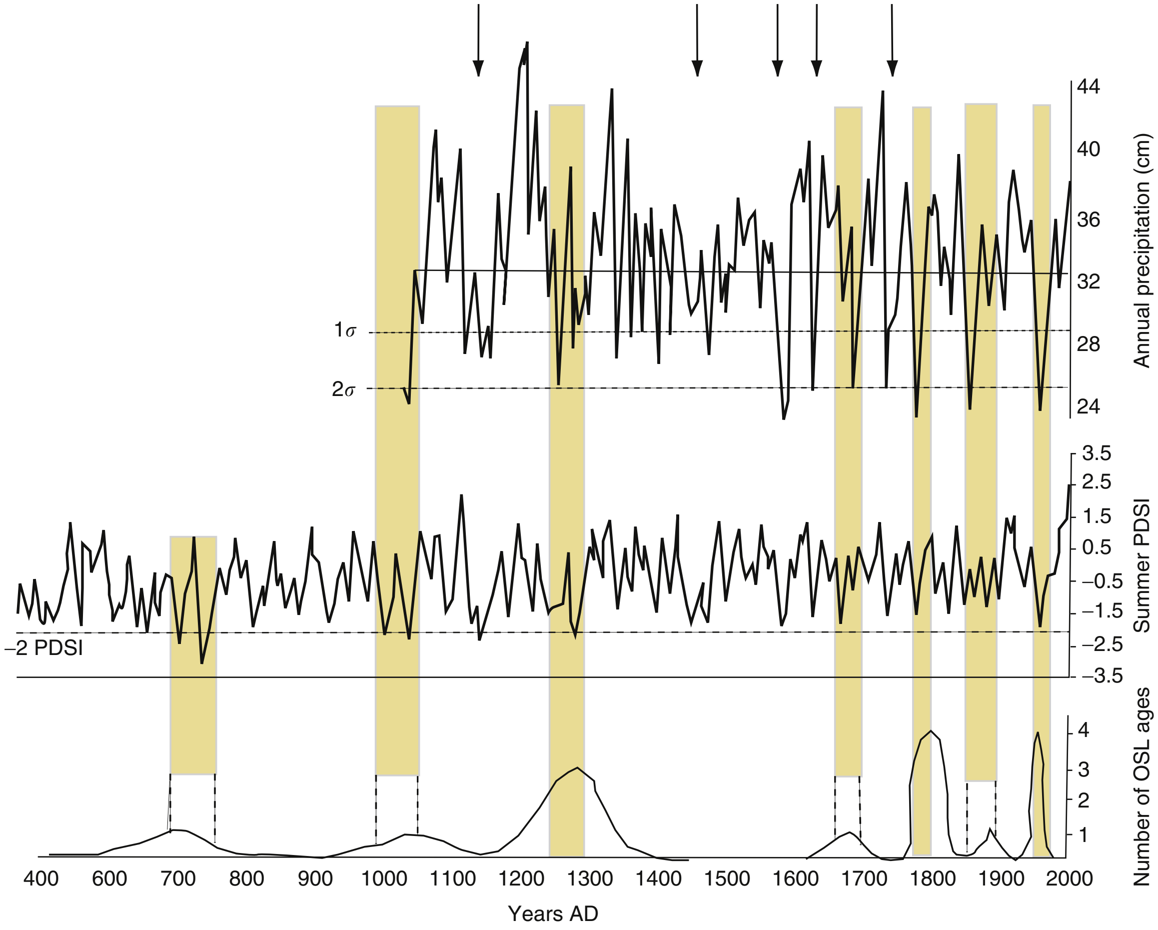

Figure 10 Relationships between records of inferred precipitation and summer Palmer drought severity index (PDSI) from tree ring data, and periods of OSL-dated dune activity at Great Sand Dunes National Park, Colorado. Vertical shaded bars indicate periods of possible correspondence between aeolian and tree ring records; arrows indicate periods of drought indicated by tree ring records, but for which there is no equivalent aeolian record. Redrawn from Figure 7 in Forman, S.L., Spaeth, M., Marin, L., Pierson, J., Gómez, J., Bunch, F., Valdez, A., 2006. Episodic Late Holocene dune movements on the sand sheet area, Great Sand Dunes National Park and Preserve, San Luis Valley, Colorado, USA. Quaternary Research 66(1), 119–132.

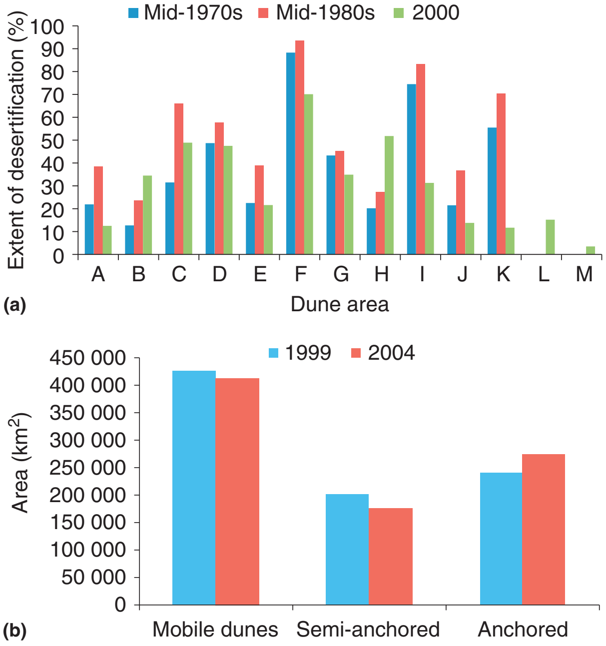

Figure 11 Changes in dune activity status in Chinese dunefields. Drawn by myself from data in Wang, X., Yang, Y., Dong, Z., Zhang, C., 2009. Responses of dune activity and desertification in China to global warming in the twenty-first century. Global and Planetary Change 67(3–4), 167–185, with permission from Global and Planetary Change.

accumulations related to the 1930s' drought can be recognized. Elsewhere in this region, a major period of linear dune formation occurred 700–1000 years ago, coincident with a period of widespread drought during the Medieval Warm Period (Mason et al., 2004; Sridhar et al., 2006). During this episode of dune formation, winds shifted direction so that the summertime southeasterly flow of humid air was replaced by dry southwesterly flow (**Figure 9**). At Great Sand Dunes, Colorado, periods of aeolian deposition in the late Holocene can be correlated with decadal-scale drought episodes recognized in tree ring records (Forman et al., 2006), suggesting an overall control of dune activity by rainfall and vegetation cover in this area (**Figure 10**).

Increases in dune activity or construction of new generations of dunes as a result of increased sediment supply have been noted in several areas. In the Mojave Desert (Clarke and Rendell, 1998), periods of dune construction followed increased flooding in the Mojave River system, likely as a result of changed circulation patterns (Ely et al., 1993). In Idaho, construction of linear and parabolic dunes in the nineteenth century occurred in a drought episode (1845–56) that followed a period of high lake levels. In this case, sediment supplied and stored in the period of high lake levels became available as lake levels dropped in the subsequent drought (Forman and Pierson, 2003).

13.9.4.2 Decadal-Scale Changes

Long meteorological records, coupled with repeated observations of the state of dune systems using aerial photographs and satellite images, have provided valuable information on how dune systems respond to climate variability on decadal scales. In China, dune systems cover as much as 23% of the arid and semi-arid areas of northern and western China. Significant variations (**Figure 11**) in the areas covered by dunes that are classified as mobile (active), semi-anchored (partially stabilized), or anchored (stabilized by vegetation) have occurred since the 1950s over much of the Chinese arid zone (Wang et al., 2006, 2008). The causes of these changes in dune activity status (described as desertification or rehabilitation) have been much debated, with some authors ascribing them to human activity, including overgrazing or land-use change, and others favoring climatic variability as the main factor influencing changes in the areas of active or stabilized dunes (Wang et al., 2006).

Wang et al. (2006) have analyzed climatic data from the 1950s in conjunction with data on areas of dunes of different status. They concluded that the period from the 1950s to the 1980s was characterized by higher wind speeds, compared to the period from the 1980s to the present. This resulted in sand drift potentials (Fryberger, 1979) that were 2–5 times greater in the 1950–80 period compared to 1980–present. As a result, vegetation cover in many dune areas doubled so that some areas of active dunes became partially vegetated, whereas in other areas sand transport was restricted to dune crests. Many partially vegetated dunes became completely stabilized by vegetation. From 1999 to 2004, the area of active dunes and partially vegetated dunes decreased by 3.7% and 11.4%, respectively, whereas the area of stabilized (vegetated) dunes increased by 13.8%. In the Takla Makan Desert, for example, dune mobility was higher in the 1960s and the mid-1980s compared to the 1990s (Wang et al., 2004a).

Mason et al. (2008) confirmed the large decrease in wind energy in the Mu Us, Otindag, and Horqin deserts since the 1970s, but observed that this change did not result in widespread stabilization of dunes, except in the eastern Mu Us area. In fact, areas of active dunes remained constant or even slightly increased over the past 40 years. They concluded that wind energy may not be as important to changes in dune activity as has been suggested and that changes in human land use in this area may have a more significant role.

At Great Sand Dunes (Colorado), Marîn et al. (2005) documented migration rates of parabolic and barchan dunes over a period of 70 years using satellite images and aerial photographs (**Figure 12**). They found that migration rates were up to 6 times higher in drought episodes compared to intervening wetter periods. More than 50% of the movement of parabolic dunes occurred during periods of drought that occurred between 1936 and 1941, 1953 and 1966, and 1998 and 1999. They identified a threshold condition with a Palmer drought severity index (PDSI) value of less than −2 (equivalent to a reduction in summer and fall precipitation of 25%) for increased dune activity.

Similar relations between dune movement and dry episodes were noted from the Coachella Valley, California, where dune migration rates in the period 1939–92 varied by as much as 200%. Overall rates appear to be inversely related to annual rainfall (Lancaster, 1997), as a result of growth of annual and ephemeral plants following wetter years.

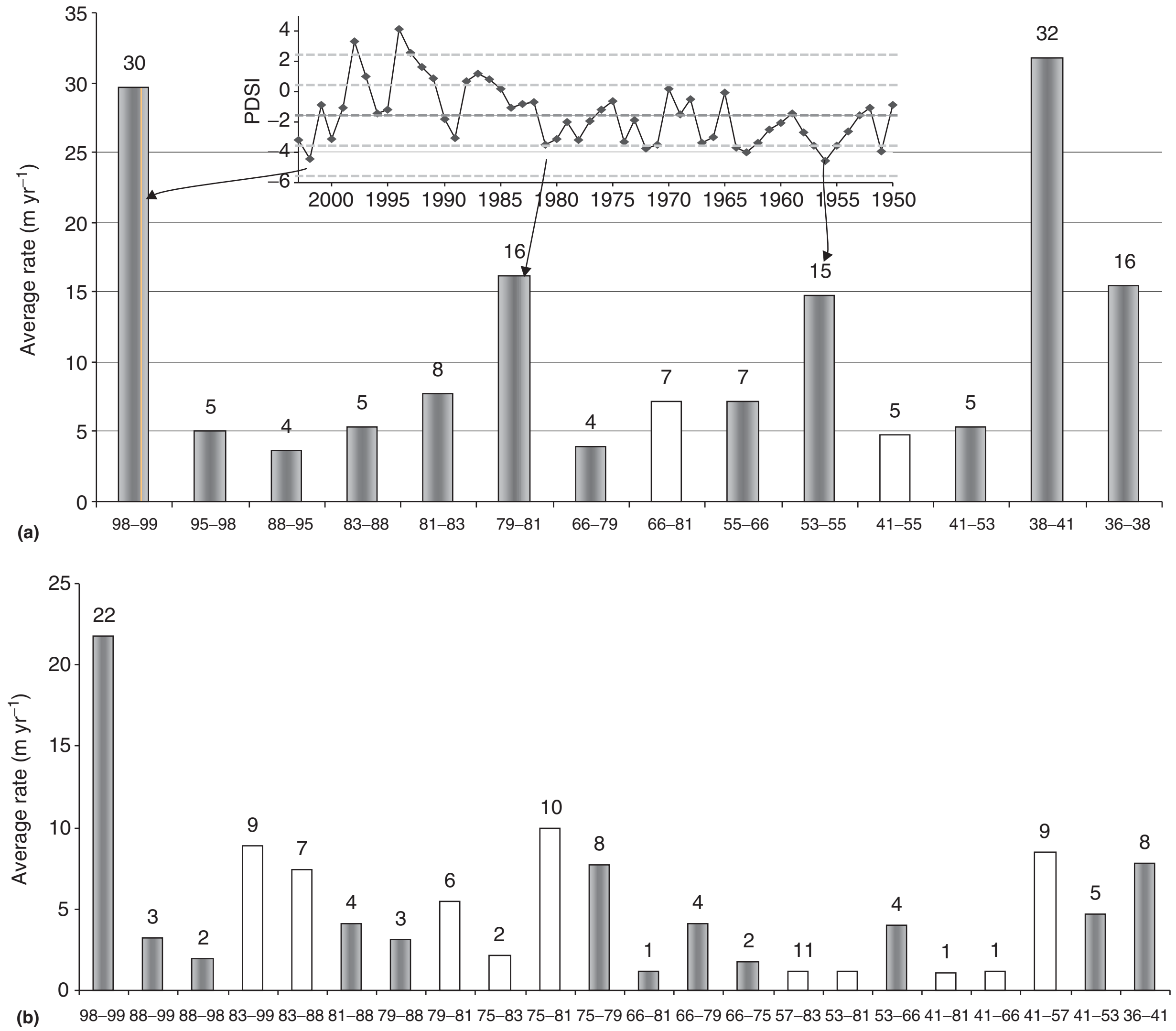

Figure 12 Variations in the rate of dune migration at Great Sand Dunes Colorado. (a) Parabolic dunes; (b) barchan dunes. Reproduced from Figure 8 in Marîn, L., Forman, S.L., Valdez, A., Bunch, F., 2005. Twentieth century dune migration at the Great Sand Dunes National Park and Preserve, Colorado, relation to drought variability. Geomorphology 70, 163–183.

In the southwestern Kalahari, the 1970s were characterized by higher rainfall and somewhat cooler temperatures and lower wind energy, whereas the 1980s were affected by severe regional drought, which was accompanied by generally higher wind speeds (Bullard et al., 1997). The result was a significant variation in indices of dune surface activity, as modeled by the dune mobility index (Lancaster, 1988) (**Figure 13**). These changes are confirmed by studies of the area of active dune sand on *Landsat* images from a drought period (1984) and a wetter period (1993) (Thomas and Leason, 2005). Using an empirically derived vegetation cover threshold for active sand movement of 14% (Wiggs et al., 1995), Thomas and Leason (2005) showed that the area affected by active sand movement varied between 16% (1984) and 6% (1993) for areas not impacted by grazing. These results highlight the spatial dynamics of such climate variability on dune systems and show that even if large areas have a low vegetation cover in dry periods, they can recover over a short period of time if human pressures are not excessive.

13.9.4.3 Response to Interannual Climate Variability

In addition to the decadal-scale responses discussed above, dune systems respond to interannual variability in climate, especially rainfall, through changes in vegetation cover and therefore sediment availability. Such responses are most notable where the vegetation cover incorporates a significant proportion of annual or ephemeral plants that respond rapidly to changes in rainfall and soil moisture. The record provided by the US Geological Survey (USGS) Desert Winds project (Helm and Breed, 1996; Lancaster and Helm, 2000) provides one example of sand-transport response to changes in precipitation, wind strength, and (indirectly) vegetation cover. At the studied locations, sand-transport rates (measured directly using sand traps) varied by an order of magnitude over the period 1985–2005, decreasing sharply during and after the El Niño years of 1992–93, and increasing in the subsequent drought years on the Colorado Plateau (**Figure 14**). At one location (Jornada, New Mexico), sand-transport rates increased significantly after 1995, perhaps

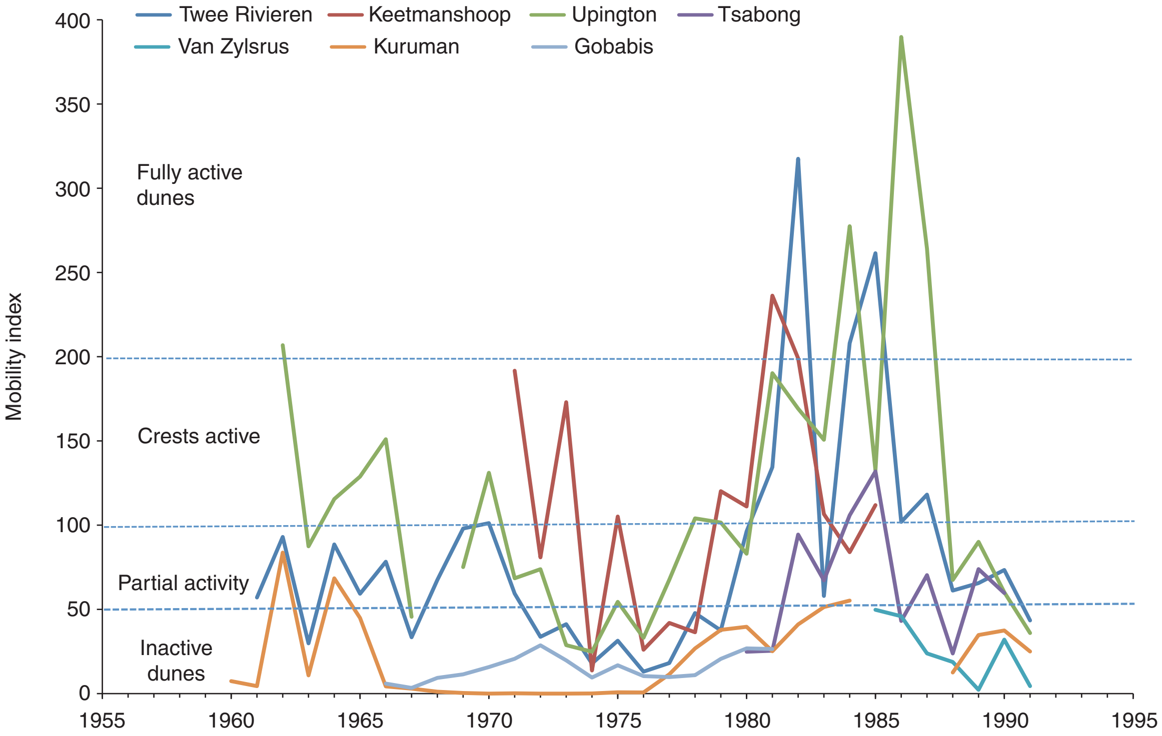

Figure 13 Temporal changes in potential dune sand mobility in the SW Kalahari. Drawn from data provided by author Bullard, Bullard, J.E., Thomas, D.S.G., Livingstone, I., Wiggs, G.F.S., 1997. Dunefield activity and interactions with climatic variability in the southwest Kalahari Desert. Earth Surface Processes and Landforms 22(2), 165–174.

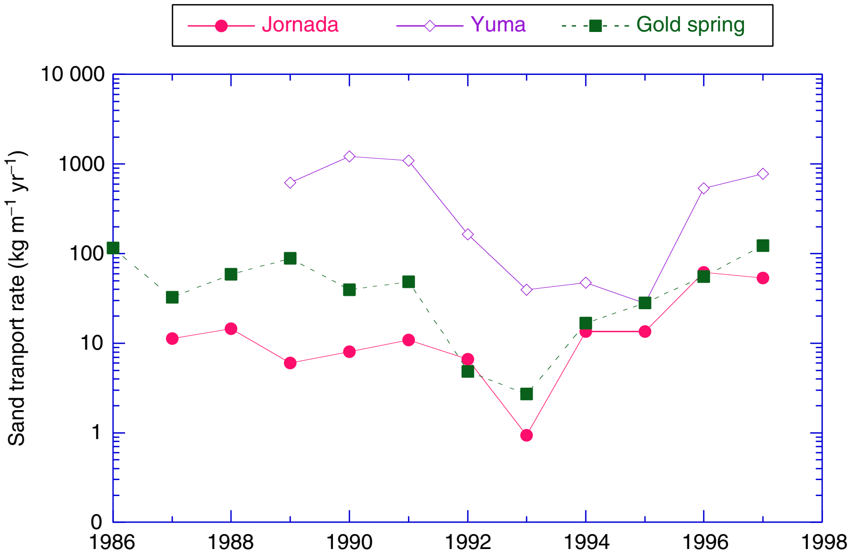

Figure 14 Relationships between measured sand flux and precipitation from USGS/DRI Desert Winds project sites. Original figure compiled by myself to be similar to published version in Lancaster, N., Helm, P., 2000. A test of a climatic index of dune mobility using measurements from the southwestern United States. Earth Surface Processes and Landforms 25(2), 197–208.

reflecting vegetation-type conversion from grassland to mesquite shrubland, resulting in a landscape of mesquite-anchored coppice dunes separated by intervening areas of bare sand (King et al., 2006; Okin et al., 2001).

The record from the USGS climate impact meterological stations (CLIM-MET) in the Soda Lake area of the Mojave Desert (Urban et al., 2009) shows a clear relationship between the growth of annual forbs and grasses following wet winter/early spring periods and periods of low or no sand flux (**Figure 15**). They noted that remnant annuals may persist for years or months and effectively stabilize the surface by increasing roughness even when rainfall is low.

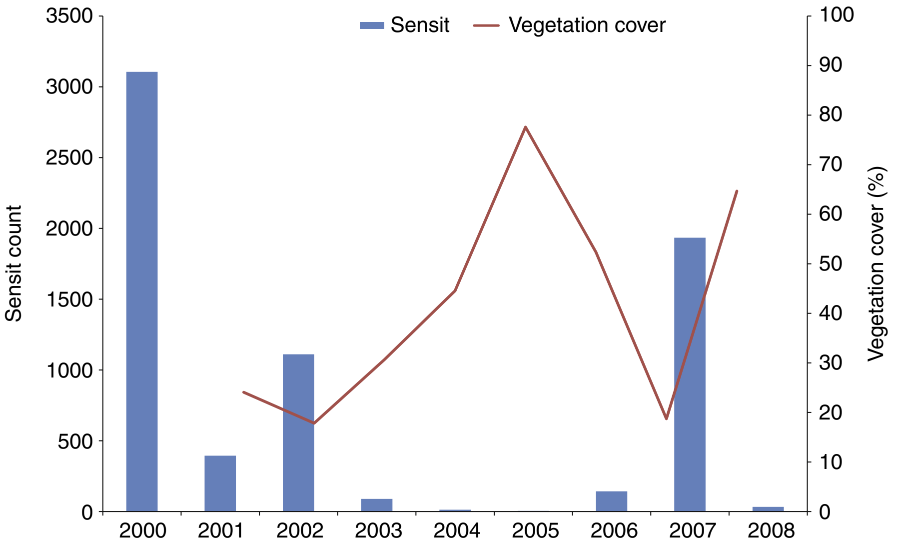

Figure 15 Relationships between sand flux (as indicated by particle counts registered by a Sensit wind erosion monitor) and vegetation cover, USGS CLIM-MET station at Balch, California. Data from http://esp.cr.usgs.gov/info/sw/clim-met/balch.html

13.9.5 Modeling the Response of Aeolian Systems to Climate Change

Understanding the response of aeolian systems to climate change in the geomorphic and sedimentary record, as well as predictions of their response to future climate change, requires development of appropriate models for relations between aeolian processes and controlling variables.

13.9.5.1 Dust Sources and Transport

Modeling of the response of dust-transport systems to climate change involves incorporation of mineral aerosol (dust) source and deposition algorithms (Zender et al., 2003) into coupled land–atmosphere–ocean–sea ice global climate models (Mahowald et al., 2006). In this approach, parametrization of a source strength algorithm incorporates information on soil texture and moisture, roughness length, and vegetation cover. Changes in dust emissions and therefore the dust loading of the atmosphere also affect radiative transfer models, with consequent effects on regional and global climate. The models can be run for present conditions and for a variety of past and future climate scenarios. Model verification is accomplished by comparing modeled rates of dust deposition with terrestrial and marine sediment records (Kohfeld and Harrison, 2001). Comparison of modeled dust loading in the atmosphere for the Last Glacial Maximum, preindustrial, modern, and doubled CO_2 climates indicates that dust production mainly responds to changes in the vegetation cover of source areas, rather than to changes in wind strength or soil moisture (Mahowald et al., 2006).

13.9.5.2 Dune Systems

A simple model of the relationship between dune mobility (more correctly sand mobility) and climatic variables is provided by indices of dune mobility, which are based on the principle that sand mobility is proportional to the wind speed above threshold and inversely proportional to effective precipitation, which determines soil moisture and vegetation cover. A widely used (e.g., Muhs and Maat, 1993; Stetler and Gaylord, 1996; Bullard et al., 1997; Wang et al., 2004a, 2009) and empirically verified model is Lancaster's dune mobility index (Lancaster, 1988), which is based on the wind erosion model developed by Chepil et al. (1963). In this model, sand

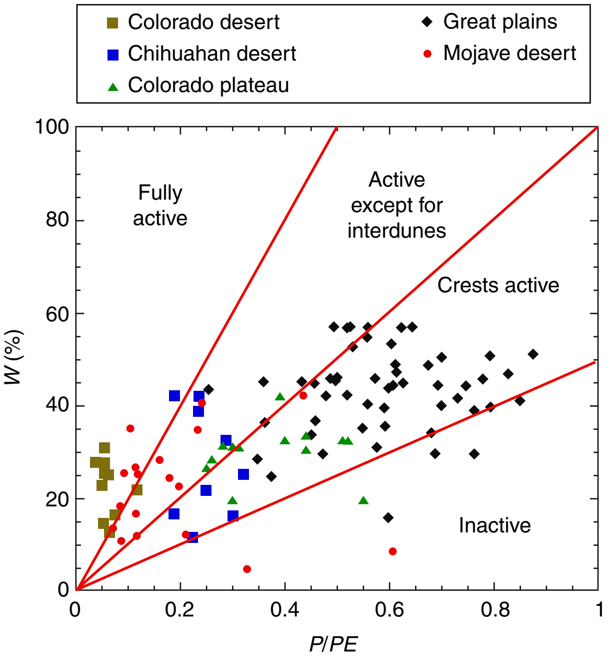

Figure 16 Relations between dune activity status and climate, Great Plains, and Mojave, Colorado Plateau, and Colorado Deserts. *W* is the percentage of time the wind is above the transport threshold. Data courtesy Dan Muhs, USGS.

mobility (M) is given by

$$M = W(P/PE)$$

where W is the percentage of time the wind is above transport threshold, P the annual precipitation, and PE the potential evapotranspiration, calculated using the Thornthwaite method. Critical empirically derived values of the index (M) are: <50, sand surfaces stabilized by vegetation, dunes inactive; 50–100, only crest areas of dunes active; 100–200, dunes active, but interdune areas stabilized by vegetation; and >200, dunes fully active. The index appears to perform quite well in a variety of climatic and geomorphic environments (**Figure 16**) and compares well to the state of dune systems observed on aerial photographs and satellite images (e.g., Muhs and Maat, 1993). It has also been verified empirically by comparison to long-term monitoring of sand flux and climatic parameters in the SW USA (Lancaster and Helm, 2000). In this study, the annual mobility index was found to vary with annual precipitation; sand-transport rates were found to be strongly correlated with the mobility index for the prior year, reflecting the lag effects as a result of growth and persistence of vegetation from year to year (**Figure 17**). In recent years, modifications of the index have been made to facilitate use of global climate model (GCM) output data and calculation of monthly values, so improving its sensitivity in regions of highly seasonal climate (Thomas et al., 2005; Wang et al., 2009).

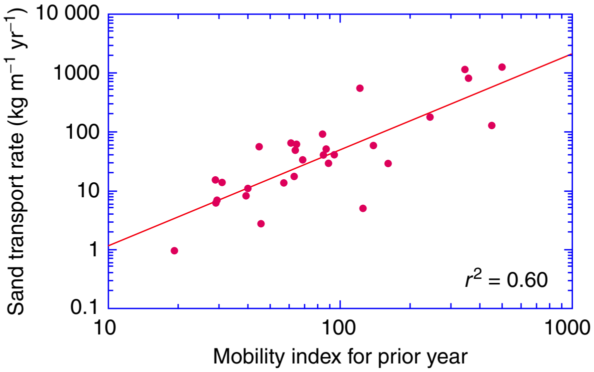

Figure 17 Relations between sand flux and mobility index. Reproduced from Lancaster, N., Helm, P., 2000. A test of a climatic index of dune mobility using measurements from the southwestern United States. Earth Surface Processes and Landforms 25(2), 197–208.

The dune mobility index provides one method for assessing the sensitivity of aeolian systems to climate variables. For example, for dunes on the Great Plains, in the Kalalari, and the Mojave Desert, the main factor affecting year-to-year changes in their mobility is precipitation, which determines soil moisture and vegetation cover and therefore sediment availability. Elsewhere, surface crusts may be a limiting factor – for example, the Negev (Allgaier, 2008). In the Australian dunefields low wind energy appears to be a major control on dune activity, in addition to a significant vegetation cover in many areas (Ash and Wasson, 1983; Hesse and Simpson, 2006).

Such empirical relations have provided the basis for conceptual models of dune system response to climate change in the Great Plains (Hugenholtz and Wolfe, 2005), which incorporate lag effects in the form of reaction and response times following perturbations (**Figure 18**). As vegetation-stabilized dunes respond to a perturbation (e.g., a period of reduced rainfall), the system response is controlled by extrinsic (mainly climatic) and intrinsic (mainly vegetation) thresholds, so that activation occurs after a threshold of vegetation mortality is crossed and vegetation cover decreases, causing sand-transport rates to increase, with attendant feedback effects between sand transport and plant cover. The response

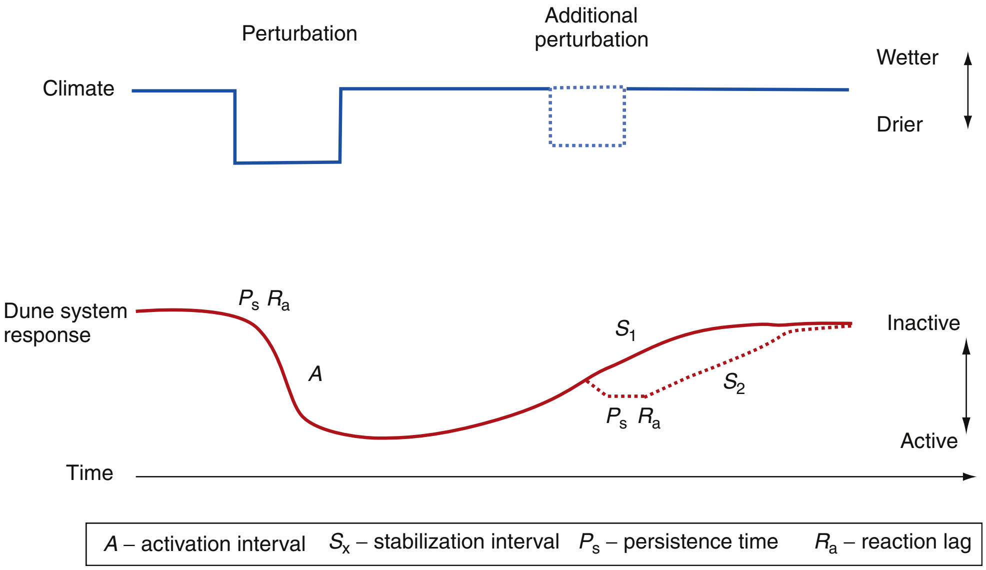

Figure 18 Conceptual model for the response of dune systems to climate change. Redrawn from Figure 9 in Hugenholtz, C.H., Wolfe, S.A., 2005. Biogeomorphic model of dunefield activation and stabilization on the northern Great Plains. Geomorphology 70, 53–70.

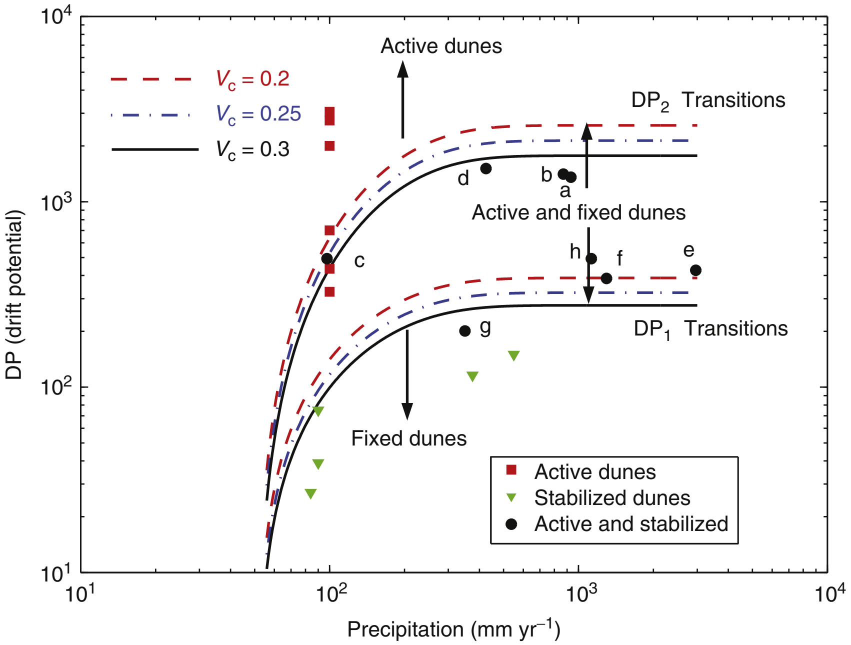

Figure 19 Computed transition points from active to fixed dunes (upper group of curves) and fixed to active dunes (lower group of curves) for different vegetation cover in relation to precipitation and sand drift potential. Reproduced from Figure 6 in Yizhaq, H., Askenazy, Y., Tsoar, H., 2008. Sand dune dynamics and climate change: a modeling approach. Journal of Geophyical Research 114, F01023, with permission from Journal of Geophysical Research.

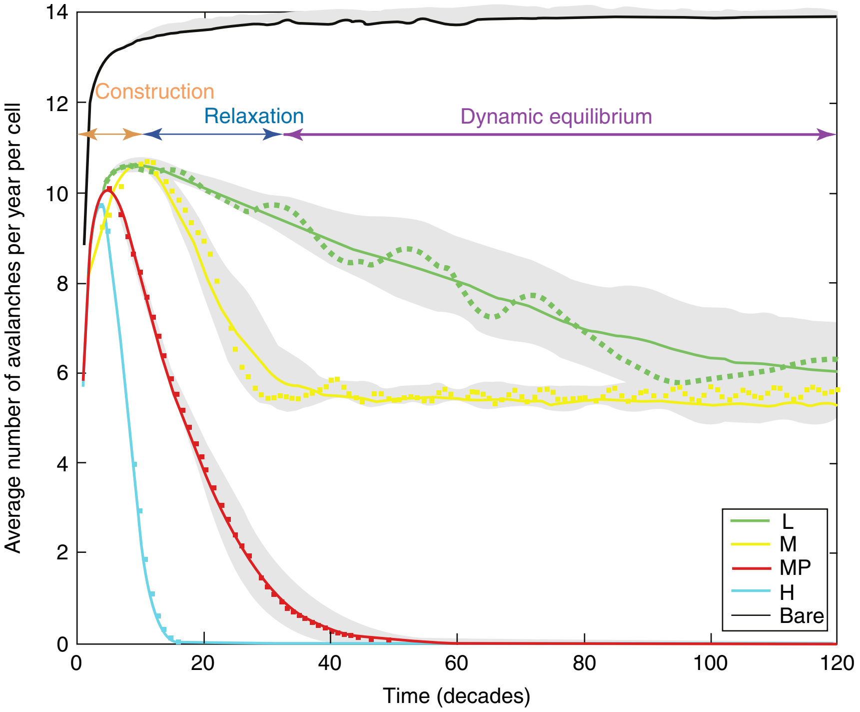

Figure 20 Change in dune activity, as indicated by the number of avalanches per year, with time for a range of vegetation growth rate scenarios. Reproduced from Figure 20 in Nield, J.M., Baas, A.C.W., 2008. The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. Global and Planetary Change 64(1–2), 76–92, with permission from Global and Planetary Change.

time is a function of the intensity of the perturbation – high-intensity perturbations produce a more rapid and spatially extensive response and change in vegetation cover. Reversion of an active system as a result of an increase in precipitation follows a path that is determined by the regrowth of the vegetation cover, which may occur in a logistic fashion, and its effects on sand transport. This pattern of change may take many decades (e.g., Wolfe and Hugenholtz, 2009).

A somewhat similar, but quantitative, approach to modeling the effects of climate change on dune systems was taken by Yizhaq et al. (2007, 2008). Their approach (*see* Chapter 11.20) emphasizes the nonlinear and hysteretic nature of the interactions between wind strength, precipitation, and vegetation cover, plus the effects of anthropogenic disturbance. They demonstrated the bistable state of the dune system and show that this is dependent on the energy of the wind regime as measured by the Fryberger drift potential. In places with very low wind energy, dunes have only one stable state, which is vegetated and fixed; at intermediate levels of wind energy, both active and stabilized dunes can coexist, whereas active dunes are the stable state in areas of very high wind energy (**Figure 19**). This approach has its limitations, however, and may not apply everywhere. Dunes in Nebraska are generally stabilized by a well-developed grassland vegetation cover, despite a high level of wind energy and drift potential (Muhs and Maat, 1993). By contrast, the Algodones Dunes are currently very active, despite a low-energy wind regime (Muhs et al., 1995).

In an alternative approach, Nield and Baas (2008) used a cellular automaton model to evaluate the effects of climate change and variability on vegetated dune landscapes. This model incorporates both ecological and geomorphic processes and their complex, nonlinear interactions, including the effects of vegetation cover on sand-transport rates and the probability of erosion or deposition occurring. Changes in vegetation cover over time are modeled using both pioneer and successional vegetation types and their resulting different growth rates. The modeled behavior closely resembles empirical data on dune areas subject to stabilization by vegetation and helps to identify evolutionary trends, thresholds, and relaxation periods (**Figure 20**). The landscape response is sensitive to both the nature of the perturbation (increasing or decreasing winds and/or vegetation cover) and the initial state of the system.

Table 1 Modeled change in dust emissions from desert areas in future climate scenarios

Model	*Year*	*Change*	*Source*
NCAR CSM	2090	–20% to –60%	Mahowald and Luo (2003)
HADCAM3	2050	–19%	Tegen et al. (2004)
ECHAM4	2050	+9%	Tegen et al. (2004)
HADAM3	2090	+200%	Woodward et al. (2005)

13.9.6 Aeolian System Response to Future Climates

Hydroclimatological observations show that changes in seasonal and annual temperature, precipitation, snowmelt and runoff, groundwater recharge, and evapotranspiration are occurring today in most drylands (Trenberth et al., 2007) and models predict that they are likely to continue in the future (e.g., Seager et al., 2007). Many areas are already experiencing significant increases in temperature and a reduction in rainfall over the past two decades, manifested in extended droughts. Given the role of aeolian systems in drylands and their sensitivity to climate change in the past as well as to historical climate variability, understanding their response to future climate change is important in predicting the effects of climate change on almost half of the Earth's land surface.

Modeling the future dynamics of dust emissions and transport involves assessment of both source area response in a variety of climate scenarios and the feedback effects between changes in atmospheric dust loading and regional and global atmospheric dynamics. The response of dust-transport systems to future

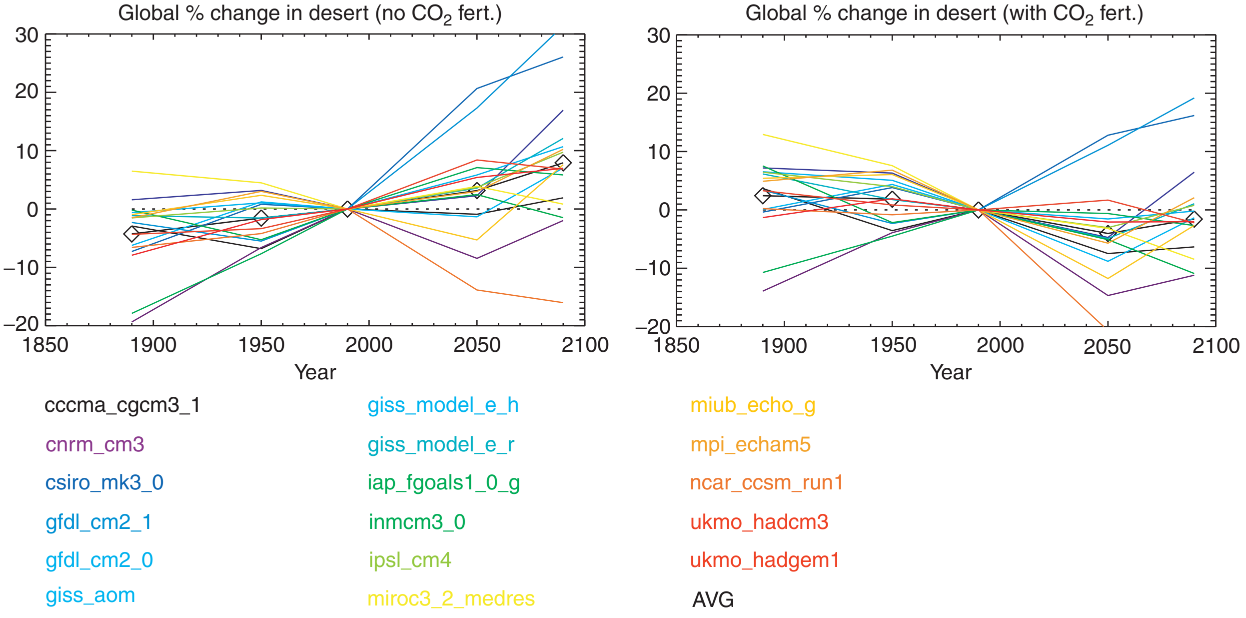

Figure 21 Change in desert area for a range of climate models with and without CO$_2$ forcing. Reproduced from Figure 2 in Mahowald, N.M., 2007. Anthropocene changes in desert area: sensitivity to climate model predictions. Geophysical Research Letters 34, L18817, with permission from AGU.

climate change is highly model dependent (**Table 1**) and ranges from a 20–60% decrease in emissions to increases of 9% to as much as 200%. The forcing of the resultant aerosols is similarly highly variable, although recent work suggests that effects of changes in dust source strength and atmospheric loading are mostly significant only at the regional level (Yoshioka et al., 2007). A major uncertainty in such estimates is the contribution of anthropogenic sources of dust as a result of land-use changes and increased human disturbance of dryland surfaces (Tegen et al., 2004). Another uncertainty is the possible enhanced growth of desert vegetation in conditions of higher atmospheric CO_2 concentration (carbon dioxide fertilization) (Mahowald, 2007). If no carbon dioxide fertilization is assumed, then desert areas are predicted to expand in the next century by a total of 7.9% compared to the period 1980–2000, although there is wide variation between models. In some areas, such as Australia and Southern Africa, the expansion of desert areas is very significant (**Figure 21**). If carbon dioxide fertilization is included in models,

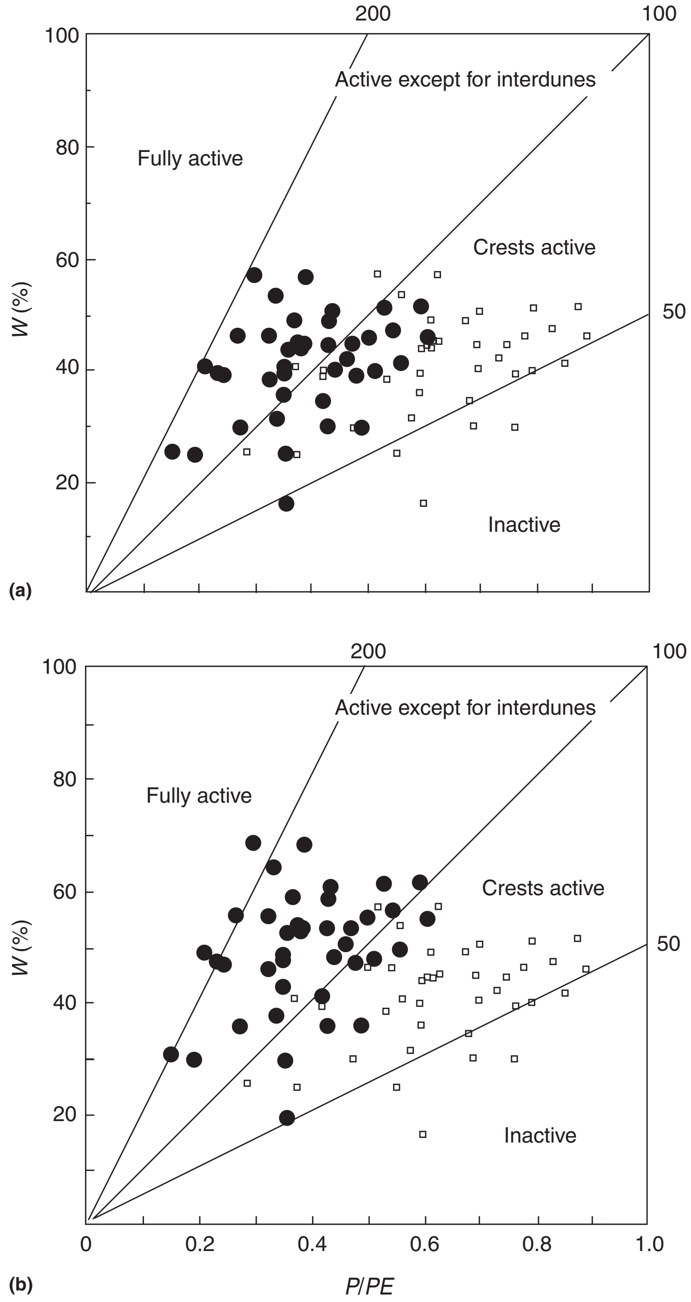

Figure 22 Change in dune activity with global warming for the Great Plains. (a) GISS GCM with modern climate (open squares) and greenhouse climate (filled circles); (b) as in (a) with 20% increase in *W*. Reproduced from Figures 2 and 3 in Muhs, D.R., Maat, P.B., 1993. The potential response of aeolian sands to Greenhouse Warming and precipitation reduction on the Great Plains of the United States. Journal of Arid Environments 25, 351–361, with permission from Journal of Arid Environments.

then there is only a slight change in desert area, because plants are able to respond to increased aridity more effectively (Smith et al., 2000).

Dune system response to future climate change may be assessed by incorporating the output from global and regional climate models into climatic indices of dune activity. The first use of such an approach was by Muhs and Maat (1993) for the Great Plains of the USA. They concluded that any change in the *P*/*PE* ratio as a result of increased temperatures and/or decreased precipitation will lead to higher values of the Lancaster mobility index and increased potential for sand mobility. Modeling of future climatic conditions for the Great Plains (**Figure 22**) suggests that the increased temperature and reduced precipitation predicted by climate models will lead to widespread reactivation of dunes and sand sheets in this region (Muhs and Maat, 1993).

Using a range of climate models and future climate scenarios, Thomas et al. (2005) incorporated a modified version of

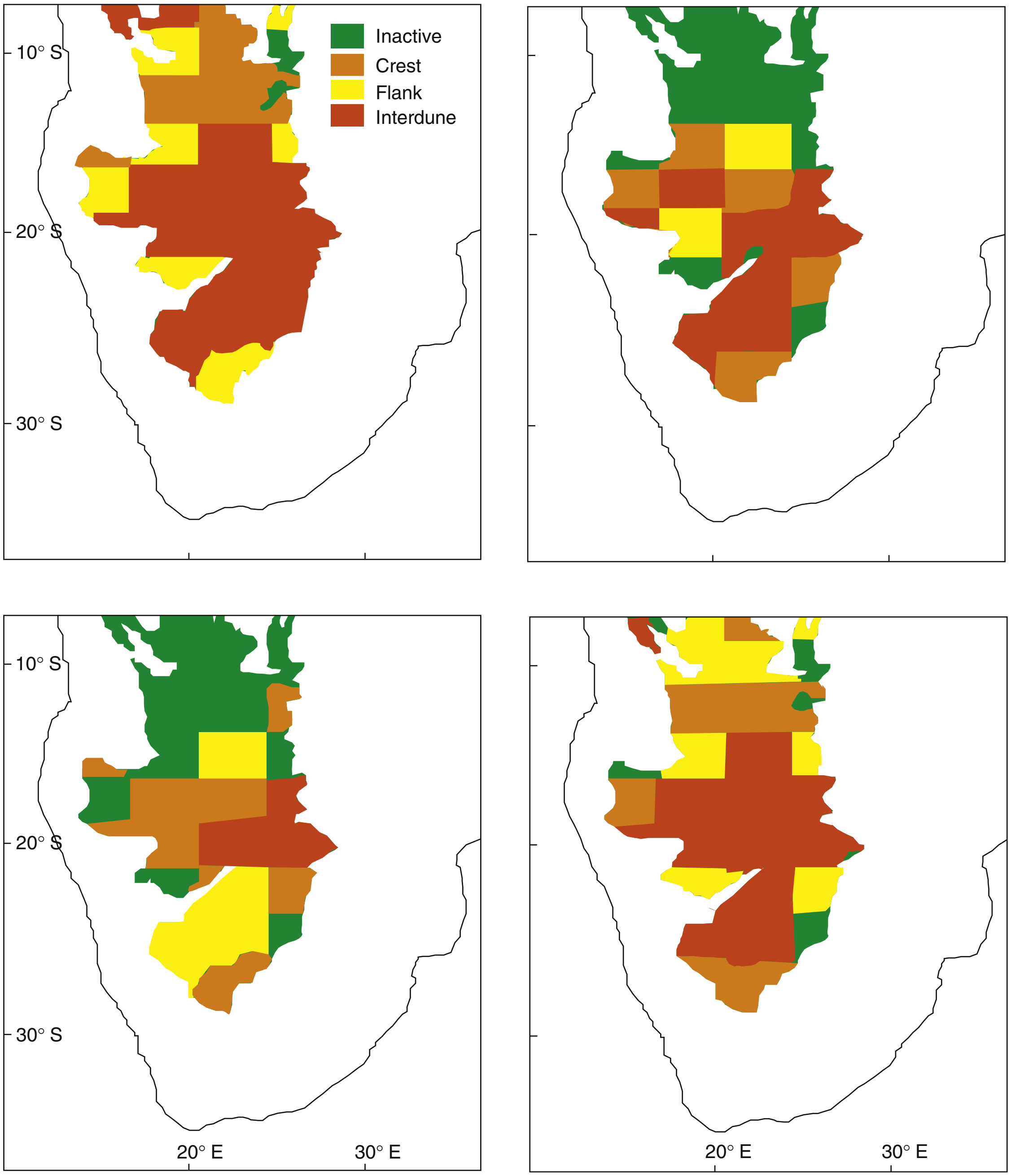

Figure 23 Response of Kalahari dune systems to future climate change. Example is for the year 2070, with each block representing a 3-month period (begins August–October at top left). Note seasonal changes in modeled dune activity. Redrawn and colored version of Figure 4 in Thomas, D.S.G., Knight, M., Wiggs, G.F.S., 2005. Remobilization of southern African desert dune systems by twenty-first century global warming. Nature 435, 1218–1221.

the dune mobility index to simulate future seasonal and annual changes in dune mobility for the largely vegetation-stabilized dunefields of the Kalahari region of southern Africa. All the GCMs produce increasing levels of dunefield activity in the twenty-first century (**Figure 23**), including fully active dunes in some areas. Such widespread dune activity has not occurred in this area since the late Pleistocene and would represent a major change in the Kalahari environment, with important effects on ecosystems and local livelihoods.

In China, Wang et al. (2009) used the European Centre Hamburg, version 4 (ECHAM4) and Hadley Centre Coupled Model, version 3 (HadCM3) models combined with a slightly modified dune mobility index in a range of IPCC scenarios to assess trends in dune activity in the twenty-first century (Intergovernmental Panel on Climate Change, IPCC). Given the wide extent of dune systems in China and the different climatic conditions they experience today, a complex spatial and temporal pattern is evident, with some regions experiencing decreased dune activity in the coming decades. Wang et al. concluded that, in many areas, for the period 2040–99, there will be increased dune activity in eastern and western China, even with increases in precipitation, largely because of the higher rates of potential evapotranspiration (increases are predicted to exceed 30% in many areas). However, in central parts of the Chinese drylands, a precipitation increase of up to 40% is predicted, leading to stabilization of dunes in this area. For all areas, only minor increases in wind strength are predicted.

Use of GCM output to simulate the future state of dune systems is not without challenges, as pointed out by Knight et al. (2004). Issues include the coarse spatial resolution of GCM output and uncertainty in estimates of future temperature and precipitation. There are also problems with integrating model output with the mobility indices. Given the spatial variability of activity in many dunefields as well as the sensitivity of dune systems to interannual variability, the use of GCM output may mask important temporal and spatial trends, which may be addressed using regional climate models, which have a higher spatial and temporal resolution.

13.9.7 Conclusions

Numerous studies have demonstrated the sensitivity of aeolian systems to climate change on a variety of timescales, as a result of changes in the supply, availability, and mobility of sediment. Evidence from the late Holocene to the historical record shows that periods of extended regional drought are likely to lead to widespread reactivation of currently vegetation-stabilized dunes in many drylands. The observational and recent sedimentary record of dust emissions and transport likewise indicates that periods of enhanced dust production are closely linked to periods of drought. Such drought episodes are predicted to become more prevalent and widespread in the coming decades as global and regional temperatures rise.

The major uncertainty in understanding the future response of aeolian systems to climate change in the future results from the wide variation, especially with regard to precipitation, in the results of global climate models for dryland areas, some of which predict reduced aridity, whereas others suggest expansion of desert areas. Also important are the possible impacts of carbon dioxide fertilization on desert vegetation and the likely effects of land-use change and human disturbance on these areas. Further research is needed to constrain these effects on both sand- and dust-transport systems.

Although conceptual models for the response of aeolian systems to climate change exist, there is a clear need to develop, parametrize, and verify quantitative models, especially for sand-transport systems, which can utilize the output from regional climate models to predict the response of these systems to future climate change.

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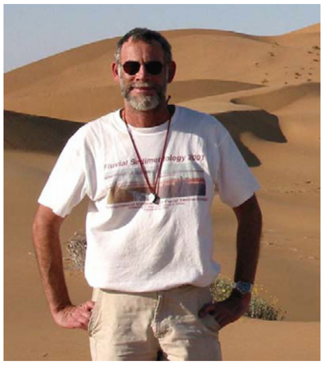
Biographical Sketch



Nicholas Lancaster is a geomorphologist with over 30 years of research experience on sand dune dynamics and Quaternary geology in desert regions. He has conducted research in deserts in Africa (Namib, Kalahari, and northern and western Sahara), Antarctica, the western United States (Mojave and Sonoran deserts), and (via remote sensing) Mars. In addition to studies of modern aeolian processes, especially dune dynamics, Lancaster has examined the response of aeolian systems to climate change on a variety of different timescales.