WILLIAM MORRIS DAVIS
Revista de Geomorfologia

AEOLIAN FORMS AND PROCESSES IN THE ANTHROPOCENE

FORMAS E PROCESSOS EÓLICOS NO ANTROPOCENO

FORMES ET PROCESSUS EOLIENNES DANS L'ANTHROPOCENE

ANDREW GOUDIE[1]

[1]University of Oxford.
E-mail: andrew.goudie@stx.ox.ac.uk. ORCID: https://orcid.org/0000-0002-5496-8207

Recebido 01/08/2021 Aceito 30/08/2021

ABSTRACT
Interest in the human impact on aeolian environments has developed since the nineteenth century and especially in recent decades. One manifestation of this is the generation of dust storms as a result of surface erosion, especially in dry lands. Dust storm frequencies have changed in response both to human pressures and to climatic change. Various methods have been developed to control dust storm activity. Dunes have also been affected by a range of human activities, and their impact can be traced back in some areas for some millennia. In coming decades, it is likely that both dust storm activity and dune movements will change as a result of changes in moisture availability and wind energy.
Keywords: Anthropocene**,** Aeolian, dunes, coasts, dust, wind erosion.

INTRODUCTION

The late Paul Crutzen and colleagues introduced the term 'Anthropocene' (e.g. CRUTZEN, 2002; STEFFEN, et al. 2007), as a name for a new epoch in Earth's history – an epoch when human activities have 'become so profound and pervasive that they rival, or exceed the great forces of Nature in influencing the functioning of the Earth System' (STEFFEN, 2010). In the last three hundred years, they suggest, we have moved from the Holocene into the Anthropocene. They identify three stages in the Anthropocene. Stage 1, which lasted from c 1800-1945 they call 'The Industrial Era'. Stage 2, which extends from 1945 to c 2015, they call 'The Great Acceleration', and Stage 3, which may perhaps now be starting, is a stage when people have become aware of the extent of the human impact and may thus start stewardship of the Earth System. However, there are many scientists who suggest that the Anthropocene has a much longer history than this scheme suggests, with early humans causing major environmental changes through such processes as the use of fire and the hunting of wild animals.

Interest in the role of humans in altering aeolian landscapes developed in the mid to late 19th century (GOUDIE; VILES, 2016). Notable here was George Perkins Marsh's *Man and Nature* (1864). Subsequently, Sokolov (1884; 1894) noted the pressures that were exerted on dunes and noted the hazards posed by dune reactivation and migration. The Dust Bowl of the 1930s in the USA provided a stimulus to studies of wind erosion, dust storm generation, and control methods, as demonstrated by the extensive works of W.S. Chepil and co-workers at the United States Department of Agriculture's Wind Erosion Research Center, established in Kansas in 1947 (e.g. CHEPIL; WOODRUFF, 1963).

Modelling and quantifying the effects of land cover and land use changes on the aeolian environment has now become a major research priority (LI et al. 2014; WEBB; PIERRE, 2018).

The study of ocean, bog, lake and ice core sediments, the analysis of long term meteorological data, the recording of trajectories of dust storms by remote sensing, the development of new forms of dust trap, the recognition of Martian dust activity, and the use of field wind tunnels, caused a huge expansion of interest in the 1970s and 1980s. It became realised that dust had a whole suite of impacts on the Earth's environment at local, regional and global scales (GOUDIE; MIDDLETON, 2006) and also on human health (GOUDIE, 2014; TONG et al. 2017).

Two big issues relating to aeolian geomorphology are how humans have affected dust, and how they have modified dunes.

Dust storms and wind erosion

Dust storms result from the entrainment of fine particles from deflated surfaces, especially in dry regions, and are an indicator of soil erosion by wind (GOUDIE; MIDDLETON, 2006; GOUDIE, 2013). They can also affect regional and global climates, and nutrient cycling. For instance, dust from the Sahara fertilizes the Amazon rainforest (SWAP et al. 1992). Among the human pressures which influence dust storm incidence is the disturbance of desert surfaces by vegetation removal, fragmentation of biological crusts, vehicle and military activity, and grazing and crop production. This often results in the lowering of the threshold shear velocity, making the surface more susceptible to wind attack (GILLIES, 2013). Humans may also produce new surfaces from which dust can be generated, including feedlots, construction sites, and mine tailings.

Another important human pressure is the drying up of lakes and soil surfaces by inter-basin water transfers and ground water depletion (see, for example, RAVI et al. 2011; GOUDIE, 2018). Desiccated lake beds, such as those of the Aral Sea in Central Asia (OPP et al. 2016), Lake Ebinur in northwest China (ABUDUWAILI et al. 2008), and Owens Lake in California, USA, are now a major source of dust (GILL, 1996; BORLINA; RENNO, 2017).

The desiccation of lakes and marshlands has been much studied in Iran (RASHKI et al. 2021). The Al-Howizeh/Al-Azim marshes that straddle the border between Iraq and Iran are highlighted by Cao et al. (2015) as one of the main dust storm source areas in Iran, a conclusion supported by Javadian et al. (2019), who found these wetlands to be one of the three most important dust sources affecting the city of Ahvaz (the others being elsewhere in Iraq). The Iranian part of these marshlands is located mainly in Khuzestan province and Arkian (2017) highlights the impact of oil extraction in Al-Azim as the primary reason for its declining water levels in recent decades. The southern shore of Lake Urmia has been identified as a major dust source within Iran and the importance of this saltwater lake bed has increased as the lake's water-level has declined markedly (EFFATI et al. 2019). It has undergone catastrophic desiccation since the later 1990s, resulting in the loss of 50% of its area by 2014. The expansion of dry, salty surfaces, from which dust is blown, has resulted in more dust events at nearby Tabriz and Urmia, particularly during spring and winter months (DEHGHANI et al. 2020). Lake Bakhtegan is a seasonal salt lake, situated east of the city of Shiraz, usually covered by standing water during the winter and spring months but reduced to a saturated salt marsh during the summer. An overall decline in water level of 6m has been measured between 1986 and 2010 due to a combination of human activities (dams, excessive use of subsurface water) and changes in precipitation and temperature (KIANI et al. 2017).

The relative roles of climate change and human impacts have exercised many investigators (MIDDLETON, 2019). Tegen and Fung (1995) estimated that up to 50% of the current atmospheric dust load originates from anthropogenically disturbed surfaces, though a more recent study by Tegen et al. (2004), has suggested that this may be an over-estimate and that dust from agricultural areas contributes <10% to the global dust load. Ginoux et al. (2012) estimated that natural dust sources globally accounted for 75% of emissions and anthropogenic for 25%. North Africa accounted for 55% of global dust emissions but only 8% were anthropogenic. Elsewhere, anthropogenic dust emissions could be much higher (75%, in Australia, for example). Conversely, an apparent upward trend in dust activity in the Middle East between 2001-2012, as revealed by the monitoring of aerosol optical depth, seems to owe little to local anthropogenic factors and to be a result of increasing temperatures and decreasing relative humidity (KLINGMÜLLER et al. 2016), though in some areas, such as parts of Iraq and Syria, recent humanly-caused desertification has been implicated (MORIDNEJAD et al. 2015).

The history of dust storm activity before the era of meteorological records can be obtained from core evidence and environmental reconstruction. Von Suchodoletz et al. (2010) speculated that humans intensified dust storm activity in the northwest Sahara as early as 7-8 ka ago, while analysis of a 3200-year marine core off West Africa shows a marked increase in dust activity at the beginning of the nineteenth century, which was a time that saw the advent of commercial agricultural activity (including the clearing of ground for groundnut production) in the Sahel (MULITZA et al. 2010). Neff et al. (2008) used analyses of lake cores in the San Juan Mountains of south-western Colorado, USA, to show that dust levels increased by 500% above the late Holocene average following the increased settlement and livestock grazing during the nineteenth and early twentieth centuries. A core from the Antarctic Peninsula (MCCONNELL et al. 2007) showed a doubling in dust deposition in the twentieth century, caused by increasing temperatures, decreasing relative humidities, and widespread desertification in the source region — southern South America. Marx et al. (2014) used a core from Australia to show that since the 1880s rates of wind erosion were 10 times higher than background Holocene levels. Archival studies by Cattle (2016) confirm the role that land cover changes (including those brought about by the cropping of marginal lands and by rabbit grazing), combined with drought phases, played in creating a dust bowl in south eastern Australia between 1895 and 1945.

The USA Dustbowl of the 1930s, caused by a combination of a major drought and by years of over-grazing and unsustainable farming techniques, demonstrated the serious nature of some past aeolian episodes. The waves of settlers that arrived in the area from 1914 to 1930, in conjunction with the increasing use of mechanised agriculture, catalysed by high wheat prices, led to exceptionally large-scale wind erosion when drought hit in 1931. The Dust Bowl may have had a feedback effect on the drought itself (COOK et al. 2009).

In the mid-twentieth century a major aeolian episode occurred in the former Soviet Union and is evident in meteorological records (SAZHIN, 1988) and in ice cores (OLIVIER et al. 2006). It resulted from the 'Virgin Lands' programme of agricultural expansion in the 1950s. In China, forced migration and agricultural expansion in the arid west during the 'Great Leap Forward' of the late 1950s and early 1960s also led to an increase in dust storm frequencies (TA et al. 2006).

It remains to be established, however, whether analysis of meteorological data, which has enabled the changing frequency of dust events to be established for the last six decades or so, indicates whether or not increasing dust storm frequencies are the norm (GOUDIE, 2014; ALOBAIDI et al. 2016; NABAVI et al. 2016). Some areas have indeed shown increasing trends (e.g., the eastern Mediterranean, north east Arabia, northwest Iraq and the east of Syria, the Gobi of Mongolia, the western USA and Korea). However, others have shown declining trends (e.g. the Canary Islands, China, Turkmenistan, Kazakhstan, Pakistan and parts of the USA High Plains and Utah). In Australia the declining trend was followed by renewed activity in the early years of the present century. Other areas (e.g. the Kalahari, south western Iran and Seistan, the

Cordoba region of Argentina) have shown marked fluctuations upwards and downwards in response to such factors as lake flooding (BUCHER; STEIN, 2016) and desiccation or climatic fluctuations such as sunspot cycles. Using a variety of data sources, Mahowald et al. (2010) suggested a doubling of atmospheric desert dust loadings took place over much of the globe in the twentieth century. This has been confirmed by Hooper and Marx (2018) whose results show that globally dust emissions increased by a factor of 2.1 times after the Industrial Revolution (1750 CE). They believed this change coincides with the development of 'industrial agriculture' and the colonisation and development of new regions, e.g. Australia.

A classic case of changing dust storm frequencies is the West African Sahel, where drought has been persistent since the mid-1960s. Analysis of wind, precipitation and visibility data by Ozer (2003) showed that remarkable changes in dust emissions have occurred since the late 1940s. He indicated that during the pre-drought conditions that existed from the late 1940s to the late 1960s yearly dust production was 126 x 10^6 tons. It rose to 317 x 10^6 tons during the 1970s and has been 1275 x 10^6 tons since 1980, a ten-fold increase. Were the increasing numbers of dust storms caused by climate change, by human actions, or by a combination of the two? In part this phenomenon seems to be related to changes in the North Atlantic Oscillation (ENGELSTAEDTER et al. 2006), North Atlantic sea surface temperatures (WONG et al. 2008) and the Atlantic Multidecadal Oscillation (JILBERT et al. 2010). The role of human population increase was, however, championed by Moulin and Chiapello (2006). However, dust emissions from the area have declined in recent years (RIDLEY et al. 2014), perhaps because of a change in climatic conditions (CHIN et al. 2014). Another possible cause is that weaker winds have resulted from increased roughness and reduced turbulence, as a consequence of the observed increase in vegetation cover in the Sahel (COWIE et al. 2013).

In some parts of the world humans have attempted to dampen down dust storm activity by developing techniques for wind erosion and dust storm control, most of them developed to protect cultivated fields from soil loss (MIDDLETON, 1990; RAVI et al. 2011; DUNIWAY et al. 2019; XIAO et al. 2021). Four main categories of methods have been used.

- Agronomic measures: crops residues, mulches, etc.
- Soil management: restricted tillage operations
- Mechanical methods: fences, windbreaks, shelterbelts, etc.
- Lake bed stabilisation: by irrigation

Sand dunes

Humans have impacted on sand dunes in a variety of ways. For example, rivers can be sources and sinks of dune sediments, so that if their channels and flow regimes are altered, dunes may be affected (DRAUT, 2012). More generally, relict Late Pleistocene and Holocene sand dunes have been reactivated on many desert margins by human activities, a process referred to by the Chinese as 'sandy desertification' (LI et al. 2016). On the edge of the Rub 'Al Khali in Arabia, very rapid dune accretion may have been caused by vegetation removal for smelting of copper and by domestic stock during the Abassid period (750-1250 AD) (STOKES et al. 2003).

Along coastlines, dunes have been modified by a whole range of human activities, not least around the Mediterranean (FEOLA et al. 2011; CICCARELLI, 2014), in the Canary Islands (HERNÁNDEZ-CORDERO et al. 2018) and in Brazil (TEIXEIRA et al. 2016). Good examples of modification of coastal dunes by human activities include those of Šilc et al. (2017) and Hernández-Cordero et al. (2017):

Afforestation

Aggregate extraction

Agriculture

Beach raking

Deforestation

Fire

Fluvial flow and sediment supply interruption

Golf courses

Grazing

Groundwater disturbance

Hunting

Inundation and eutrophication by waste water

Invasive plants

Littoral drift interruption by jetties, etc

Military activity and warfare

Mining and sand extraction

Nutrient enrichment

Overgrazing by domestic stock

Pipeline landfalls

Plantations

Rabbits, introduction of

Recreation

Sewage outfall construction

Shoreline stabilisation

Timber exploitation and wood gathering

Tourism

Training wall construction and dredge spoil dumping which change bathymetry and erosion attack

Trampling by humans

Urbanisation

Vehicular disturbance

There are numerous examples of dune systems being transformed quite early in the Holocene. Polynesian migrants, for instance, appear to have modified dune systems in New Zealand (HORROCKS et al. 2007) and aboriginal peoples seem to have induced dune activity in the Great Plains of Canada (WOLFE et al. 2007) and on the Channel Islands of California (ERLANDSON et al. 2005). In Germany dunes may have been destabilized as early as the Mesolithic (NICOLAY et al. 2014) and showed reactivation to land use changes later in the Holocene (KÜSTER et al. 2014). The inland dunes of Hungary (KISS et al. 2012) were also modified by phases of human activity during the Sub-Atlantic and some changes in the European sand belt may date back to the Neolithic (TOLKSDORF; KAISER, 2012). However, it has not always been easy to discriminate between phases of increased dune activity caused by changes in climate (including windiness) and those caused by human activities (CLARKE; RENDELL, 2009; ROSKIN et al. 2013). Indeed, phases of dune instability may occur when both appropriate climatic conditions and human pressures coincide (BEERTEN et al. 2014).

In Europe the tempo of change probably increased in medieval times (PROVOOST et al. 2011) and into the nineteenth century (BUYNEVICH et al. 2007), but in some areas has been further accelerated in recent decades because of such activities as vehicular disturbance, tourism, the spread of accidentally introduced plants such as marram (*Ammophila*), animal introductions, eutrophication by nitrates in waste water or polluted air, groundwater pumping, and urbanisation. On the eastern seaboard of the USA a suite of human activities, including the depredations of voracious hogs, caused large-scale dune mobilization in the nineteenth century (SENTER, 2003).

In addition, there has been increasing attempts to try undertake deliberate modification of dune systems (RANWELL; BOAR, 1986; PORTZ et al. 2018) by planting of trees and grasses such as marram, or by beach nourishment. Planting of grasses and trees has been undertaken on European coastal dunes since the Middle Ages, and sand fences have been used since at least as early as the sixteenth century. Some of these techniques aim to stabilise dune surfaces to reduce dune migration while others seek to restore dune activity (MARTÍNEZ et al. 2013a, b). Methods have been developed for dune and sand movement control (WATSON, 1990) include:

- Dune removal
- Reshaping, trenching, sod cutting
- Covering with gravel, spraying with oil, chemical stabilizers, etc.
- Sand fences, checkerboards, etc.
- Planting of grasses (e.g. *Ammophila*) or trees and shrubs (e.g. *Hippophaë rhamnoides*, and *Artemisia halodendron*)
- Shelterbelts and windbreaks

Studies of the comparative effectiveness of these different techniques have been undertaken in recent years (BRECKLE et al. 2008; WARREN, 2013), not least in China. For example, Zhang et al. (2004) found that the best means of stabilizing moving dunes in Inner Mongolia were straw checkerboards and the planting of *Artemisia halodendron*. This finding was confirmed by a study in the Kerqin Sandy land (LI et al. 2009), while in north east China

Miyasaka et al. (2014) found that tree planting was more effective in stabilising dunes than shrub planting or exclusion of grazing. Along a highway in the Taklamakan, checkerboards, reed fences and nylon nets were found to be effective (DONG et al. 2004). As regards other locations, on the desiccated bed of the Aral Sea, some salt tolerant plants have proved to be effective in sand stabilization (SHOMURODOV et al. 2013). In northwest Nigeria, Raji et al. (2004) found that shelterbelts were the most effective technique, and were superior to mechanical fencing. Chemical stabilizers (HAN et al. 2007) and geotextiles (ESCALENTE; PIMENTEL, 2008) have been used with some success, but some devices are prohibitively expensive (e.g. chemical fixers) while others, such as checkerboards, are not. Nonetheless, there is the potential to use new technologies, including, for example, encouraging bacterially-induced carbonate cementation (CHEN et al. 2016) and using GPS to enable the planting of circular buffer strips in centre-pivot irrigated fields (ANGADI et al. 2016).

However, attempts to fix and control dunes may not be ecologically or aesthetically desirable and there is an increasing realisation that dunes, especially in coastal situations, should in some cases be rejuvenated or returned to their natural state by such techniques as control of groundwater, beach replenishment, reductions in nutrient enrichment, and removal of invasive plants and plantations (RHIND; JONES, 2009; CLARKE; RENDELL, 2014).

Future Anthropocene Climate Changes

Possible future climate changes will impact upon aeolian activity. The Intergovernmental Panel on Climate Change (IPCC, 2007) suggested that in drylands temperatures could increase by between 1 and 7°C by 2017-2100 compared to 1961-1990, and that precipitation levels could decrease by as much as 10-20% in the case of the Sahara but increase by as much as 10-15% in the Chinese deserts. In SW Australia precipitation could decrease by as much as 40% (DELWORTH; ZENG, 2014). Most areas that are currently dry, such as the Sahel (SYLLA et al. 2010) may see enhanced aridity because of reductions in precipitation. Zeng and Yoon (2009) have suggested that as conditions become drier and vegetation cover is reduced, there may be vegetation-albedo feedbacks which will enhance any aridity trend. By 2099 their model suggests that globally the area covered by warm area may expand by 34%. Droughts may also become more prevalent over wide areas (WANDERS et al. 2015), though some areas may experience more frequent hurricane activity. There may also be changes in ENSO frequency and intensity (LATIF; KEENLYSIDE, 2009).

Future climatic change may be important for dust storm activity (TONG et al. 2017). If soil moisture declines as a result of changes in precipitation and/or temperature, there is the possibility that dust storm activity could increase (WHEATON, 1990). A comparison between the Dust Bowl years of the 1930s and model predictions of precipitation and temperature for the U.S. Great Plains indicates that mean conditions could be similar to or worse than those of the 1930s (ROSENZWEIG; HILLEL, 1993). If dust storm activity were to increase as a response to global warming it is possible that this could have a feedback effect on precipitation that would lead to further decreases in soil moisture (MILLER; TEGEN, 1998). Munson et al. (2011) have argued that increased drought brought about by reduced precipitation and higher temperatures, will reduce perennial vegetation cover in the Colorado Plateau and thus cause an increase in aeolian activity. In the Bodélé depression of the Central Sahara, in spite of the possibility of higher rainfall amounts predicted by some models, higher wind velocities may increase its dust activity in coming decades (WASHINGTON et al. 2009).

By contrast in northern China, there is evidence that dust storm activity has recently decreased, partially in response to changes in the atmospheric circulation and associated wind conditions (JIANG et al. 2009) and it might decrease therefore still further in a warming world (ZHU et al. 2008). As warming has occurred, wind velocities have fallen (WANG et al. 2007) though some recovery has taken place in recent years (LIN et al. 2013) ‘Atmospheric stilling’ has been a widespread feature of recent warming decades in Australia and elsewhere (VAUTARD et al. 2010), though the pattern is not always clear, with regional and temporal differences being evident in the Iberian Peninsula (AZORIN-MOLINA et al. 2014) and in China (LIN et al. 2013). During the last 30–50 years, an average trend of −0.140 metres per second per decade in measured near-surface wind speed across the global terrestrial surface has been observed (AZORIN-MOLINA et al. 2016). Modeling studies have suggested that more generally in low latitudes extreme wind events will become less frequent with global warming, and this has been confirmed for the USA (BRESLOW; SAILOR, 2002). One explanation for this is that according to General Circulation Models high latitudes will warm more than low. There will, therefore, be a smaller temperature difference between the Equator and the Poles and this means weaker monsoonal wind speeds will occur. Another factor of potential importance in China is the earlier greening of vegetation resulting from higher spring temperatures. This may reduce spring time dust activity (FAN et al. 2014).

Sand dunes, because of the control exerted by vegetation cover on sand movement, have in the past proved susceptible to changes of climate. This because some areas, such as the South West Kalahari or the High Plains of the USA, have been prone to changes in precipitation and/or wind velocity because of their location in climatic zones that are close to a climatic threshold between dune stability and activity. Indeed, the occurrence of mega-droughts has been very important in determining the degree of dune activity in the western USA (HANSON et al. 2009). Dunes have repeatedly switched between activity and stability in response to Holocene droughts.

Detailed scenarios for dune remobilization by global warming have been developed for the mega-Kalahari in southern Africa (THOMAS et al. 2005). Much of this vast region is currently vegetated and stable, but GCMs suggest that by the end of this century all dune fields will be reactivated. This could expose fine material to wind attack and dust storm generation (BHATTACHAN et al. 2013; 2014). However, the methods used to estimate future dune field mobility are still full of problems and much more research is needed before we can have confidence in them (KNIGHT et al. 2004). So, for instance, in contrast to Thomas et al. Ashkenazy et al. (2012) have argued that the Kalahari dunes are unlikely to be subjected to sufficiently dry or windy conditions for them to become greatly mobilized by the end of this century. Liu et al. (2016) have modelled the response of dune activity to climate change in the Tibetan Plateau, and indicated that there might be a 7 to 9% reduction in the annual dune activity index before 2035 due to changing climatic factors which included increasing precipitation and declining wind speed.

Coastal dunes will be impacted upon by future sea-level changes (CLAUDINO-SALES, 2018), which will cause beach retreat and overtopping to occur (SAYE; PYE, 2007). As sea levels rise, coastal protection structures may prevent dune movement inland. Moreover, groundwater levels may change, either in response to climate change or to rising sea-levels (CLARKE; AYUTTHAYA, 2010). Either way, this will impact upon dune slack habitats (CURRELI et al. 2013). Dune vegetation may be directly affected by changes in temperature and precipitation (MENDOZA-GONZÁLEZ et al. 2013; JACKSON et al. 2019). Coastal dunes might also be eroded by possible increases in storm attack, though not all models indicate that storminess will increase (WINTER et al. 2012).

CONCLUSIONS

The human impact on landforms and land-forming processes is substantial and has been going on since prehistoric times. Although it is often difficult to sort out the relative roles of natural climate changes from those of human impacts, there is no dispute that during the Anthropocene such phenomena as dust storms, wind erosion of surface materials, and sand dunes, have been modified by a range of human activities. There is also no doubt that these phenomena will be modified in the face of future anthropogenic climate changes.

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