

Review

Variability and Trends in Dust Storm Frequency on Decadal Timescales: Climatic Drivers and Human Impacts

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Received: 16 May 2019; Accepted: 10 June 2019; Published: 12 June 2019



Abstract: Dust storms present numerous hazards to human society and are particularly significant to people living in the Dust Belt which stretches from the Sahara across the Middle East to northeast Asia. This paper presents a review of dust storm variability and trends in frequency on decadal timescales from three Dust Belt settlements with long-term (>50 years) meteorological records: Nouakchott, Mauritania; Zabol, Iran, and Minqin, China. The inhabitants of each of these settlements have experienced a decline in dust storms in recent decades, since the late 1980s at Nouakchott, since 2004 at Zabol, and since the late 1970s at Minqin. The roles of climatic variables and human activities are assessed in each case, as drivers of periods of high dust storm frequency and subsequent declines in dust emissions. Both climatic and human variables have been important but overall the balance of research conclusions indicates natural processes (precipitation totals, wind strength) have had greater impact than human action, in the latter case both in the form of mismanagement (abandoned farmland, water management schemes) and attempts to reduce wind erosion (afforestation projects). Understanding the drivers of change in dust storm dynamics at the local scale is increasingly important for efforts to mitigate dust storm hazards as climate change projections suggest that the global dryland area is likely to expand in the twenty-first century, along with an associated increase in the risk of drought and dust emissions.

Keywords: dust storm; wind erosion; mineral dust; drylands; air quality; climate hazards; Nouakchott; Minqin; Zabol

1. Introduction

Dust storms are caused by strong, turbulent winds entraining fine-grained material from dry, unconsolidated sediments in places where vegetation cover is sparse if not completely absent. These events are important to the workings of the Earth system, with a wide range of effects on the atmosphere, lithosphere, biosphere, hydrosphere and cryosphere [1]. In consequence, the mineral dust cycle has emerged as a core theme in Earth system science [2], with much dust research driven by interest in its interactions with climate in particular [3].

When dust storms occur in areas mismanaged by human society, they frequently represent a form of desertification or land degradation involving loss of topsoil by wind erosion. Dust storms also present numerous other direct hazards to human society [4], which include crop damage, the causation and/or aggravation of several human health problems, and hazards to all forms of transport. These hazards are particularly significant for the residents of deserts and semi-deserts—commonly referred to as drylands—where dust storms are most frequent. Globally, the largest and most persistent dust sources are located in the Northern Hemisphere, mainly in the so-called Dust Belt, a broad swath of dryland stretching from the west coast of the Sahara across the Middle East to northeast Asia [5].

This Dust Belt contains much of the global drylands and numerous dust sources, many—though not all—associated with topographical lows characterized by deep alluvial deposits.

It is the hazardous nature of dust storms that has brought them to the attention of the United Nations General Assembly, which has adopted resolutions entitled “Combatting sand and dust storms” in 2015 (A/RES/70/195), 2016 (A/RES/71/219), 2017 (A/RES/72/225) and 2018 (A/RES/73/237). These resolutions acknowledge that dust storms represent a threat to livelihoods, environment and economy and are likely to impede the achievement of several Sustainable Development Goals.

The study of dust storms incorporates research at multiple spatial scales, from the planetary perspective of global climate models to the interest in individual fine particles and how they are emitted from soil surfaces. Understanding the multiple interactions between dust processes operating at these various scales is a significant challenge [6]. Dust research also spans a range of temporal scales, and variability in the frequency and intensity of dust-raising has been recognised seasonally, because of droughts, and over much longer timescales [7–9].

Dust generation, dust transport and indeed dust deposition are modulated by climate. Parameters such as surface winds and the magnitude, timing and distribution of precipitation affect whether, where and when dust grains may be eroded from a sediment surface. Climate in source regions also directly affects vegetation cover—a key element in the wind erosion system—but vegetation and other determinants of surface erodibility are similarly affected by human impacts. Principal among human activities that can influence wind erosion are agricultural practices and water management schemes. In some locations, such as the Aral Sea [10], the anthropogenic contribution to atmospheric dust loads is well established, but at the global level the scale of human impact is very uncertain.

Current estimates of anthropogenically-generated soil dust as a proportion of total mineral dust emissions globally range from 50% to less than 10% [11,12]. This large range reflects the fact that our understanding of dust dynamics is by no means complete. Many uncertainties remain and, in consequence, our attempts to model windblown mineral dust emissions have definite limitations. Much of the data used in dust models is derived from satellite imagery which has been used in the study of dust with considerable success since the 1980s, enabling important advances in our understanding of source areas, transport pathways and deposition zones. Satellites provide the best means for studying the spatially large-scale characteristics of dust storms, but their datasets extend for just a few decades at best.

Study of decadal variability and trends in dust storm frequency is better served by datasets covering longer time series. At a few sites, in situ measurements of atmospheric dust have been taken over numerous decades (e.g., [13]), and a number of proxy techniques have been developed to study dust over similar timescales (e.g., [14,15]), but the most geographically extensive datasets are those derived from meteorological observations taken at weather stations. Analysis of meteorological observations has been undertaken to ascertain and explain regional trends at the global level [16,17] but many of the nuances and detail important to trends at individual sites are inevitably lost in studies at that scale.

The focus in this paper is on individual settlements, where inhabitants face hazards associated with dust storms, within regions where large variability and trends in dust storm frequency have been identified over decadal timescales. The analyses reported here rely heavily on dust storm and visibility data from individual weather stations (where a dust storm is defined as a dust-raising event that reduces visibility to 1000 m or less) as a key line of evidence. It relates changes in dust storm frequency to climatic variables and to land use with the purpose of furthering our understanding of how dust generation is affected both by weather and climate but also by human activities. In some cases, the anthropogenic impact is in the form of mismanagement, leading to enhanced deflation, but elsewhere dust storm trends are associated with conscious attempts to reduce wind erosion and mitigate dust storm hazards.

The importance of the dust storm issue has been highlighted by the United Nations General Assembly resolutions cited above. It is underscored by climate change projections indicating that the

global area of drylands is likely to expand [18,19] and the expected increase in the risk of drought [20] and dust emissions [21] in the twenty-first century. Dust mobilisation is critical to a large proportion of the human population, particularly those resident in the Dust Belt. This paper examines the drivers of change in dust storm variability at three Dust Belt settlements: in West Africa (Nouakchott, Mauritania); south Asia (Zabol, Iran), and northeast Asia (Minqin, China).

2. Sahel/Sahara: Nouakchott, Mauritania

The coast of West Africa has been a focus of interest in Saharan dust for a great many years [22,23] and much of the more recent research has looked at how and why long-distance flows of mineral dust over the Atlantic have varied over time. Dust storm frequency in Sahelian Africa increased sharply in the early 1970s and a link between dust emissions and drought was clearly established [24]. African dust emissions transported to the Caribbean also rose abruptly in the early 1970s, and again the increase was attributed mainly to drought in the Sahara/Sahel region [25] which in turn was driven largely by changes in the global distribution of sea surface temperature, or SST [26].

Dust flows from West Africa across the Atlantic peaked in the early 1980s. Since then, aerosol optical depth (AOD) of dust over the mid-Atlantic monitored by the AVHRR satellite decreased by about 10% per decade (between 1982 and 2008), a trend that persisted through both winter and summer [27]. This decline was viewed by [28] as part of a multi-decadal covariability of North Atlantic SST, Sahelian rainfall and dust. They postulated a positive feedback between those three variables on multi-decadal time scales such that warm (cold) North Atlantic Ocean surface waters produce wet (dry) conditions in the Sahel thus leading to low (high) concentrations of dust over the tropical North Atlantic, which in turn warms (cools) the North Atlantic Ocean. Coincident with the dusty phase of this variability is the possibility that atmospheric dust also acts to suppress rainfall in the region through another feedback mechanism [29].

The link between drought and dust-raising is via the effects of rainfall on soil moisture and vegetation: a drought period leads to drier, less cohesive soils and a decline in vegetation cover, both of which make wind erosion more likely. The relative timing of seasonal rains and dust-raising periods in the Sahel have yielded correlations between previous-season rainfall and vegetation growth and hence dustiness [24,25]. Variability in dry-season vegetation cover has also been linked causally to Sahelian dust production in more recent, post-drought times [30]. However, the relative role of vegetation in dust emissions from this part of the world is debatable given that the Sahara's largest dust sources are in hyper-arid zones [31], areas with very little vegetation cover at any time in the contemporary era. Several modelling studies have concluded that surface winds exercise a more critical influence on North African dust emissions [15,27], although [32] suggest that changes in the wind field may be the result of vegetation-driven changes in surface roughness.

The importance of human activities that destabilise soil surfaces and degrade vegetation cover—facets of desertification—is also dictated in part by our understanding of which dust sources are active in the Sahara and Sahel (e.g., [33]), as well as the fact that desertification as an issue has been controversial [34,35]. Nevertheless, agropastoral management practices in the Sahel do enhance wind erosion rates, as demonstrated recently by field observations [36] and modelling studies [37].

Observations made in Mauritania's capital city, Nouakchott, have played an important role in the debate over dust generated in this part of the world, both through the dust–drought link [24] and the health implications of high atmospheric dust loads [38]. Nouakchott's urban area grew substantially during the 1970s and 1980s, absorbing large numbers of drought-stricken nomads, and its population increased from around 40,000 people in 1970 to between 800,000 and 900,000 in 2001 [39].

During the 1960s, Nouakchott experienced fewer than two dust storms a year, but the annual totals rose through the 1970s to peak at 85 dust storm days in 1983 and remained high throughout the 1980s before declining in the 1990s (Figure 1). The 1970s and 1980s were a period of drought in the Sahel [40]. At Nouakchott, the 1977 rainy season brought just 2.7 mm of precipitation, making that year the driest since records began in 1931. Similarly low precipitation totals were recorded in 1983

and 1984. It seems that a full recovery from the droughts of the 1970s and 1980s in West Africa has not occurred because a major change in the rainfall regime took place around 1968 [41]. This conclusion is reflected in the annual rainfall totals received at Nouakchott: the post-1987 mean (155 mm) is markedly greater than the 1967–1987 figure (108 mm) but does not match the pre-1967 mean of 170 mm [42].

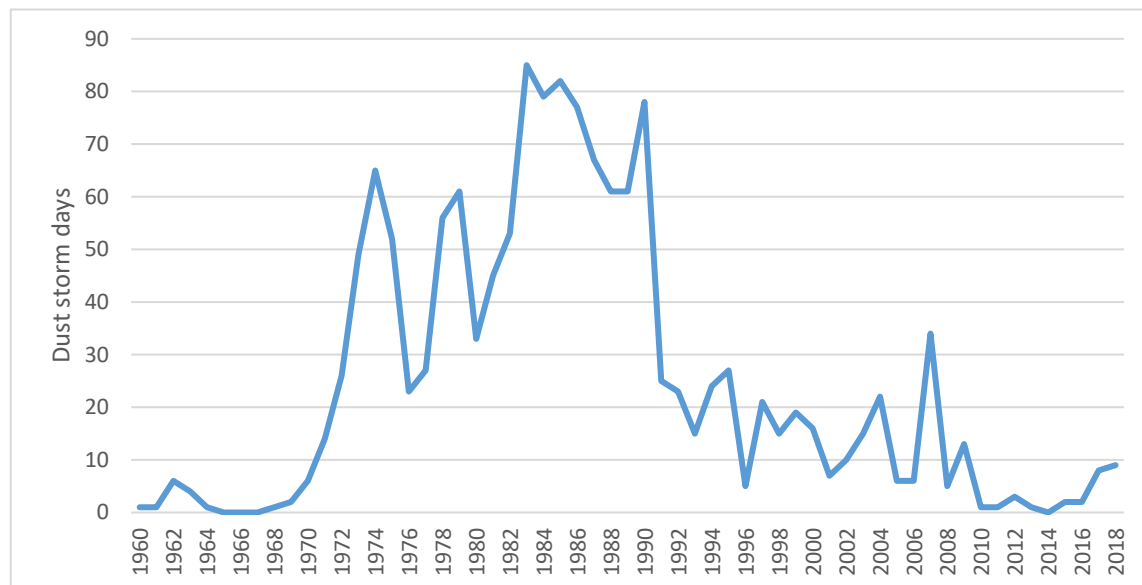


Figure 1. Annual frequency of dust storm days 1960–2018 at Nouakchott (18.12° N 15.95° W). (Data source: Office National de la Météorologie, Mauritania).

Another shift in climatic parameters at Nouakchott has also occurred. Littaye et al. [42] note that the great drought period of the 1970s and 1980s was also marked by an increased frequency of easterly winds at Nouakchott, a factor that further helps to explain the particularly frequent dust storms of the period.

Dating from the mid-1970s, Nouakchott and its environs has also been the focus of considerable efforts to reduce wind erosion, stabilise sand dunes and combat desertification. Between 1975 and 1992, the Nouakchott Green Belt Project established a 750-ha area around the city with the particular intention of improving peri-urban agriculture. In 1992, the Mauritanian government initiated a programme of aerial seeding from low-flying aircraft along major highways in and out of Nouakchott using a variety of local species to stabilise wind-erodible surfaces. This was followed by a project to stabilise a further 800 ha of inland dunes to the northeast of the capital over the period 2000–2007 [43]. Analysis of a series of high-resolution remote sensing images covering the period 1985–2010 found a considerable decrease in mobile dunes and an increase in afforested area, particularly to the north and east of the city [44]. It is highly likely, therefore, that these afforestation projects also contributed to the decline in dust storm activity dating from the early 1990s.

3. Hamoun Basin: Zabol, Iran

The Hamoun Basin, which straddles the political boundary between Iran and Afghanistan, has long been recognised as one of the dustiest regions of south Asia [45], particularly during the months of June–August when the region is subject to the northerly Levar or Wind of 120 Days, one of the most persistent and intense wind systems in the world [46]. Dust storm sediments in the region are notable for their high salinity [47] and a range of socio-economic impacts have been identified [48], including hazards to human health [49,50].

Located at the southeastern end of the much larger endorheic Sistan Basin, the Hamoun Basin consists of a depression dominated by a series of shallow, marshy lakes fed by rivers from the mountains of the Hindu Kush. These lakes vary in size both seasonally and from year to year, but are rarely

more than 3 m deep. When dry, the lake beds become sources of dust storm sediments. [51] have demonstrated a close relationship between the annual area of exposed dry lake beds in the Hamoun Basin in July and the annual variability of the number of dusty days recorded in the city of Zabol. Water levels in the lakes are, in turn, dependent on both local and regional precipitation as well as on snowfall and snowmelt in the mountains within the catchment area.

Dust storm frequency at Zabol displays considerable year-to-year variability (Figure 2), with trends hard to identify, perhaps with the exception of a general decline in dust emissions between 2001 and 2018. Dust storm activity was elevated over the period 2000–2004, a period of severe drought when the Hamoun lakes were particularly dry as the inflow of water decreased dramatically. Some lakes became completely desiccated at this time [51,52]. This period followed a decade of much higher water availability, peaking in 1998 after large-scale snowmelt flooding in the Hindu Kush in Afghanistan. Rashki et al. [51] note that water-levels peaked in spring 1998 when the lakes coalesced to create one large lake with a surface area of some 5700 km². Before this period, the late 1980s were characterised by relatively limited inflows into the Hamoun lakes [53], a time of elevated dust storm activity. Kharazmi et al. [52] describe the period from 2005 to 2016 as being one of episodic recovery in which water levels increased in some years but not all, and dust storm activity was variable in response.

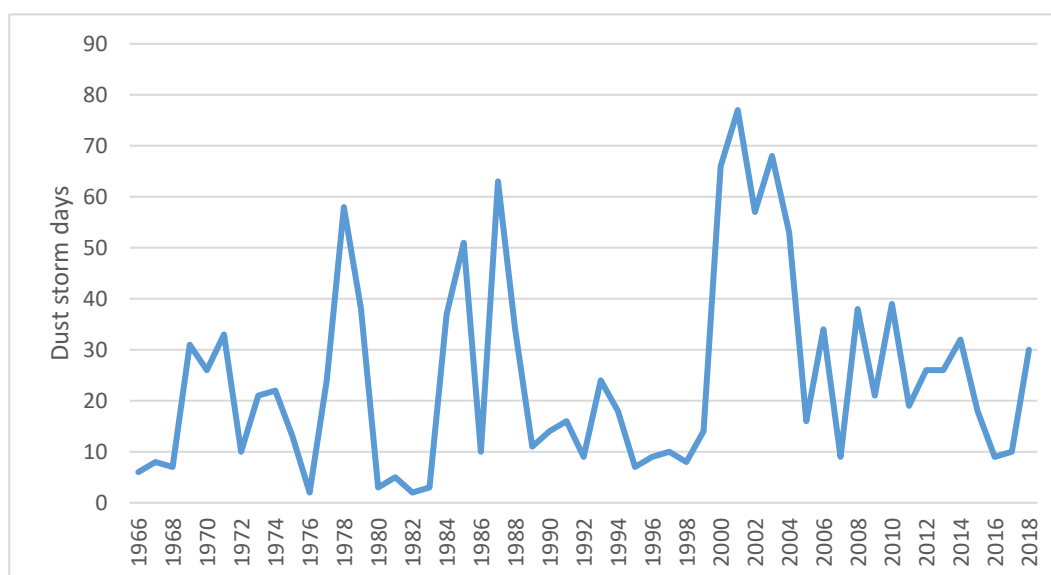


Figure 2. Annual frequency of dust storm days 1966–2018 at Zabol (31.09° N, 61.54° E). (Data source: Zabol meteorological station).

All the research on dust storms in the Hamoun Basin agrees on the importance of dry lake beds as the prime source of dust storm sediments, although the relative importance of individual lakes is less clear. Modelling work by Behrooz et al. [54], for instance, identifies one dry lake, Hamoun Puzak, as ‘by far the dominant dust source’ (p.1) affecting Zabol. Lake levels are reliant on rains and snowmelt predominantly in the Hindu Kush mountains [55] and the main river feeding the Hamoun Basin, the Helmand (also known as the Hirmand), is notable for the large variation in annual discharge from year to year [56]. However, both the Helmand River and its main tributary, the Arghandab River, were dammed in Afghanistan in the 1950s to supply water for domestic use and agriculture, and water diversions from the Helmand took place in Iran in the 1990s and 2000s to supply four new reservoirs: the Chah Nimeh. Assessing the impact of these water management systems on the Hamoun lakes has been hampered by a lack of data and the prolonged period of almost constant civil war and political strife in Afghanistan since 1980. None the less, UNEP [53] concluded that irrigation schemes reliant on the dams mentioned here probably contributed to the desiccation of the Hamoun lakes in the period between 1999 and 2004. Kharazmi et al. [52] also highlight an expanding human population, along with

increases in agricultural and grazing areas as potential contributors to periods of low water-availability in the Hamoun Basin. Interestingly, Behrooz et al. [54] point to cultivated land as the second most important dust source affecting Zabol, ahead of some lake beds.

4. Northeast Asia: Minqin, China

Numerous studies have identified a decreasing trend in dust-raising in many parts of northern China, particularly in the late twentieth century, and a number of reasons have been cited for the decline. Guan et al. [57] found that the decrease in dust storm frequency across much of northern China over the period 1960–2007 was caused mainly by a gradual reduction in wind speeds. These authors concluded that vegetation cover (as measured by the Normalised Difference Vegetation Index or NDVI) and precipitation were negatively correlated with dust storm frequency, but the effect was weak. Conversely, Lee and Sohn [58] also found that most dust source areas in China experienced a continuous decline in wind erosion over a 34-year period (1974–2007), but they attributed the trend to enhanced precipitation and its influence on soil moisture and surface vegetation. The effects of earlier spring vegetation green-up in suppressing dust storm activity were emphasised by Fan et al. [59], while Zhu et al. [60] invoked a weakening of the westerly jet stream in northern China and Mongolia to explain the declining trend. Qian et al. [61] suggested that the decline in dustiness in north-eastern China was driven by reduced cyclone frequency caused by warming in Mongolia and cooling in northern China that reduced the meridional temperature gradient. Teleconnections induced by large-scale standing pressure oscillations in the atmosphere have also been linked to variations in dust storm frequency in northern China, including the Antarctic Oscillation [62], the Arctic Oscillation [63] and ENSO [64].

Interestingly, as Middleton [65] notes, no mention is made in any of these dust storm variability studies of policies designed to control desertification and/or dust storms, despite the fact that China is well-known for its many large-scale land restoration and afforestation schemes designed to combat desertification and control dust storms in its northern drylands. These schemes include the Three Norths Forest Shelterbelt programme (otherwise known as the Great Green Wall or GGW), initiated in 1978 and not scheduled for completion until 2050 [66], the Beijing–Tianjin Sand Source Control programme in Inner Mongolia, operational since 2001 [67], and the Grain-for-Green programme, a set-aside scheme initiated in 1999 with the aim of converting cropland to forest and grassland [68].

Assessments of how effective these projects have been, specifically in preventing dust storms, are not all in agreement. The GGW's efficacy has been subject to considerable debate, with Wang et al. ([66] p.13) declaring that "Although numerous Chinese researchers and government officials have claimed that the afforestation has successfully combated desertification and controlled dust storms, there is surprisingly little unassailable evidence to support their claims." These authors did find that the scheme had achieved some beneficial effects in reducing dust storms and controlling desertification, but that the importance of the project seems to have been overstated. Nonetheless, a great improvement in vegetation cover in regions where the GGW programme has been implemented was demonstrated by [69] who concluded that the programme had effectively reduced dust storm intensity in northern China since the 1980s. A similar conclusion regarding vegetation cover was reached by Zhang et al. [70] in their assessment of several afforestation programmes over the period 1982 to 2013, but Wu et al. [71] found that vegetation response to the first 10 years of the Beijing–Tianjin Sand Source Control programme was distinctly patchy.

Other researchers have highlighted a trend towards greater vegetation cover in northern China generally in recent decades but primarily due to greater rainfall and warmer temperatures [72,73]. In the Taklamakan Desert, where Yang et al. [74] identified a declining trend in sandstorms from 1961 to 2010 and a similar trend in blowing sand and dust after 1979, these authors state that "there is no obvious effect of human activities on the decrease in the number of blowing dust events during the last 50 years."

The town of Minqin and its surrounding oasis farmland in Gansu province is situated in a key source area for dust storms in China, at the eastern end of the Hexi Corridor, between the Badain Jaran Desert to the northwest and the Tengger Desert to the east [75]. Long-term exposure to dust among farmers in Minqin has been linked to chronic respiratory system diseases and symptoms—rhinitis, bronchitis, and coughs [76] and the risk of hospitalization in the area for respiratory and cardiovascular ailments is typically elevated during dust events and in the days following [77].

A generally decreasing trend in dust event frequency since the late 1970s at Minqin is characterised by lower frequencies from the 1990s onwards (Figure 3). Zhang et al. [78] highlighted the importance of abandoned farmland as a significant local source of wind erosion in Minqin after 1980. Farmers had, for many years, extended the cultivated area to plant seed-melon and then abandoned these fields as seed-melon prices declined, while poor irrigation practices and rising soil salinity also contributed to the abandonment of farmland and a generally decreasing vegetation cover within Minqin oasis [79]. The loss of vegetation, which Xie and Chen [80] trace back to the 1950s, has also been associated with sand dune encroachment from the north and west. A period of enhanced wind erosion at the margins of the oasis dating from the 1970s to the 1990s was identified by Zhang et al. [81] from their analysis of satellite imagery.

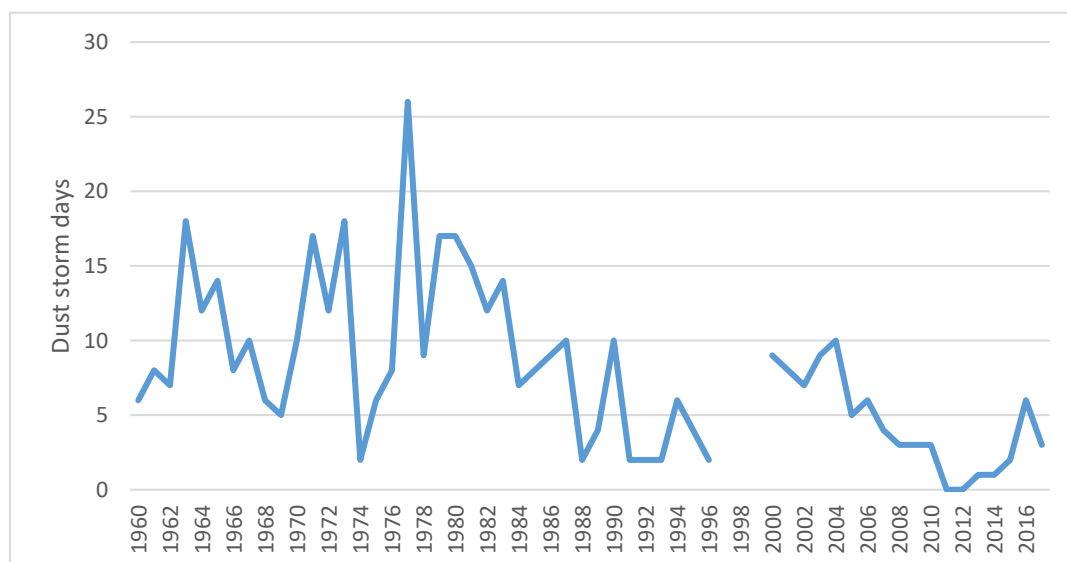


Figure 3. Annual frequency of dust storm days 1960–2017 at Minqin (38.63° N, 103.08° E). (Data source: Chinese Meteorological Administration, with data for years 1997–1999 unavailable).

Large-scale afforestation efforts to address the wind erosion issue began in Minqin in the 1950s and these efforts have been accompanied since the beginning of the 2000s by a shift in China's policy discourse towards an ethos of conservation, resulting in greater vegetation cover over the period 2000–2010 [79]. However, analysis by Wang et al. [66] concluded that the evidence did not support the hypothesis that afforestation contributed significantly to controlling either dust emissions or windy days at Minqin. Zhang et al. [78] also note that annual dust storm frequency is inversely related to annual precipitation totals at Minqin, a relationship that is particularly clear after 1980 when these authors emphasise the local origin of many dust events. They also found a strong relationship between the annual numbers of days with sandstorms and days with high wind speeds (>17 m/s). The importance of winds was also emphasised by Guan et al. [82] who concluded that high wind speeds were the main factor controlling dust storm frequency in their analysis of data from six meteorological stations—one of which was Minqin—in the area surrounding the Tengger Desert over the period 1960–2007. Dust storms in northern China are typically generated by prefrontal winds [83], so the

reduced cyclone frequency highlighted by [61] has undoubtedly played a role in the decline in dustiness at Minqin.

5. Discussion and Conclusions

Analysis of long-term meteorological records of dust storms at Nouakchott (58 years), Zabol (52 years) and Minqin (54 years) illustrate considerable year-to-year variability in addition to decadal trends in frequency. The important role of climatic factors in the wind erosion system has been highlighted at all three settlements. A run of drought years was instrumental in enhancing dust storm frequency at Nouakchott during the 1970s and 1980s and changes in surface winds, as well as rising precipitation levels, implicated in the subsequent easing of dust emissions. At Minqin, a long-term decline in dust storm frequency since the late 1970s is associated with higher precipitation totals and lower wind speeds, the latter in turn associated with fewer frontal cyclones. Lack of meteorological and hydrological data hampers strong conclusions on the importance of climatic drivers in the dust storm situation at Zabol, but lake levels in the Hamoun Basin are undoubtedly dependent on precipitation and snowmelt in the larger Sistan Basin and the dustiest years at Zabol (2000–2004) occurred during a period of severe drought.

Various human activities have also been significant in determining dust-storm frequency variations. Abandoned farmland has been a significant local source of wind erosion in Minqin and water management schemes in Iran and neighbouring Afghanistan are likely to have contributed to recent desiccation of the Hamoun lakes. Conversely, efforts to stabilise surfaces susceptible to wind erosion have contributed to declining dust emissions at Nouakchott and Minqin.

The drivers of these human actions have been both direct and indirect, sometimes deliberate, at other times inadvertent. This analysis of dust storm variability at three Dust Belt settlements has also highlighted the indirect effects of wider socio-economic and political factors in determining wind erosion occurrence and frequency. Seed-melon prices had an impact on farmers' land use at Minqin and government-sponsored schemes to reduce wind erosion and stabilise sand dunes by seeding and planting to encourage a vegetation cover have been noted at Minqin and Nouakchott. The societal drivers take on a transboundary dimension at Zabol, where infrastructural development (dam-building) in Afghanistan has affected water availability in the Hamoun lakes.

Assessment of the relative importance of natural processes and human management (or mismanagement) is not straightforward, but the balance of research conclusions favours natural processes (precipitation totals, wind strength) overall at the three settlements studied. However, this is not to suggest that schemes to combat wind erosion have had no impact, and the success of soil conservation schemes in reducing dust events has been noted elsewhere (e.g., [84,85]).

Understanding how dust generation is affected by weather and climate on the one hand, and by human activities on the other, is critical for our attempts to predict future variability in dust storm frequencies. Such predictions, in turn, constitute a significant step in our efforts towards mitigation of the numerous hazardous impacts of atmospheric mineral dust. This paper has shed some light at the local scale on three Dust Belt settlements that have experienced serious dust storm problems over the last 50 years or so. It has highlighted the complexity of their wind erosion situations. Dust emissions depend on local meteorological conditions (surface wind speed, precipitation) and local surface properties (e.g., vegetation cover, soil moisture, sediment availability). Both sets of conditions may change at different timescales, in part driven by climatic conditions that are subject to seasonal, interannual and decadal variability and trends. The human impact on wind erosion occurs both directly, particularly through land use practices, and indirectly via social, economic and political forces, which also vary over different timescales. All of these drivers of change can interact, at and between multiple scales. Appreciating the complexity of these wind erosion situations is of particular importance given twenty-first-century climate change projections indicating that global drylands are likely to expand, along with an expected increase in the risk of drought and dust emissions generally.

Funding: This research received no external funding.

Acknowledgments: The author would like to thank the following for kindly providing data: Sidi Ould Mohamed at the Office National de Météorologie in Nouakchott, Alireza Rashki, Saviz Sehatkashani, Xunming Wang and Ting Hua. The author also wants to acknowledge the helpful comments made by three anonymous reviewers.

Conflicts of Interest: The author declares no conflict of interest.

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