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Bowing Sand, Dust, and Dunes, Then and Now—A North American Perspective

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Abstract

Dune fields of the present day, the Dust Bowl disaster of the 1930s U.S. Great Plains, and contemporary efforts to forecast, simulate, and understand dust storms have a striking, uniform commonality. What these apparently diverse phenomena have in common is that they all result from blowing sand and dust. This review paper unifies these three disparate but related phenomena. Its over-arching goal is to clearly explain these manifestations of windblown sand and dust. First, for contemporary dune fields, we offer reviews of two technical papers that explain the eolian formation and the continuing development of two major dune fields in southeastern California and northwestern Sonora, Mexico: the Algodones Dunes and the Gran Desierto de Altar. Second, historical, geological, meteorological, and socioeconomic aspects of the 1930s Great Plains Dust Bowl are discussed. Third, and last, we return to the present day to summarize two lengthy reports on dust storms and to review two technical papers that concern their forecasting and simulation. The intent of this review is to acquaint the interested reader with how eolian transport of sand and dust affects the formation of present-day dune fields, human agricultural enterprises, and efforts to better forecast and simulate dust storms. Implications: Blowing sand and dust have drastically affected the geological landscape and continue to shape the formation of dune fields today. Nearly a century ago the U.S. Great Plains suffered through the Dust Bowl, yet another consequence of blowing sand and dust brought on by drought and mismanagement of agricultural lands. Today, this phenomenon adversely affects landscapes, transportation, and human respiratory health. A more complete understanding of this phenomenon could (and has) led to more effective mitigation of dust sources, as well as to a more accurate predictive system by which the public can be forewarned.

Keywords: Dune fields of today, Dust Bowl of the 1930s Great Plains, science of dust storm formation, forecasting and simulating dust storms

1. Introduction

This review paper attempts to unify a single phenomenon – blowing sand and dust – as it concerns dune field formation, the 1930s Dust Bowl of the Great Plains, and the science of dust storm formation. This unification is first brought to life (in this paper's first section) by the presence of active sand dune fields, which, in effect,

are repeating the same processes that led to sandstone formation, albeit in a nascent, formative manner. The second section of the paper continues with this theme of time as it portrays the 1930s Dust Bowl of the U.S. Great Plains. One of the papers summarized in this section relates the conditions of the Dust Bowl to a 1,000- year pageant of drought and moisture cycles in the western U.S. The third and last section of this review paper, grounded in the present day, first discusses two lengthy reports on dust storms, one of global extent with the other limited to Arizona. It then goes on to review contemporary efforts to understand, to monitor, and to forecast and simulate these dust storms. In sum, this review paper attempts to shed light on blowing sand and dust in prehistoric and historic time, and in the time of the present.

A cosmopolitan nuisance, blowing dust and sand affect virtually all semi-arid and arid landscapes [1], and has been doing so from deep geological time until the present day.

In their initial stage of formation, sand dunes depend on four related causes:

1. on the presence of a (usually) nearby source of sand, such as an oceanic beach;
2. on surface winds with sufficient speeds to suspend the sand and dust particles;
3. on these surface winds having a dominant, prevailing direction; and.
4. on the presence of a downwind receptor area capable of receiving and maintaining the transported sands [2–4].

The geological approach to blowing sand and dust, given an introductory summary above, can be more fully investigated by the curious reader through visiting these sand dune fields and through attending courses in the subject at the community college or at the university level. Furthermore, geological textbooks are widely available and can be studied independently [5–8]. Visiting present-day sand dunes offers the curious individual the advantages of travel and exploration throughout much of North America [9]: from northwestern Sonora, Mexico, to the Oregon coast, through the Midwest, and east as far as Cape Cod. This paper presents geological analyses of two such dune fields.

In addition to this approach, a second way to understand blowing dust and sand relies on historical reviews of particularly dusty periods. Although there are many to choose from, one of the better documented and the more instructive took place in the 1930s in the Great Plains of the U.S. and is known as the “Dust Bowl” [10]. This review paper presents some historical and meteorological insights into this nightmare.

Last, the paper explores modern-day dust storm magnitudes and frequencies, as well as their meteorological and landscape causes [11]. The paper goes further into this subject by describing how weather forecasters predict these storms and how atmospheric scientists come to understand their formation, transport, and eventual dissipation, [12, 13].

To summarize, this paper offers a three-fold synthesis of the natural phenomenon of blowing sand and dust. First, in the present day, how can extant dune fields shed light on their formation? Second, what can we learn about dust storms from an historical/scientific review of one of the worst recorded of such episodes, i.e. the infamous Dust Bowl in the Great Plains of the U.S. in the 1930s? Third what are the physical bases of dust storm formation and how do communities of meteorologists and atmospheric physicists study dust storms with the goal of reducing their deleterious effects on the land, on the atmosphere, on transportation, and on the respiratory health of the public?

2. North American sand dunes today

Many dune fields, but certainly not all, in North America, are found in semi-arid or arid regions. Because of this association, it is instructive to know about the four principal deserts of North America: namely, the Chihuahuan, the Sonora, the Mojave, and the Great Basin deserts. Although each of the four is unique in its geographic distribution, in its landforms, in its local meteorology, and in its vegetation, all share a dry climate with sparse precipitation. **Figure 1**, which illustrates these deserts, shows that they are in northern and northwestern Mexico and the southwestern and western U.S.

Table 1 is a partial list of dunes in North America [11] that can be visited and explored today, all of which are protected as national parks, national recreation areas, or international biospheres. The table gives some basic geographical and meteorological information about each dune field: its area, its annual rainfall, and its low and high temperatures. Most of the areas given are for the extent of the active dune fields: exceptions are noted in the table. These dune fields are ordered from the southwest and the west coast, through the intermountain states, into the Midwest, and to the east coast of the U.S., with a far-northern outlier being the last in the table.

Geologists, geographers, and paleoclimate scientists have conducted many studies of these dunes, deducing the dynamics of their formation and of their present-day movements, paying close attention to the patterns of wind speeds, of wind directions, and of precipitation. Although this research has produced a considerable volume of journal articles and reports, this section will be limited to two

Figure 1.
Deserts of North America [11]: with 10 dune fields indicated.

#	Name	Location	Area (km ²)	Rainfall (mm)	Temperatures	Ref.
1	Gran Desierto de Altar	NW corner of Sonora, Mexico	5,7000	62	High: 45°C (113°F) Low: 10 °C (50°F)	[14]
2	Algodones Dunes	SE California, near Yuma, AZ	720	83	High: 42°C (107°F) Low: 11°C (43°F)	[15]
3	Death Valley National Park	Southeastern California	13,650 For the entire national park	38	High: 46°C (115°F) Low: 4°C (39°F)	[14]
4	Oregon Dunes	Oregon coast	134	1980	High: 22°C (71°F) Low: 0.5°C (33°F)	[16]
5	White Sands National Monument	Southcentral New Mexico	590	230	High: 36°C (97 oF) Low: 0°C (32 oF)	[14]
6	Great Sand Dunes National Park	Southcentral Colorado	603	283	High: 27°C (80°F) Low: < 0°C (32°F)	[14]
7	Nebraska Sand Hills	West-central Nebraska	51,000 For the entire region	430–580	High: 41°C (105°F) Low: –34°C (–30°F)	[14]
8	Sleeping Bear Dunes	Lower peninsula of Michigan	132	Rain: 726 Snow: 1970	High: 27°C (81°F) Low: 12°C (11°F)	[17]
9	Dunes of the Outer Banks	Coastal N.Carolina and Virginia	3,200 or the entire island chain	Rain: 1,245 Snow 15	High 31°C (88°F) Low: 3°C (38°F)	[18]
10	Dunes of Cape Cod	Coastal Massachusetts	34	Rain and Snow: 1,195	High: 26°C (78°F) Low: –4°C (25°F)	[19]
11	Kobuk Valley National Park	Alaska, north of the arctic circle	83 dune fields only	Rain and Snow: 331	High 19°C (66°F) Low: –24°C (–11°F)	[14]

Note: of these eleven dune fields, only the first three and the fifth are in a desert landscape.

Table 1.
Some dune fields in North America.

dune fields. These were chosen primarily because the authors are at least somewhat familiar with each one, given their proximity to Phoenix, Arizona. For example, in driving from Phoenix to San Diego on Interstate–8, one drives through one of these dune fields (Algodones). The corresponding author made this drive once when the sands were being suspended by turbulent winds such that the visibility was reduced to about 100 m. As for the other choice (Desierto de Altar), while the corresponding

author has not been there, he has been very close while on a drive from Yuma, Arizona, through San Luis Rio Colorado (a city in north-eastern most Baja California, Mexico on the Arizona border), along the Colorado River delta south to the Gulf of California city of San Felipe. This drive affords a view of the Desierto de Gran Altar. Hence, the choice of these two nearby dune fields is a personal one.

2.1 Algodones dunes (southeastern California)

“Algodones” in Spanish means cotton. Fans of the Star Wars series of films may recognize the Algodones dune field—also known as the Imperial Dunes—as portions of the imaginary planet of Tatooine. This field is 72 km long by 10 km wide and extends along a northwest-southeast line that correlates with the prevailing northerly and westerly wind directions [20]. The weather is generally hot and dry, with the highest monthly average daytime temperature of 41.7°C (106.4°F), with monthly rainfall varying from 0.25 to 12 mm. Deserts can be cold, especially in winter nights, and these dunes are no exception, with the lowest monthly average temperature being 10.6°C (42.6°F).

The source of the sand of these dunes is the windblown beach sands of ancient Lake Cahuilla, itself formed by the meandering Colorado River as its waters periodically flowed into the Salton Sink. The most recent Lake Cahuilla covered much of the Imperial, Coachella, and Mexicali Valleys as late as 1450. The most popular theory holds that the Algodones Dunes were formed from windblown beach sands of Lake Cahuilla. The prevailing westerly and northwesterly winds carried the sand eastward from the old lake shore to their present location [20].

One study conducted in the 1980s, [21], thoroughly examined the formation and dynamics of these dunes, and a summary of their work follows. **Figure 1** from their paper, shown as **Figure 2**, gives the geographical setting of the area.

First, the authors use the term “draa”, defined as a large sand dune hundreds of miles long and hundreds of feet high, often with smaller dunes that form on the leeward and windward faces. This term comes from the North African dialectal Arabic and Berber languages. Dunes are anything but static, and the migration rate of the Algodones Dunes has been measured at 0.09 meters per year. The dunes vary in width from 0.9 to 4.5 km, in length from 0.5 to 1.2 km, and in their inter-dunal distances from 0.7 to 1.5 km. Their journal article has many photographs and intricate diagrams of these dunes, but their work can be summarized by their conclusions.

1. The complex crescentic draas in the southern third of the Algodones dune field have crescentic and coalesced crescentic or star-like dunes superimposed on their stoss slopes. (Note that the term “stoss” means facing toward the direction from which an overriding glacier impinges, as in the stoss slope of a hill).
2. The draa is in equilibrium with the current wind regime in that: it is oriented perpendicular to the long-term primary wind resultant direction.
3. Although the draa is transverse to the average wind direction, winds approach the draa at an oblique angle a large percentage of the time. Because of this angle the draa exhibits features both of oblique and longitudinal bedforms as well as transverse bed forms.
4. The draa exhibits a complex bedform modified by a secondary airflow pattern.
5. The resultant migration direction of the draa is oblique to, and more easterly than, the resultant sand drift potential direction.

Figure 2.

Map of the Algodones dune field: The dashed line near the bottom is the border between the U.S. and Mexico; Figure 1 from [21].

6. The internal structure of the draa being generated at the base of the lee slope consists of two types: steeply dipping simple cross-strata, and compound crossstrata. Paleowind directions from such cross-strata should produce an internal structure that reflects both the direction of secondary airflow on the lee slope ... and the average wind direction that orients the draa (8). Draas can form both simple and compound crossstrata; their deposits will have great lateral variation.

In their work the authors thoroughly examine the interplay between wind speed and direction with the resultant dune configurations and movements. The paper employs geologically complex terminology and concepts and is probably unsuited for those readers without at least a moderate geological background. What the authors do not mention is that these dunes have served as a popular recreation area for nearby residents (e.g. Yuma, Arizona) to operate their dune buggies on weekends in winter.

Not far from the Algodunes Dunes is the Gran Desierto de Altar, an extremely dry and austere dune field in northwestern Sonora, Mexico that is a recognized biosphere preserve.

2.2 Gran Desierto de Altar

Translated as the “great desert of the altar (or shrine)”, at the top of the Gulf of California, just across the Arizona border in Mexico, lies the Altar Desert, part

of the El Pinacate y Gran Desierto de Altar, a biosphere reserve and world heritage site [22]. The desert is a small part of the much larger Sonoran Desert that encompasses much of the southwestern United States and northwestern Mexico. The Colorado River, which has its delta immediately to the west and just upwind of the Altar Desert, supplied abundant sand for the dunes' formation. This dune field is considered the largest and most active in North America. At one time centuries or millennia ago this dune field had as its northwestern most finger the Algodones Dunes, although today the two dune fields are separated by about 40 km. It includes the only active erg dune region in North America. (An "erg dune region" is a broad, flat area of desert covered with wind-swept sand with little or no vegetative cover.) This desert extends across much of the northern border of the Gulf of California, spanning more than 100 km east to west and over 50 km north to south. It constitutes the largest continuous wilderness area within the Sonoran Desert [22].

As with the Algodones Dunes, much research has been conducted in this immense sand sea, but a summary of only one investigation will be presented here [23], whose authors present a detailed map of the dunes (**Figure 3**) and the following conclusions.

Since middle Pleistocene time [roughly 1.3 mya], the Gran Desierto sand sea formed as an eolian deposit. Primary sand sources are the ancestral Colorado River flood plain and delta, the modern Colorado River flood plain, littoral sands from the Gulf of California, and local alluvial sources. Brief periods of eolian deposition (characterized by migration of crescentic dunes) were separated by long, stable intervals during which existing sand populations were modified from crescentic dunes to star and other complex dunes. In the present day, the low rates of sediment generation and transport in the Gran Desierto suggest that it is in a stable period, a situation that has probably existed during much of the late Holocene [the Holocene period is 12,000 years ago to the present].

The authors present numerous numerical analyses of the size and shapes of these dune fields, and they show many satellite images. All things considered, this is a highly technical paper that might elude the understanding of the casual reader. These are the only two technical summaries of geological work done in North

Figure 3. Map and geological setting of the Gran Desierto de Altar (Figure 1 of [23]): Note the proximity of the Algodones dunes, just 40 km northwest of the western edge of the Gran Desierto sand sea. Also notable is the U.S., Mexico border, the dashed line in the upper center of the map.

American dune fields that appear in this paper. The interested reader can find similar work on the others.

With the discussions of sandstone formation and extant dune fields completed, this paper moves on to review the historical and technical literature concerning the Dust Bowl of the 1930s.

3. The U.S. Great Plains dust bowl of the 1930s

Before examining the Dust Bowl, it is worth noting that on a global scale dust storms of major proportions have been documented at least for the last 200 years [14]. Furthermore, paleoclimate research has shed light on droughts and dust storms in the last several millennia [24]. **Table 2** gives eight of the more recent major dust storms [15]. Such storms in semi-arid and arid regions of the world have occurred throughout human history and long before, as the sandstone formations discussed in the first section of this paper attest. Of these eight dust storms, one took place in the Middle East, one in China, two in Australia, and four in the U.S. Immediately below the table is a brief damage assessment for each storm.

- A. *Black Sunday (Dust Bowl)*: 300 million tons of topsoil were lost.
- B. *Great Bakersfield dust storm*: Swamp coolers were blown off the roofs of buildings. Windows were shattered. Trees, fences, and swamp coolers had blown down throughout the region. Below-grade freeways, canals, and creeks were buried in sand and dust. The storm resulted in five deaths and \$40 million in damage. Over 25 million cubic feet of topsoil from grazing land alone was moved.
- C. *Melbourne dust storm*: The winds brought down power lines and clogged electrical junction boxes with dust, causing them to short-circuit. Railroads could not function.
- D. *Interstate-5 dust storm*: This date, the Friday after Thanksgiving, had heavier traffic than usual on Interstate-5. The dust storm caused a series of chain reaction accidents, which mainly occurred in five groups spread across 1.5 miles (2.4 km) of highway; while one 20-car pile-up occurred in the northbound lanes, the remainder of the crashes were in the southbound lanes. In total, 104 vehicles were involved in the accident, including 93 cars and 11 semi-trailer trucks. 17 people died in the accidents, and an additional 150 people were injured.
- E. *Australian dust storm*: Vehicular and air transportation were disrupted. Ambulance services received around 140 calls from people having breathing

Name	Date	Affected regions	dam.
Black Sunday (Dust Bowl)	April 14, 1935	Texas, Oklahoma panhandles	A
Great Bakersfield dust storm	December 19–21, 1977	San Joaquin Valley, California	B
Melbourne dust storm	February 8, 1983	Victoria, Australia	C
Interstate-5 dust storm	November 29, 1991	San Joaquin Valley, California	D
Australian dust storm	September 23, 2009	S. Australia, New South Wales	E
China dust storms	Spring 2010	China, parts of southeast Asia	F
Arizona dust storm	July 5, 2011	South-central Arizona	G
Tehran dust storm	June 2, 2014	Tehran, Iran	H

Table 2.
Recent major dust storms: “dam.” is for damages from the storms; see the letter keys below. Individual references are not shown here; merely typing the storm’s name and date into a search engine brings up the information.

difficulties: more than 50 calls were made from Sydney, 50 from the state's west, 23 from the north and 12 from southern regions.

F. China dust storms: In the spring of 2010 many provinces of China were suffering from a severe drought that saw some 51 million citizens enduring water shortages. The series of dust storms that then ensued was in part a consequence of the desertification of extensive regions of the country. The annual direct economic losses attributable to desertification are estimated at US\$ 7.7 billion. It is believed that the indirect economic losses arising from desertification amount to 43.5 billion US\$ per year.

G. Arizona dust storm of 5 July 2011: Severe disruption of vehicular and air transportation, although no deaths or injuries were reported.

H. Tehran dust storm: 5 men were killed, more than 30 people were injured, and a few cars were destroyed. Falling trees and objects in balconies were destroyed. 65 electric lines of 20 KW were damaged and disconnected.

With these major dust storms enumerated, this review paper now proceeds to examine the Dust Bowl of the U.S. Great Plains, which started in 1930 and lasted for a decade. Severe drought hit the Midwest and southern Great Plains in 1930. Massive dust storms began in 1931. A series of drought years followed, further exacerbating the environmental disaster. By 1934, an estimated 35 million acres of formerly cultivated land had been rendered useless for farming, while another 125 million acres—an area roughly three-quarters the size of Texas—was rapidly losing its topsoil. Regular rainfall returned to the region by the end of 1939, bringing the Dust Bowl years to a close [15].

One of the affected states was Kansas, where in the 1940s an historian at the University of Kansas produced definitive studies of dust storms in the latter half of the nineteenth century [16–18]. Because the following discussion is limited to the Dust Bowl, these works have not been used in this paper, but they are included in the references for the interested reader. Instead, more contemporary research is relied on, and there is no shortage of such scholarship.

For instance, a team of Canadian researchers has assembled a comprehensive historical/scientific review of the Dust Bowl [19]. They present the geographical setting and the severity of the dustiest areas in their **Figure 1**, shown below as **Figure 4**. Although published seven years ago, their paper has perhaps the best and most comprehensive descriptions of the entire Dust Bowl saga, including its natural causes, its anthropogenic causes, and its disastrous consequences of soil erosion, of economic losses, and of forced mass migrations.

The underlying natural causes of the Dust Bowl have been succinctly described [19]:

Through data analysis and modeling, the authors state, that the causal mechanism for Dust Bowl era droughts on the Great Plains has been linked to ocean temperature anomalies. It appears that Pacific sea surface temperatures, especially as expressed by cold tropical temperatures during the La Niña phase of the El Niño Southern Oscillation, have the most direct influence.

The above-summarized work, a magnum opus, with copious geographical, historical, climatic, and economic analyses, is most suitable for the lay person. In sum, the authors cover much ground in a diversity of disciplines in a thorough, straightforward, and comprehensive manner.

The next summary, [24], though more localized, is of comparable analytic detail. Focusing on the region of northeastern Kansas and northwestern Missouri, a research team assembled rainfall records from 20 different cities and towns for the years 1850–2008 (**Figure 5**). They adjusted the records for 1850–1924 to account for negative biases in daily precipitation totals of less than 0.5 inches, which resulted in an overall increase of two percent above the historical records. In any case, the authors put the Dust Bowl into a broader historical perspective and conclude that

Figure 4. The Great Plains and the dust bowl proper: Note that the most severely affected area was limited to NE New Mexico, N Texas, W Oklahoma, SW Kansas, and SE Colorado; Figure 1 of [19].

the drought of 1855–1864 may have been the most severe and sustained *spring* moisture deficit over the Kansas-Missouri study area; and that the drought of the Dust Bowl era was by far the most severe and sustained *summer* precipitation deficit over the area. Nonetheless, when the precipitation data are summarized by growing season, the Dust Bowl drought was not remarkably more severe than the droughts of the 1860s, 1910s, and 1950s.

Perhaps the most seminal contribution of the above-summarized work is how the authors put the 1930s Dust Bowl into a much longer historical context. This context is lengthened considerably by the article summarized next.

Another research team [25] gives a much longer view of moisture/drought in the Dust Bowl area with the Palmer Drought Severity Index (PDSI). This index approximates soil moisture relative to ‘normal’ conditions, using meteorological data and assumptions about soil properties. ‘Drought’ is here defined as starting

Figure 5. Monthly precipitation from 20 Kansas and Missouri meteorological sites: Figure 2 of [24], augmented by marker lines for 1860 and 1935; AMJ, April, May, and June; JA, July, August; AMJJA, April – August. Note the difference in vertical scales: The top two go from zero to 600 mm, the bottom, from zero to 1200 mm.

the first month when the PDSI is less than -1 for three or more months and ending the month before the PDSI is greater than -1 for two or more months.” **Figure 6** presents this drought index for 1,000 years in southeastern Colorado.

This prehistorical to historical reconstruction shows that this drought index sank below -3 about 12 times, with the worst (-4) and longest duration in 1470, compared with the 1935 Dust Bowl value of -2.8 . This suggests two points: (1) that severe droughts occur roughly every 80 years, and (2) that the drought conditions of the Dust Bowl were severe but that other droughts have been worse. The strongest point in this research, which relies on tree ring data, is its temporal expansion from years and a century and a half to a complete millennium. In the works summarized so far, then, we go from the 1930s, to 1850–2008, and to 1000–2000 – the short, medium, and long-term views.

Yet another research approach to better understand the Dust Bowl examines changes in the land surface [26]. The authors state that “the drastic land-cover

Figure 6.

Five-year moving average of palmer drought severity index values for ... southeastern Colorado ... for 1000–2000 AD. The values [come] from tree ring records. (Figure 17 of [25]).

change from pre-settlement to the 1930s in the Great Plains resulted in a strong increase in the surface albedo. (“Surface albedo” quantifies the fraction of the sunlight reflected by the Earth’s surface.) On average, the albedo changes from ~ 0.16 in the native grassland to ~ 0.20 in dryland cropland, and such a change can considerably alter the surface energy budget. In [their] simulations, changes in surface albedo from pre-settlement to the 1930s land-cover resulted in a 5 Wm^{-2} reduction in solar energy absorbed at the surface (averaged over the Great Plains from May to July).” (Incoming solar radiation is often expressed as energy (Watts) per square meter (m^{-2} .) They extend this argument by explaining how these energy budget changes contributed to the 1930s drought. **Figure 7** depicts how surface albedo has changed from the 1930s to the present day.

Although the work just summarized may seem somewhat unrelated to dust emissions, it does analyze dust potential through changes in the surface land cover. Arguably, surface land cover dictates the potential for dust suspension under any given set of intense meteorological conditions. This paper would be accessible to most general readers.

In contrast to the above regional analysis, another researcher investigated the relation between meteorology and dust emissions [27] on a micro-scale for a north Texas dust storm that occurred in 1937. **Figure 8** displays the micro-geographic extent of dust emissions for a 4 km^2 sand dune area in Texas.

The authors conclude that:

1. Lower-level atmospheric and surface air temperatures are the strongest drivers of Dust Bowl dust events, followed by low relative humidity. Anomalies in this thermal gradient and moisture carried by the Great Plains Low Level Jet occurred on dust event days that were not present on days without dust events within the same season.

Figure 7.
1930s surface albedo minus present-day surface albedo. The tiny dots are water bodies that have distinctively different albedo from the land; Figure 3a of [26]. The differences between the two albedos are lowest in the Rocky Mountains and highest in W. Texas near El Paso.

2. Four modes of dust events were related to the season of occurrence and dominant meteorological controls. Two modes characterize “blowing season” events, with spring (MAM) dust events related to an inversion of surface and atmospheric air temperatures, and summer (JJA) dust events associated with intensified surface heating. The third mode of dust event occurs during the winter (DJF) after an extended dry period, and the fourth dust event mode reflects the passage of vigorous synoptic cold fronts that can occur in any season. (Note: [MAM = March, April, and May; JJA = June, July, and August; DJF = December, January, and February].)
3. PM_{10} emissions from common dust sources across the Southern High Plains indicates that anthropogenic disturbance of surface crusts can increase their magnitude from 0.001 to $0.01 \text{ mg m}^{-2} \text{ s}^{-1}$ from siltier soils. (The units here are milligrams (mg) per meter (m) squared, per second (s).) Emissions from loose, uncultivated sandy soils, however, can emit similarly potent levels of dust, suggesting a more complex narrative for landscape degradation in the 1930s Dust Bowl.

This paper is of moderate technical difficulty but would be understandable to most general readers. Admittedly, the authors partake of a somewhat oblique

Figure 8. Potential dust emissions from the Dalhart sand dune area in Dallam County, TX for an event on April 7, 1937. (a) Aerial photograph of the case study area captured on October 5, 1936. (b) Contemporaneous soil texture map produced by the soil conservation service. (c) Available bare surface area in photograph to emit dust by soil texture, the percent silt in the mapped soil unit, and the derived PM10 flux rate. (Figure 15 from [27]).

approach to dust emissions in their concentration on landscape characteristics; but, after all, landscape cover must be considered an essential, if not paramount, ingredient in the severity and frequency of dust storms.

From these more physical-science oriented summaries, this review paper now delves into the human misery of the Dust Bowl -- a tragedy of sad and immense proportions. This section relies on remarks by an Oklahoman physician, as chronicled in [10], p. 173. "In a report delivered to the Southern Medical Association [in April 1935], Dr. John H. Blue of Guymon, Oklahoma, said he treated fifty-six patients for dust pneumonia and all of them showed signs of silicosis; others were suffering early signs of tuberculosis. The doctor had looked inside an otherwise healthy farm hand in his early twenties and told him, "You are filled with dirt". The young man died the next day. The doctor then discusses silicosis, stating that prairie dust has a high silica content, and comparing the respiratory distress of Dust Bowl citizens to that of underground miners. He points out one important difference: silicosis in miners takes many years to build up, whereas doctors in the Dust Bowl were seeing a condition like silicosis after just three years of storms. For those residents who stayed the course, the human toll must have been devastating. For many of those who migrated, as depicted in John Steinbeck's *The Grapes of Wrath*, the outcome was also less than rosy. This reference [10], a clear historical, journalistic account of the Dust Bowl, would be accessible to all readers.

After the sections of this paper on present-day dune fields and the 1930s Dust Bowl, the concluding section first explains the basics of dust storms as described in two lengthy reports. Included in this discussion is a summary of how and why these storms are formed and how the public is alerted to them. Second, from two technical articles, it explains how scientific communities grapple with the difficulties of numerically simulating dust storms, work which might ultimately lead to a better predictive capacity.

4. Dust storms, their causes, effects, and attempts to forecast and model them

This third and concluding section describes both the basics of dust storms and how forecasting and numerical simulation of dust storms are accomplished today. Dust and sandstorms afflict most arid and semi-arid regions of the world, cause serious problems in commercial air traffic and vehicular traffic, degrade building surfaces, lead to increased house and office cleaning costs, and adversely affect human respiratory health. Because of their ultra-high turbulence as they contact the land surface, and because their resultant particulates concentrations are extremely heterogeneous in both time and space, accurately simulating these phenomena remains an elusive goal. Despite these shortcomings in the simulations, weather forecasters are still faced with the necessity of predicting these storms' locations, durations, and severities. These predictions then allow authorities such as the National Weather Service or highway departments to broadcast near real-time warnings to the vehicular-driving public.

As the authors live in Arizona, the next remarks concern the landscapes and weather of this state. Arizona has three distinct physiographical provinces: (1) lowland deserts in the south and southwest, (2) rugged mountainous highlands in its north-central region, and (3) the Colorado Plateau -- a broad, high-elevation plain comprising its northern third. In the populated areas the elevations range from 43 m (140 feet) above sea level in the far southwest corner at Yuma

to about 2100 m (6,900 feet), an elevation that extends from the north-centrally located Flagstaff in a broad swath to the east-southeast, culminating in the far east-central region next to New Mexico. These substantial elevation differences lead to pronounced differences in weather. Extreme inclement weather often leads to vehicular crashes, whether it is heavy rain, thick fog, heavy snowfall, icy roads from wet winter rain or snow, or blowing dust. Except for fog, a rare phenomenon in Arizona, this marked spatial variation in weather leads to vehicular crashes from all these extreme weather conditions somewhere in the state. The following discussion is limited, however, to the lowland deserts and blowing dust. The focus here is on how the predictive capacity of the weather-forecasting and of the atmospheric science communities has been brought to bear on developing better dust predictions to reduce vehicular crashes and to reduce population exposure to unhealthful levels of airborne particulates. In recent years, a considerable body of work on this subject has been conducted by the National Weather Service, by the Arizona Department of Transportation, by other governmental agencies, and by academic researchers.

4.1 Dust storm and sandstorm basics

Two lengthy reports provide information for this discussion, first, a global report assembled by multiple researchers for the United Nations Environmental Programme [1], and second, a comparable report limited to Arizona [28]. Both reports thoroughly discuss the atmospheric physics and meteorology of dust storms and sandstorms. Both estimate the economic damage wrought by dust storms. Both consider mitigation efforts to reduce the flux of anthropogenic dust. To the interested reader, both are worth obtaining and studying.

Dust storms occur whenever strong winds encounter dry, erodible land surfaces. Entrainment of particles occurs when the wind shear stress exceeds the ability of the surface material to resist detachment or transport. Wind erosivity is a product of wind velocity and wind flow characteristics, especially turbulence near the ground. In addition to ambient wind speed, vegetation and land-form characteristics of surface roughness play a large role in determining wind erosivity. Local wind conditions are also influenced by wind systems generated over larger areas, and thus may depend on land use and other physical characteristics in neighboring regions. Consider the “dry, erodible land surfaces”, which, according to [1], consist of 75% natural landscapes, such as the Sahara or Gobi Deserts and dry lake beds, and of 25% anthropogenic land surfaces, such as active or abandoned agricultural fields, unpaved roads, large mining and construction sites, and so forth. Mitigating dust emissions can only be directed to the anthropogenic dry land surfaces, so mitigation discussions are limited to this human-caused one fourth of the problem. The global report [1] presents their Table 2.2, p. 10, that gives the different types of land surfaces that can or cannot produce dust in high winds (**Table 3**).

Although many of these land surfaces have low or moderate dust or sand potential, the more important ones are (1) lakes that are ephemeral or are of dry, non-consolidated surfaces; (2) high-relief alluvial deposits that are both unarmored and unincised; and eolian sand dunes. Most agricultural soils for growing crops have been accumulated through alluvial processes, oftentimes augmented by the deposition of loess, so these fields when in between crops or when fallow or abandoned have high potential for dust emissions. Lakes in this list of dust potential actors are sometimes shallow water bodies constructed in large irrigation projects, but for various reasons the upstream waters that could be diverted to fill them become unavailable, leaving expansive dry lake beds prone to heavy dust emissions. In contrast with the eolian sand dunes and natural dry lake beds, these two categories of dust producers are amenable to mitigation.

Geomorphic type	Typical texture	Importance for dust emissions
Lakes		
Wet	Sand, silt, clay	Low
Ephemeral	Silt, clay	High (if sandblasting, medium)
Dry consolidated	Silt, clay	Low
Dry, non-consolidated	Silt, clay	High (if sandblasting, medium)
High relief alluvial deposits		
Armored, incised	Mega-gravel, gravel, sand	Low
Armored, unincised	Mega-gravel, gravel, sand	Low
Unarmored, incised	Gravel, sand, silt, clay	Medium
Unarmored, unincised	Sand, silt, clay	Medium-high
Low relief alluvial deposits		
Armored, incised	Gravel, sand	Low
Armored, unincised	Gravel, sand, silt, clay	Medium
Unarmored, incised	Sand, silt, clay	Low
Unarmored, unincised	Sand, silt, clay	Medium
Stoney surfaces	Gravel, sand, silt, clay	Low
Sand deposits		
Sand sheet	Sand	Low to medium
Eolian sand dunes	Sand	Low to high
Loess	Silt, clay	Low-medium
Low emission surfaces: bedrock, rocky slopes, dunecrust, snow/ice permanent cover	Mega-gravel, gravel, sand, silt, clay	Low

Table 3.
Different land surface types that can (or cannot) produce blowing sand and dust, (Table 2.2 of [1]).

The literature on landscape characteristics of dust potential, and on the atmospheric physics and meteorology of the formation, transport, and eventual dissipation of dust storms is both voluminous and can be highly technical. For greater detail, the reader is referred to the two already cited reports or other textbooks or journal articles. Both long reports would be comprehensible for the average reader.

To summarize dust storms, their *formation* comes about from extremely high surface winds, produced either from massive thunderstorms or from synoptic weather fronts. Their direction and distance of *transport* is determined by the continuing influence of these winds, in conjunction with their continued ability to contact erodible land surfaces. Their *dissipation* occurs as the wind speeds decrease with the weakening of either the thunderstorm activity or the large-scale frontal movements. The global report presents in their Figure 2.2 and Table 2.1 a clear conceptualization of the phenomenon, along with the influential physical characteristics of weather variables, of soil surfaces, of vegetation, and of landforms, shown as **Figure 9** and **Table 4**.

Figure 9.
Dust storm formation processes (Figure 2.2 of [1]).

Climate	Sediment or soil	Vegetation	Landform
Wind speed (+)	Soil/sediment type	Type	Surface roughness (+/–)
Wind direction	Particle composition	Coverage (–)	Slope (–)
Turbulence (+)	Soil/sediment structure	Density	Ridge
Precipitation (–)	Organic matter (+)	Distribution (+/–)	
Evaporation (+)	Carbonates (–)		
Air temperature (+/–)	Bulk density		
Air pressure (+)	Degree of aggregation (–)		
Freeze–thaw action (+/–)	Surface moisture (–)		

(+) indicates that the factor reinforces wind erosion; (–) indicates that the factor has a protective effect, reducing wind erosion; (+/–) indicates that the effect can be positive or negative depending on the processes involved.

Table 4.
Key physical factors influencing wind erosion (Table 2.1 of [1]).

In the Arizona report [28] the authors state that in Phoenix from 1948 to 2015 the number of summer dust storms ranges from three to five in the earlier years down to one to three in the latter years. They speculate that the decrease in frequency may stem from the expanding Phoenix urban area, in which formerly outlying agricultural lands with considerable dust potential have been converted into residential and commercial buildings, into landscaping that includes parks and lawns, and into what generally is called the “built environment”. They present one photograph of a dust storm, shown as **Figure 10**.

Figure 10.

Dust storm of 5 July 2011, as it approaches the National Weather Service office at Sky Harbor airport in Phoenix: (Figure 36 of [28]).

As for the observational tools and methods of predicting these dust storms, the authors offer the following, summarized in **Table 5**.

That concludes the summaries of the lengthy global and Arizona reports on all aspects of dust storms. This review paper now continues, and concludes, with a discussion of how these storms can be forecast or simulated.

4.2 Forecasting and simulating dust storms

The narrative immediately above covers the day-to-day observational tools and predictive systems for dust storms. At least two questions remain: (1) how are these dust storms studied by numerical simulations, and (2) how well do these simulations match the various observations such as satellite observations, Doppler radar images, and ground-based measurements of particulates concentrations? What follows are two examples of recent research on dust storm simulations. Both examples are highly technical papers unsuited for the non-technical reader.

One instructive example of the difficulties in performing these simulations and of what improvements might be forthcoming, can be found in the work of [12]. The authors assert that “regional-to-global models generally do not accurately simulate these storms”, for two reasons: “(1) using a single mean value for wind speed per grid box, i.e., not accounting for subgrid wind variability and (2) using convective parametrizations that poorly simulate cold pool outflows”. Their remedies take two forms. First, they “incorporate a probability distribution function for surface wind in each grid box to account for subgrid wind variability due to dry and moist convection.” Second, they use “lightning assimilation to increase the accuracy of the convective parameterization to better simulate cold pool outflows”.

These researchers built the subgrid wind variability and lightning assimilation into two different physico-chemical models: the Weather Research and Forecasting

Tool, warning, or prediction system	Remarks
Low-cost air quality sensors	\$100; measures [PM ₁₀] every 30 seconds; data sent to a central server
Traditional continuous particulates monitors	Operated by air pollution agencies; data can be retrieved near real-time
Human weather spotters	Trained; report blowing dust to NWS offices
Automated Surface Observing System (ASOS)	Hourly reports, data in 1- to 5-minute intervals; at all major and many smaller arizona airports
Doppler weather radar with horizontal and vertical pulses	Detects only the major storms; give 2-dimensional pictures; only three operate in Arizona
Satellite imagery	Clear depiction of large dust storms; but only two passes per day over any one area, so unlikely to capture many storms
Traffic cameras and web cams	Useful, but unable to distinguish dust storms from other smaller dust sources
Dust storm warning and wireless emergency alerts	Through existing NWS platforms and the media through the emergency broadcast system; now based on smaller areas (polygons) to avoid alerting citizens who may be 100 km away from the storm.
Electronic message signs on highways	Arizona Department of Transportation has many of these, urban and rural.
Social media, especially Twitter	Valuable for both obtaining information about dust storms and disseminating critical safety information
Safety and education	Dust safety while driving: “Pull Aside Stay Alive”
Prediction system	Global Forecast System (GFS) model and the North American Mesoscale (NAM) model, both low resolution; Arizona Regional Weather Research and Forecasting (AZ-WRF) model, a high resolution model

Note: all rows in this table are from [28], except row #2 and the last row, both added by the authors.

Table 5.
Observational tools, warnings, and prediction systems for dust storms.

Model (WRF) and the Community Multiscale Air Quality model (CMAQ). The windblown dust emissions parameterizations employed incorporate saltation bombardment (sandblasting) and a novel dynamic relation for the surface roughness length. To better estimate vegetative cover, these researchers used the fraction of absorbed photosynthetically available radiation (fPAR) from the Moderate Resolution Imaging Spectroradiometer (MODIS), which is a satellite-based instrument. Earlier work showed that the modeled airborne soil concentrations agreed quite well with observations in the spring, but that it underestimated these concentrations in summer, when convective dust storms are most frequent and most severe.

As for improving convection through lightning assimilation, the authors used the Kain-Fritsch convective scheme in WRF by activating its deep convection where lightning is observed and suppressing it where lightning is absent.

The authors went on to test their modified model on the major dust storm of 5 July 2011, which began with late afternoon severe thunderstorms near Tucson, Arizona. Cold pool outflows associated with this region of large storms moved northwest toward Phoenix, bringing with them a wall of dust extending 160 km wide and 1.5–1.8 km high. Both modifications – to the winds within the subgrids and to the deep convection scheme employed when lightning was present – enabled

the simulated particulates concentrations from CMAQ to better match the measured $[PM_{10}]$, as shown in **Figure 11**. [Note: “[PM_{10}]” is read as “concentrations of PM_{10} ”.]

The work just summarized is highly technical, even for atmospheric scientists who study these phenomena. Missing from this work is any explicitly numerical comparison of model-generated versus observed $[PM_{10}]$. While the concentration maps of **Figure 11** are illustrative, they are far from definitive. The next (and last work) summarized, which does have these explicit comparisons, is also on the technical side, but perhaps is not quite as obtuse, an opinion better left to the interested reader.

This is the work of [13], in which researchers analyzed nine dust storms in south-central Arizona with the Weather Research and Forecasting model with chemistry (WRF-Chem) at 2 km resolution. The all-important windblown dust emission algorithm was the Air Force Weather Agency model [29]. In all simulations of air pollutant concentrations, it is essential to get the emissions quantified accurately both temporally and spatially. For windblown dust emissions this goal frequently proves to be elusive because the available coverages of soil moisture, surface roughness, and vegetative cover suffer from both insufficient resolution and from temporal delays between the observations of these variables and the event itself. In this highly dynamic environment, with rainfall stochastically distributed in localized pockets, and with soil surface texture varying widely even within small areas, the uncertainties of the emitted dust flux reach unreasonable proportions. Nonetheless, one proceeds with what information one has.

In comparison with ground-based $[PM_{10}]$ observations, this modeling system unevenly reproduces the dust-storm events. The model adequately estimates the location and timing of the events, but it is unable to precisely replicate the magnitude and timing of the elevated hourly $[PM_{10}]$. Furthermore, the model underestimated $[PM_{10}]$ in highly agricultural Pinal County for two reasons. First, because it underestimated surface wind speeds and, second, because the model’s erodible fractions of the land surface data were too coarse to effectively resolve the active and abandoned agricultural lands.

In Phoenix the model’s performance depended on the event, with both under- and over-estimations partly due to incorrect representation of urban features. Increasing the fraction of erodible surfaces in the Pinal County agricultural areas improved the simulation of $[PM_{10}]$ in that region. Both 24-hr and 1-hr measured

Figure 11. Simulated hourly PM_{10} surface concentrations ($\mu g\ m^{-3}$) at 06:00 UTC on 6 July 2011 (23:00 local time on 5 July 2011) from three runs (left to right) (1) (control --no lightning assimilation (LTGA) and no subgrid wind variability (SGWV), (2) with SGWV, and (3) with SGWV and LTGA), overlaid with the observations of 11 PM_{10} monitoring sites. (this is lowest panel from Figure 6 of [12]).

Figure 12. Model static fields: (a) main land cover and land use type in south-Central Arizona, and (b) fraction of erodible surface (Figure 2 of [13]).

[PM₁₀] were, for the most part, and especially in Pinal County, extremely elevated, with the former exceeding the health standard by as much as 10-fold and the latter exceeding health-based guidelines by as much as 70-fold.

The authors present several graphics that depict, among other things, the landscape and the degree of erodible surface (Figure 12).

Figure 13 is a sample of the model's inability to match the observations, in which each panel represents a different dust storm. The observations in each case came from eight to 13 continuous PM₁₀ monitoring sites, all in Pinal County. In two storms the model grossly over-estimated the observed values; in the other four the model greatly underestimated the measured peak concentrations.

Figure 13.
Comparison of averaged PM_{10} time series over Pinal County for different cases: (a) April 13–14, 2006 (total 8 sites), (b) July 7–18, 2009 (total 9 sites), (c) January 21–22, 2010 (total 12 sites), (d) July 21–22, 2012 (total 13 sites), (e) June 30–July 1, 2013 (total 18 sites), (f) July 3–4, 2014 (18 sites), (g) June 27–28, 2015 (total 18 sites), and (h) July 7–8, 2014 (total 18 sites) (Figure 3 of [13]).

The authors conclude: “Given the severity and frequency of these dust storms and conceding that the modeling system applied did not produce the desired agreement between simulations and observations, additional research in both the windblown dust emissions model and the physico-chemical model is called for.”

Thus, concludes the last part of this four-part review paper that has presented information on sandstone formation, on sand dune field formation and dynamics, on the 1930s Dust Bowl saga, and on dust storm and sandstorm basics and the forecasting and prediction thereof. The interested reader is encouraged to consult the references for a more in-depth look into these subjects.

5. Conclusions

Although sand dunes, the Dust Bowl, and forecasting and simulating dust storms may appear as three widely separated topics, they share the common bond of arising from wind-blown sand and dust. Active for millions of years and still quite active at present, this disturbing phenomenon of arid and semi-arid regions wreaks havoc with the soil, disrupts vehicular and airborne transportation, causes multiple vehicular injuries and fatalities, and degrades human respiratory health. While the geological and esthetic prospects of sand dune fields enrich the naturalists’ hearts, the opposite is the case for the misery of the Dust Bowl and for the profound difficulties in predicting and simulating these dust storms. Because one quarter of these storms can be attributed to anthropogenic mismanagement of soil surfaces, it appears imperative for the agricultural and soil conservation

communities to redouble their efforts at reducing the dust flux from the disturbed portions of the soil surface. Only through such concerted actions will the productivity of the agricultural fields be maintained and will the atmospheric environment be restored to a more benign equilibrium.

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Conflict of interest

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Abbreviations and definitions

μm	micron, one millionth of a meter, e.g. a human hair is 70 μm in diameter; the thickness of 20-pound typing paper is 100 μm
mya	millions of years ago
km	kilometer: one km equals 0.63 miles

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