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# Evidence of Active Dune Sand on the Great Plains in the 19th Century from Accounts of Early Explorers

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**Eolian sand is extensive over the Great Plains of North America, but is at present mostly stabilized by vegetation. Accounts published by early explorers, however, indicate that at least parts of dune fields in Nebraska, Colorado, Kansas, New Mexico, and Texas were active in the 19th century. Based on an index of dune mobility and a regional tree-ring record, the probable causes for these periods of greater eolian activity are droughts, accompanied by higher temperatures, which greatly lowered the precipitation-to-evapotranspiration ratio and diminished the cover of stabilizing vegetation. In addition, observations by several explorers, and previous historical studies, indicate that rivers upwind of Great Plains dune fields had shallow, braided, sandy channels, as well as intermittent flow in the 19th century. Wide, braided, sandy rivers that were frequently dry would have increased sand supplies to active dune fields. We conclude that dune fields in the Great Plains are extremely sensitive to climate change and that the potential for reactivation of stabilized dunes in the future is high, with or without greenhouse warming.** ©1995 University of Washington.

## INTRODUCTION

Eolian sand sheets and sand dunes, first mapped on a regional scale by Thorp and Smith (1952), are common landforms on the Great Plains of North America (Figs. 1 and 2). These deposits are mostly stabilized by a sparse vegetation cover, but active sand is found in some places, particularly in cultivated areas. Aerial photographs show that presently stabilized sand dunes in some parts of the Great Plains were active during the 1930s drought (Melton, 1940; Muhs and Maat, 1993), although some of the increased eolian activity was likely due to poor land-use practices as well as climate (Chepil, 1957). On the Southern High Plains of Texas and New Mexico, "fence-line dunes" formed during the 1950s drought; such dunes are easily visible on recent 1:24,000-scale topographic maps, but are not found on pre-1950 topographic maps. In addition to eolian sand movement, dust storm frequencies were significantly higher in both the 1930s and 1950s droughts (Holliday, 1987). Minimally developed soils with only A/AC/C profiles on stabilized dunes and sand sheets indicate that large tracts of eolian sand were active in the recent geologic past. Radiocarbon dating indicates that eolian sands with these soil profiles were active in the past 1500 yr in Nebraska, Colorado, Kansas, and Texas (Ahlbrandt *et al.*, 1983; Holliday, 1985; Forman *et al.*, 1992; Johnson, 1992; Madole, 1994; Muhs *et al.*, 1995). Most of these investigators feel that Great Plains droughts, through a reduction in plant cover, are a primary factor in activation of eolian sand in the region.

Because the Great Plains region has a semiarid climate, vegetation, soils, and eolian sand respond quickly to shifts in the balance between precipitation and evapotranspiration. Relatively high temperatures accompany droughts on the Great Plains (Madden and Williams, 1978). Summer droughts in the region are the result of persistent subtropical upper-atmosphere high-pressure cells over the southern United States that block the penetration of moist air masses from the Gulf of Mexico. Clockwise circulation of the high-pressure cells draws relatively warm air from the southwestern deserts into the Great Plains (Nace and Pluhowski, 1965). The combined effect of reduced precipitation and increased temperatures is a marked decrease in the P/PE (precipitation/potential evaporation) value, which will decrease plant cover. Because there is evidence of rather severe droughts on the Great Plains during the past century (Meko, 1992), we wished to see if early explorers recorded evidence of eolian sand activity prior to the late 19th century, which is when most settlement took place.

## HISTORIC ACCOUNTS OF ACTIVE EOLIAN SAND IN THE 19TH CENTURY

The Nebraska Sand Hills is the largest dune field in the western hemisphere, and covers more than 57,000 km$^2$ (Fig. 1). It has stabilized barchanoid-ridges, barchans,



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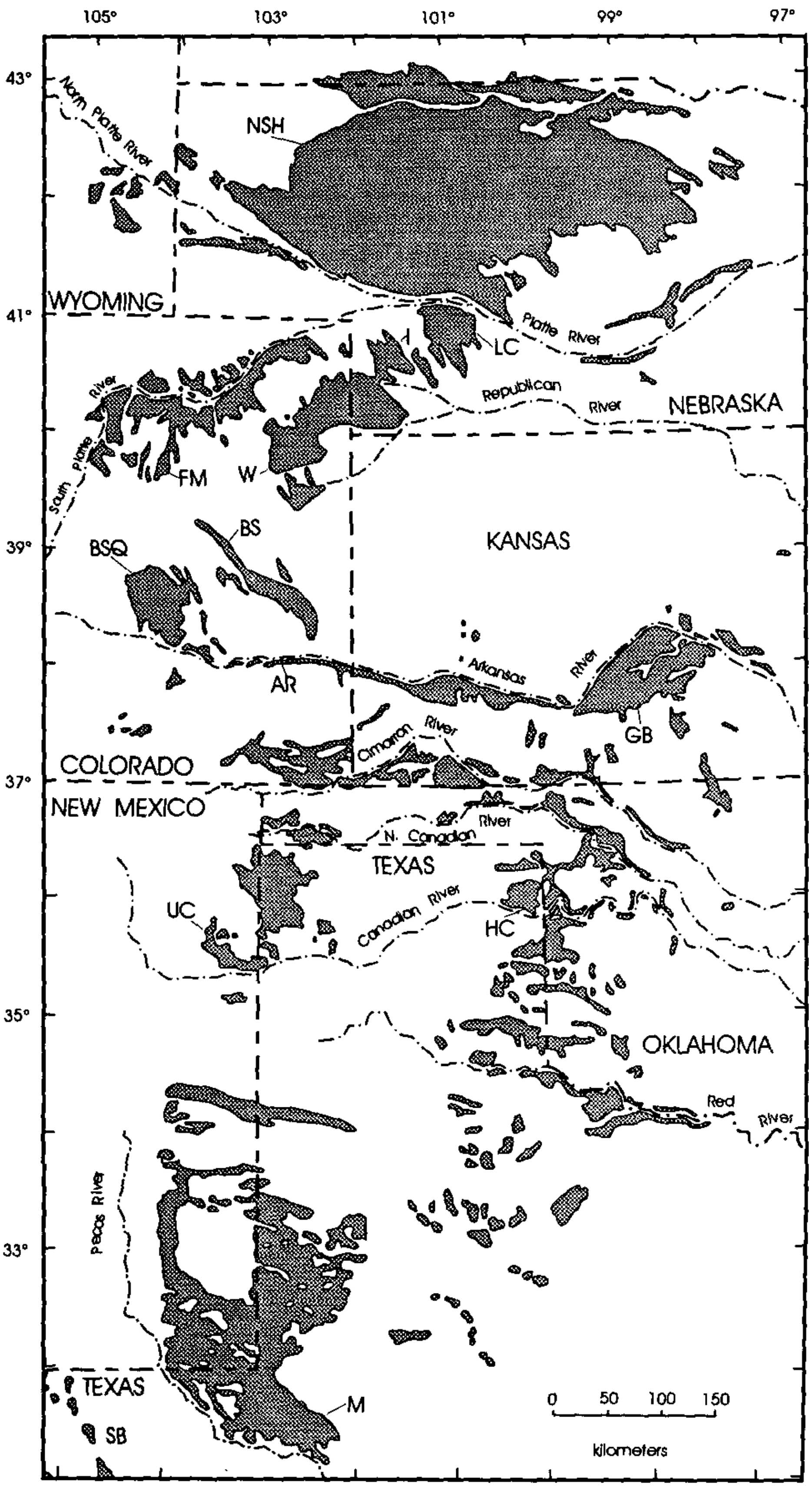


FIG. 1. Map showing the distribution of mostly stabilized dune sand and eolian sheet sand in the Great Plains and adjacent parts of the Chihuahuan Desert. NHS, Nebraska Sand Hills; LC, Lincoln County dune field; I, Imperial dune field; W, Wray dune field; FM, Fort Morgan dune field; BS, Big Sandy Creek dune field; BSQ, Black Squirrel Creek dune field; AR, Arkansas River dune field; UC, Ute Creek dune field; HC, Hemphill County dune field; M, Monahans dune field; SB, Salt Basin dune fields. Compiled from geologic data in Dane and Bachman (1965), Westin *et al.* (1971), Scott (1968, 1978), Sharps (1976, 1980), Love and Christiansen (1985), Swinehart (1990), Kuzila *et al.* (1990), Ross (1991), Hartman and Scranton (1992), Madole (1994), and U.S. Soil Conservation Service (unpublished STATSGO soil data).

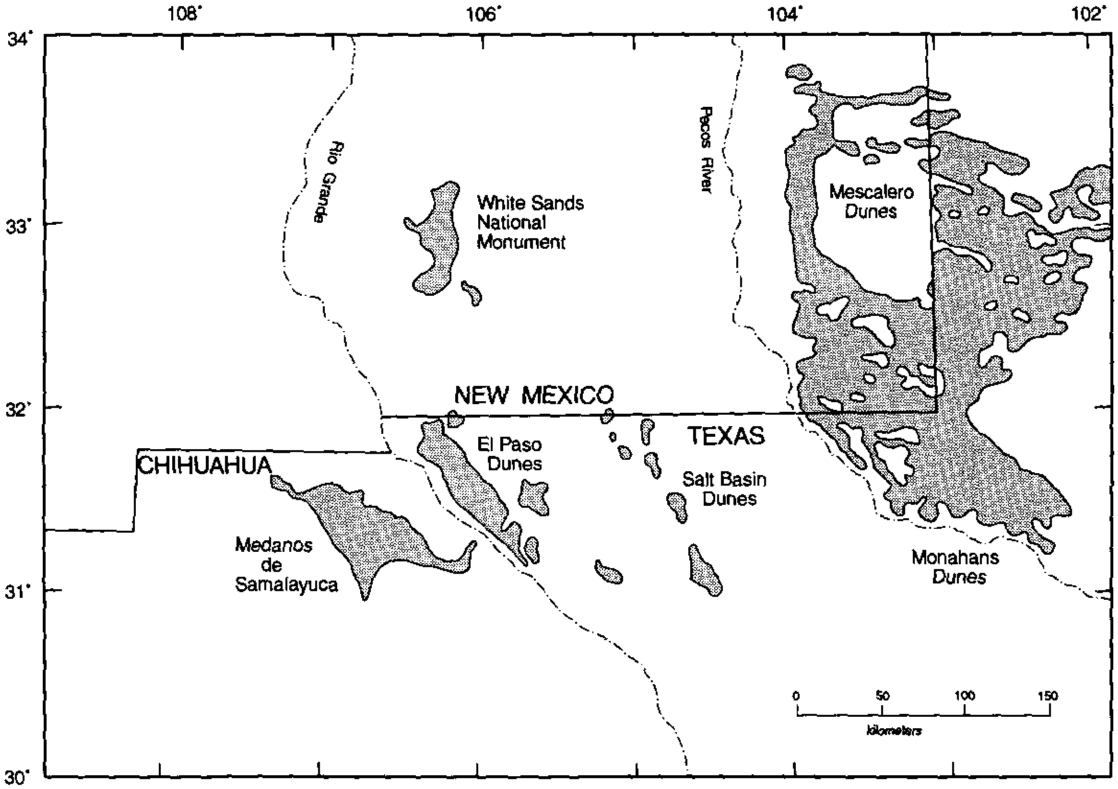


FIG. 2. Map showing the distribution of mostly active eolian sand (shaded) in the Chihuahuan Desert and Southern Great Plains. Compiled from geological data in Dane and Bachman (1965), Morrison (1969), and Hartman and Scranton (1992).

linear dunes, parabolic dunes, dome-like dunes, and sand sheets (Swinehart, 1990). However, at least two historic accounts suggest that within the past 200 yr eolian sand was active in the Nebraska Sand Hills. James Mackay may have been the first European to visit the Nebraska Sand Hills (in 1796; Diller, 1955; Miller, 1990). He describes southeastern Cherry County as follows, along with a translation given by Diller (1955, p. 127):

> —Grande Desert de sable Mouvant ou l'on ne trouve ni bois, ni terre, ni Roches, ni eau, ni animaux d'aucune espece, si ce n'est de petites Tortues bariolees, dont il y a une quantite infine. [Great desert of drifting sand, without trees, soil, rock, water, or animals of any kind, excepting some little varicolored turtles, of which there are vast numbers.]

Determination of whether the account of *sable Mouvant* ("drifting sand") is an accurate description of active eolian sand, or simply literary license, is difficult. However, evidence for a lack of stabilizing vegetation over at least some parts of the Nebraska Sand Hills in 1855 may also be found in a report by Warren (1856, pp. 8–9):

> *The Sand Hills (les Buttes de Sable)* present their most characteristic appearance just north of the Calamus river, spread out in every direction to the extreme verge of the horizon. (See sketch.) The sand is nearly white, or lightish yellow, and is about three-fourths covered with coarse grass and other plants . . . The scenery is exceedingly solitary, silent, and desolate, and depressing to one's spirits.

Warren's description of "about three-fourths covered with coarse grass and other plants" may refer to bare dune crests with vegetated side slopes and interdunes or a degree of vegetation cover on the scale of a few meters. However, his sketch (Fig. 3) with bare dune crests leads us to interpret this passage as referring to a *landscape* that is ~25% active sand, with most activity on dune crests.

Outside of the main body of the Nebraska Sand Hills, there are smaller, stabilized dune fields south of the South Platte River in southwestern Nebraska, informally designated the Imperial and Lincoln County dune fields (Fig. 1). Edwin James recorded Stephen Long's expedition across this area in June 1820 (James, 1823, Vol. I, p. 475):

> The intense reflection of light and heat from the surface of many tracts of naked sand, which we crossed, added much to the fatigue and suffering of our journey. We often met with extensive districts covered entirely with loose and fine sand, blown from the adjacent hills.

In northeastern Colorado, a number of discrete dune fields with stabilized eolian sand (Fig. 1) consist mostly of parabolic dunes and sand sheets (Scott, 1968, 1978; Sharps, 1976, 1980; Muhs, 1985; Madole, 1994). John Fremont, enroute to the South Platte River from Kansas, traveled through the Wray dune field of northeastern Col-

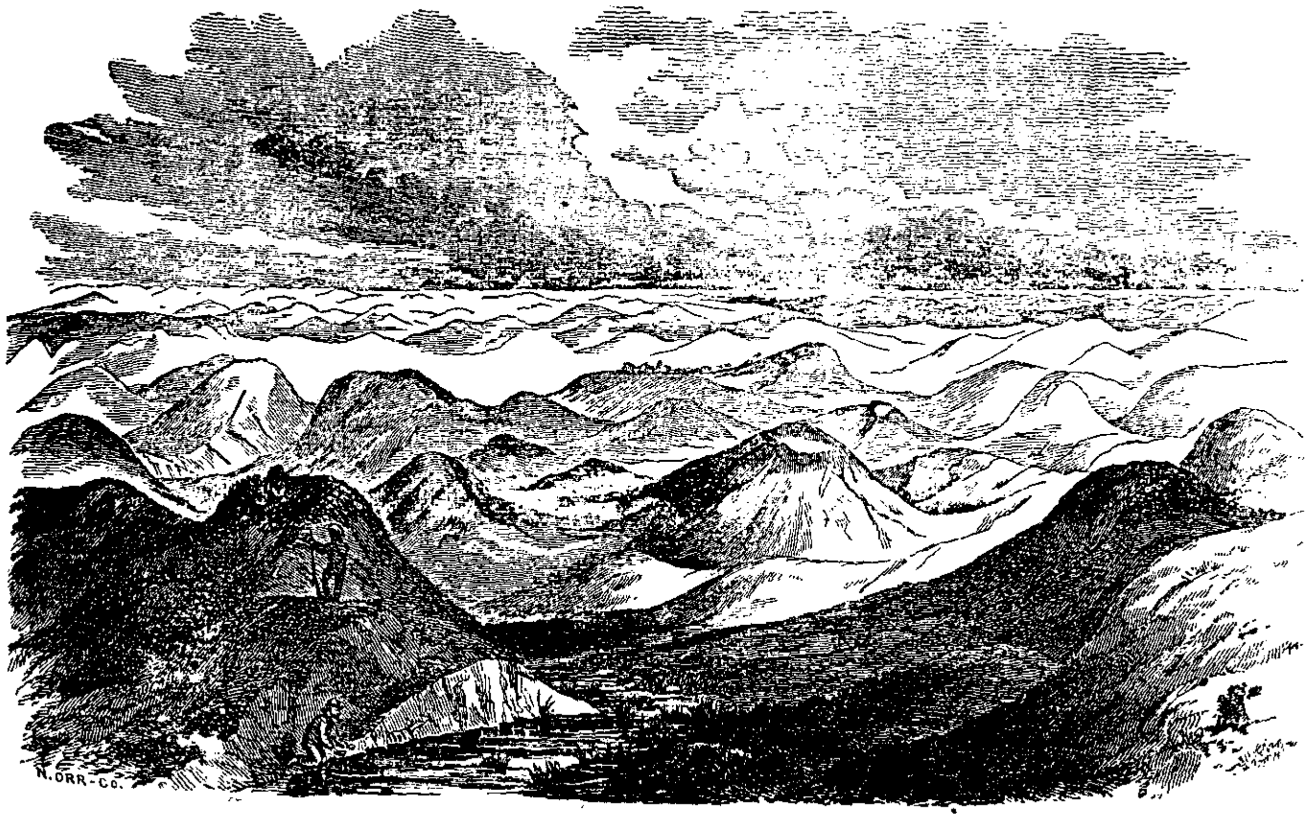

FIG. 3. Lt. G. K. Warren's 1855 sketch of the Nebraska Sand Hills landscape.

orado (Fig. 1), and described the landscape (Fremont, 1845, p. 109):

> Shortly after leaving our encampment on the 26th, we found suddenly that the nature of the country had entirely changed. Bare sand hills every where surrounded us in the undulating ground along which we were moving; and the plants peculiar to a sandy soil made their appearance in abundance. A few miles further we entered the valley of a large stream, afterwards known to be the Republican fork of the Kansas, whose shallow waters, with a depth of only a few inches, were spread out over a bed of yellowish white sand 600 yards wide. With the exception of one or two distant and detached groves, no timber of any kind was to be seen; and the features of the country assumed a desert character . . .

The seemingly contradictory statement of "bare sand hills" juxtaposed with "plants peculiar to a sandy soil made their appearance in abundance" may mean that Fremont was referring in the former case to the crests and side slopes of dunes, and in the latter case to interdune areas. In the Wray dune field and other dune fields of northeastern Colorado, high-relief parabolic and compound parabolic dunes have poorly developed soils with A/AC/C profiles, indicating relatively youthful sediments, whereas soils in interdune areas have well-developed A/Bt/C profiles, indicating a much greater age for interdune sediments (Muhs, 1985).

Stabilized eolian sands are present along much of the southern bank of the Arkansas River, extending from just east of Pueblo, Colorado, nearly to Wichita, Kansas (Fig. 1). Although small areas of these dunes were active in the 1930s (Muhs and Maat, 1993), most tracts of dunes are now stabilized by vegetation, judging from aerial photographs. However, Zebulon Pike's 1810 dissertation on the Louisiana territory contains the following passage (Coues, 1895, p. 525):

> These vast plains of the western hemisphere, may become in time equally celebrated as the sandy deserts of Africa; for I saw in my route, in various places, tracts of many leagues, where the wind had thrown up the sand, in all the fanciful forms of the ocean's rolling wave, and on which not a speck of vegetable matter existed.

Based on Pike's routes (Coues, 1895; Scott, 1975), it is likely that he is referring here to dunes along the south side of the Arkansas River in Kansas and eastern Colorado. Later explorers also verified active sand along the Arkansas River. The 1820–1821 Long expedition split into two parties after reaching the Rocky Mountains and before their return to the east. John Bell's party proceeded east along the Arkansas River and some of the sand they observed in Kansas was clearly stabilized by vegetation (James, 1823, Vol. II, p. 205):

> The soil during the afternoon's ride was a deep, fine, white sand, which rendered the traveling very laborious, under the debilitating influence of an extreme temperature of 94 degrees of Fahrenheit's scale, and affected the sight by the glare of light, which it so freely reflected. The chief produce of these tracts of unmixed sand, is the sunflower, often the dense and almost exclusive occupant.

Although the dunes in this region seem to be somewhat stabilized by vegetation, near the Great Bend sand prairie (Fig. 1), they recorded (James, 1823, Vol. II, p. 206) that

> The sandy soil and growth of sunflowers, still continues on the river bottoms, and the surface of the opposite bank, still swells into occasional hillocks of naked sand.

We interpret these passages to mean that dune fields along the south side of the Arkansas River were not fully active, but certainly there was some active sand. Jacob Fowler (in Settle *et al.*, 1970, p. 31) also described the Great Bend area in 1821:

> . . . and in a leavel Rich Pirarie the Sand Hills appeer all a long on the South Side and near the River—the are not more then 60 or 70 feet High and the Cuntry eavel beyound them to a great distance . . .

This passage implies that the Great Bend sand prairie area was at least in some parts covered with grasses. However, in the western Great Bend area (Pawnee County, Kansas), Fowler described the dunes as follows (in Settle *et al.*, 1970, pp. 34–35):

> . . . the Sand Hills Still appeer on the South Side of the River and to appeerence distetute of vigetation as they are Bald While those on the north are a Hard Black Soil With Some progecting Rocks and Covered With vigetation mostly a Short grass . . .

Significantly, Fowler could distinguish between nonvegetated (sand dunes) and vegetated (bedrock bluffs covered with loess) landforms. In the second half of the 19th century, Dodge (1877, p. 34) wrote of the "sand streams" that parallel the rivers of the Great Plains:

> These streams when united follow the right or south bank of the Arkansas in a belt of from five to thirty miles in width. Sometimes this belt will leave the river for a few miles; at other times the sand-bluffs stand sheer from the water to the height of 200 feet.
>
> The sand takes every variety of form. At one place the long gentle slopes, covered with grass, give at a little distance no indication of the nature of the ground beneath; at another, the high bare knolls, cut in rifts by the wind, look in the sunlight like huge snow-drifts. In some places the 'hills,' or knolls, change their forms with every wind; in others, the wind seems to have no effect whatever. The most curious fact connected with these sand-streams, or ranges of knolls, is that, however much they may and do vary in form, however they may be and are shifted by the ever-changing winds, all variations and changes take place within the regular limits or boundaries.

We question his estimate of "200 feet," but Dodge's 1877 account is consistent with the 1820s accounts of Bell and Fowler that both active and stabilized dunes were present along the Arkansas River in the 19th century. By the late 19th century, there were still both active and stabilized sands in western Kansas, based on Hitchcock (1898, p. 62):

> A well-marked range of sand-hills extends along the Arkansas river on the south side. At Garden City these hills are eight miles across the dunes. At Hartland there are several miles of shifting dunes known as the bald hills. The dunes are probably fifty feet high from base to summit, and entirely devoid of vegetation except around the base. They slope gradually toward the southwest from which direction come the prevailing winds, while on the opposite side the inclination is the greatest possible for loose sand. . . . The inhabitants of the region informed me that the bald hills are less extensive than formerly.

We conclude, therefore, that for most of the 19th century, there were both active and stabilized dunes along the south side of the Arkansas River.

The 1820–1821 Long expedition journeyed along the Canadian River in New Mexico and Texas (Fig. 1). Their overall description of the eolian sand in this part of their travels clearly indicates a significant amount of active dune sand (James, 1823, Vol. II, p. 120):

> Extensive tracts of loose sand, so destitute of plants and so fine as to be driven by the winds, occur in every part of the saline sandstone formation southwest of the Arkansa.

The phrase "southwest of the Arkansa" here refers not to the dunes immediately south of the Arkansas River shown on Figure 1, but rather to the entire region explored by Long's group. On August 28, 1820, Long and James gave some notion of the geographic extent of the active eolian sand they had been observing along the Canadian (James, 1823, Vol. II, p. 147):

> We had observed that the sand-drifts, extending along all that part of the river we had passed in the three last weeks, were, almost exclusively on the northern bank. The country we were now passing is too fertile and too closely covered with vegetation, to admit the drifting of the sand, except from the uncovered bed of the river; yet along the northern side of the valley we frequently saw naked piles of sand, which had been wafted to considerable distance by the winds. From the position of these sand banks, as well as from our experience, we were induced to believe that the high winds of this region, are mostly from the south, at least during the dry season.

Based on the few geographical positions that can be determined from James' account (see Tucker, 1963), as well as our estimates of their rates of travel (15–30 km/day), the "three last weeks" of observations of active eolian sand suggests that these explorers were viewing the dune fields east of Ute Creek and north of the Canadian River in northeastern New Mexico, and north of the Canadian River in Hemphill County, Texas (Fig. 1). Aerial photographs of the dunes north of the Canadian River from Ute Creek to the Oklahoma line show only local areas of active sand at present, and most of these are on isolated dune crests. Calculations of overall sand drift potentials using present-day wind data confirm that eolian sand in this area should indeed move from the southwest to the northeast, consistent with James' 1820 observations.

The Monahans dune field of the southernmost High Plains of Texas (Figs. 1 and 2) is largely active today and has barchanoid-ridge, transverse, barchan, akle, parabolic, and coppice dunes (Machenberg, 1984). Numerous early explorers observed large tracts of active eolian sand in the Monahans dune field, including Michler (1850, p. 37):

> Upon reaching the sand hills, we found, for the first twelve miles, low ridges of sand, running parallel to each other, plains of the same kind interspersed between them, with small hillocks. The sand was here of a black color. Then come the white sand hills, which are really an object of curiosity. They are a perfect miniature Alps of sand—the latter perfectly white and clean: in the midst of them you see summit after summit spreading out in every direction, not a sign of vegetation upon them—nothing but sand piled upon sand. They form a belt two or three miles in width, and extend many miles in a northwest direction.

Michler's observations of an active Monahans dune field are confirmed by Marcy (1850, p. 206), who also gives some dimensions of the active dune field:

> They extend (so far as we have explored) at least fifty miles in nearly a north and south direction, and from five to ten miles east and west; they are white drift-sand thrown up with much uniformity into a multitude of conical hills, destitute of soil, trees, or herbage.

Pope (1855, p. 69) also described and estimated the size of the Monahans dune field in this account:

> These "Hills" present a curious and interesting geological formation. They extend about fifty miles from north to south, and fifteen miles east to west. They consist of white drift-sand, thrown up into innumerable conical mounds, totally destitute of all vegetation.

Thus, there is little question that the Monahans dune field was active in the mid-19th century, based on three independent observers' accounts, and covered an area of ~600–1900 km$^2$. We measured a total area of ~300 km$^2$ of active sand in the Monahans dune field from 1984 aerial photographs.

## CAUSES OF EOLIAN SAND ACTIVITY IN THE 19TH CENTURY

### *Climatic Factors*

Lancaster (1988) generated an index of dune mobility ($M$) that is proportional to the amount of time that wind is above the threshold velocity for sand ($W$), and inversely proportional to the ratio of precipitation ($P$) to potential evapotranspiration ($PE$). Higher values of $M$ correspond to greater degrees of dune activity. Lancaster recognized, from field studies in southern Africa, four classes of dune activity: (a) inactive dunes, $M < 50$; (b) dunes with active crests only, $M = 50–100$; (c) dunes that are fully active except for plinths and interdune areas, $M = 100–200$; and (d) fully active dunes, $M > 200$ (Fig. 4a).

We computed modern $W$ and $P/PE$ values using Lancaster's method for weather stations in three different climatic regions with varying degrees of dune activity: (a) the cool, semiarid/subhumid northern and central Great Plains, where dunes are largely inactive; (b) the warm, arid Chihuahuan Desert (Fig. 2), including the Monahans area, where dunes are largely active now, and were in the 19th century (Hall, 1857; Dodge, 1877; King, 1948; Berg, 1969; Morrison, 1969; McKee and Douglass, 1971; Jaco, 1971); and (c) the hot, arid Colorado Desert of southeastern California and northern Mexico, where dunes are fully active today and were in the 19th century as well (Muhs *et al.*, 1995a). The Lancaster index correlates well with observed degrees of dune activity for the Great Plains (largely inactive or only with crests active) and the Colorado Desert (fully active). The index has only partial agreement with degree of dune activity in the Chihuahuan Desert where, with the exception of the El Paso dunes (10–12% active), dunes are largely active. For example, White Sands National Monument has mostly active dunes (McKee and Douglass, 1971), yet the $M$ values for nearby Alamogordo, New Mexico, and Holloman AFB are 54 and 88, respectively, because of $W$ values of ca. 16%. A better correspondence is found between degree of dune activity, when viewed from a regional perspective, and $P/PE$ values (Fig. 4b). We conclude, therefore, that the present degree of dune activity in western North America appears to be largely a function of the $P/PE$ value; wind strength, measured by $W$, may be of lesser importance. Observations of active dune sand in areas of the central and northern Great Plains in the 19th century, therefore, suggest that $P/PE$ values could have been lower than the present at that time.

Dendroclimatic data point to severe droughts on the Great Plains in the 19th century. Tree-ring records from drought-sensitive cedars in western Nebraska extend back almost 800 yr and record 11 droughts with greater duration than the 1930s period (Weakley, 1962). Newer tree-ring data from the eastern margin of the Great Plains from Minnesota to Texas and the western margin of the Great Plains from Montana to New Mexico show that there were droughts over the entire region during the early 1800s, 1820s, 1860s, and 1890s (Meko, 1992). The 1820s and 1860s droughts exceeded the 1930s drought both in intensity and duration; active sand was observed in all 19th century droughts (Fig. 5).

Because the response time of dune vegetation and eolian sand to Great Plains droughts is unknown, it is not possible to determine if a specific drought period was the cause of active eolian sand observed in the 19th century. However, given that eolian sand was active in the 1930s in the Southern High Plains and western Kansas (Melton, 1940; Muhs and Maat, 1993), and that the severity of at least two 19th-century droughts exceeded that of the 1930s drought, we conclude that the potential for climatically induced sand movement during the 19th century was high.

### *Sand Supply*

Recent trace-element geochemical studies have demonstrated that the Fort Morgan and Wray dune fields in

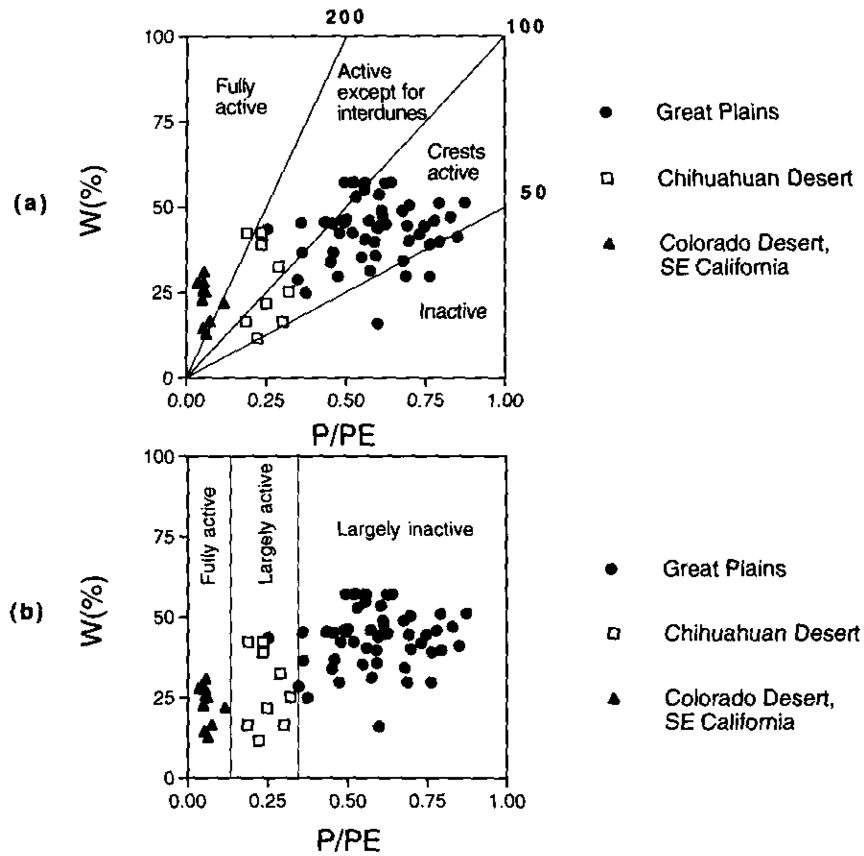


FIG. 4. Plot showing amount of time that wind is above the threshold velocity for medium sand (*W*) versus ratio of precipitation (*P*) to potential evapotranspiration (*PE*) for various regions where eolian sand is present: (a) with dune activity classes based on Lancaster (1988) and (b) dune activity classes based only on *P*/*PE* values. Data from Muhs and Maat (1993), Muhs *et al.* (1995a), and the present study.

northeastern Colorado (Fig. 1) were derived from South Platte River sediments rather than sediments eroded from the Ogallala Formation (Muhs *et al.*, 1995b). Examination of Figures 1 and 2 shows that many dune fields in the Great Plains and Chihuahuan Desert are near major rivers, such as the Platte, Arkansas, Cimarron, North Canadian, Canadian, and Pecos rivers, as well as the Rio Grande. Fluvial sediments, therefore, could be a significant source of eolian sand in other dune fields as well as those in northeastern Colorado. Three historical observations made during the 1820s, 1860s, and 1890s droughts (Fig. 5) show that eolian sand was deflated out of river valleys at these times. Long and James reported sand being deflated from the Canadian River valley in 1821 (James, 1823, Vol. II, pp. 122–123):

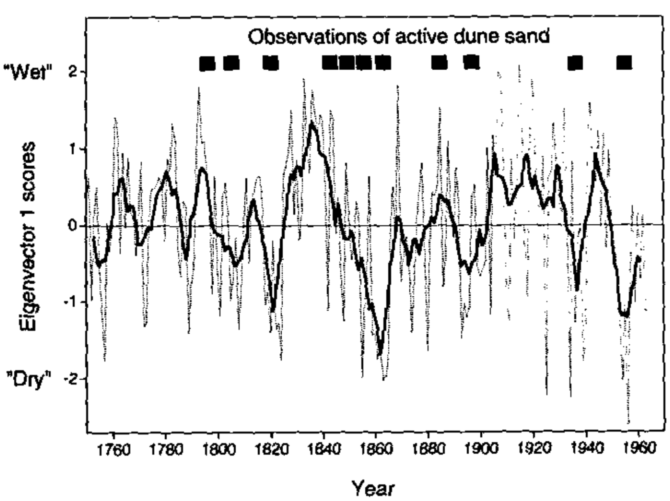


FIG. 5. Plot of Meko's (1992) tree-ring eigenvector scores from 1750 to 1964 A.D., where positive scores indicate relatively wet periods for the entire Great Plains region, and negative scores indicate relatively dry periods (dotted faint line); solid bold line is a 7-yr moving average. Also plotted (solid squares) are years of observations of active dune sand cited in the text.

> The sky continued clear, but the wind was high, and the drifting of sand occasioned much annoyance. The heat of the atmosphere became more intolerable, on account of the showers of burning sand driven against us, with such force as to penetrate every part of our dress, and proving so afflictive to our eyes, that it was with the greatest difficulty we could see to guide our horses. The sand is carried from the bed of the river, which is here a naked beach, of more than half a mile wide, and piled in immense drifts along the bank. Some of these heaps we have seen covering the trunk and a portion of the upper branches, of what appeared to be large trees.

Malin (1946, p. 267) noted that during the 1860s drought, the Leavenworth *Daily Times* of October 24, 1863, reported that in the South Platte River portion of southwestern Nebraska there had been no rain for nearly a year and "clouds of dust and sand arise from what was once the bed of the river." During the 1890s drought, G. K. Gilbert (1896, pp. 579–580) described sand being deflated from the Arkansas River, Big Sandy Creek, and Black Squirrel Creek in eastern Colorado (Fig. 1):

> On the broad plains underlain by the upland sands and gravels there are a number of local districts where the sand is fine enough to be moved by the wind and the vegetation is too scant to hold it. It is there blown about and gathered into dunes. If the wind blew as frequently and as strongly from one direction as another, the hills would make no progress; but all through the district the prevailing winds are from the northwest, and the sand hills therefore travel toward the southeast . . . Another source of dune sands is found in stream beds. Nearly all the streams of the district carry sand along their beds and build it into flood plains . . . the parts of the stream beds laid bare at low water, being without vegetation, are subject to the attacks of the wind. The sand is blown on the banks and built into dunes, and the dunes move slowly across the country.

We examined modern aerial photographs of river valleys and adjacent downwind areas of dunes along the Canadian River (the Ute Creek and Hemphill County dune fields), the South Platte River (the Imperial and Lincoln County dune fields), the Arkansas River (from La Junta, Colorado to Dodge City, Kansas), and along Big Sandy and Black Squirrel Creeks in eastern Colorado (Fig. 1). There are a few active dune crests along the Canadian River and Black Squirrel Creek and numerous ellipse-shaped areas of active sand south of the Arkansas River. We found almost no areas of active sand in the dune fields of southwestern Nebraska south of the South Platte River (other than where cultivated), or in eastern Colorado near Big Sandy Creek. Active sand in the Arkansas River and Black Squirrel Creek dune fields is considerably downwind of the river valleys, and is separated from them by areas of fully stabilized sand. Moreover, the Arkansas River valley itself (as well as the South Platte and Canadian Rivers) has a well-vegetated floodplain with very few areas of bare sand exposed. The few areas of active sand visible at present are not being fed by river valley sources, therefore, but are reactivated areas of previously stabilized sand.

Numerous studies (Schumm and Lichty, 1963; Schumm, 1977; Williams, 1978; Nadler and Schumm, 1981; Eschner *et al.*, 1983; Hadley and Toy, 1987) show that the North Platte, South Platte, Republican, Arkansas, and Cimarron rivers underwent changes in channel morphology in the past century and a half. Since the latter half of the 19th century, the North Platte, South Platte, Platte, and Arkansas rivers decreased in channel width, increased in channel depth, and changed from a braided pattern to a single-channel form (Williams, 1978; Nadler and Schumm, 1981; Eschner *et al.*, 1983). Schumm (1977) and Eschner *et al.* (1983) attribute these changes to progressive encroachment of vegetation on sandbars because flood peaks are no longer large enough to scour vegetation from the sandbars. The decrease in magnitude of flood peaks, in turn, is the result of flow regulation due to dam construction, return flow from irrigation, and interbasin transfers; these processes also increased the magnitude of low flows and decreased the number of days of no flows. In essence, therefore, the rivers underwent a change from an intermittent to a perennial character. These changes have important effects on sand supply to adjacent dune fields: (1) formation of a *relatively* deep, narrow channel and well-vegetated floodplain decreases the river valley surface area that would be subject to deflation by wind; (2) deep, narrow channels tend to be dominated by suspended sediment loads (silt and clay), in contrast to sandy loads typical of wide, shallow or braided channels; and (3) a decrease in the number of days of no flows would decrease the number of days when dry river beds would be subject to deflation by wind. Therefore, along the North Platte, South Platte, Platte, and Arkansas river valleys, more sand would have been available for deflation by wind in the 19th century than at present.

### *A Model for Eolian Activity*

Using the observations of climatic and sediment-supply controls on dune activity discussed above, we have formulated a general model for eolian activity (Fig. 6). Under conditions of low precipitation and high temperature, vegetation cover on dunes decreases due to a decrease in the ratio of precipitation to evapotranspiration. Increased temperatures produce greater surface heating, and perhaps greater gustiness. With relatively low precipitation, river systems have highly variable flood flow conditions, resulting in wide, braided, sandy channels and frequent days of no flows. The combination of all these processes results in increased eolian activity due to greater sand supply as well as fewer vegetation limits on sand transport. The model may explain not only 19th century eolian activity but also earlier Holocene dune activity (Ahlbrandt *et al.*, 1983; Muhs, 1985; Holliday, 1985, 1989; Forman *et al.*, 1992; Forman and Maat, 1990; Swinehart, 1990; Johnson, 1992; Madole, 1994; Muhs *et al.*, 1995b).

It is important to note that increased eolian activity in the Great Plains could result from conditions different from those presented in the model. Shallow, braided, sandy channels could also result from stream aggradation due to inputs of glacial outwash. New data from northeastern Colorado indicate that eolian sand sheets derived from the South Platte River were deposited at some time during the Pinedale glaciation (Madole, 1995; Muhs *et al.*, 1995b). Climate-model simulations indicate that at the Pinedale glacial maximum, climatic conditions in northeastern Colorado may have been considerably cooler and drier than at present (Thompson *et al.*, 1993). If these

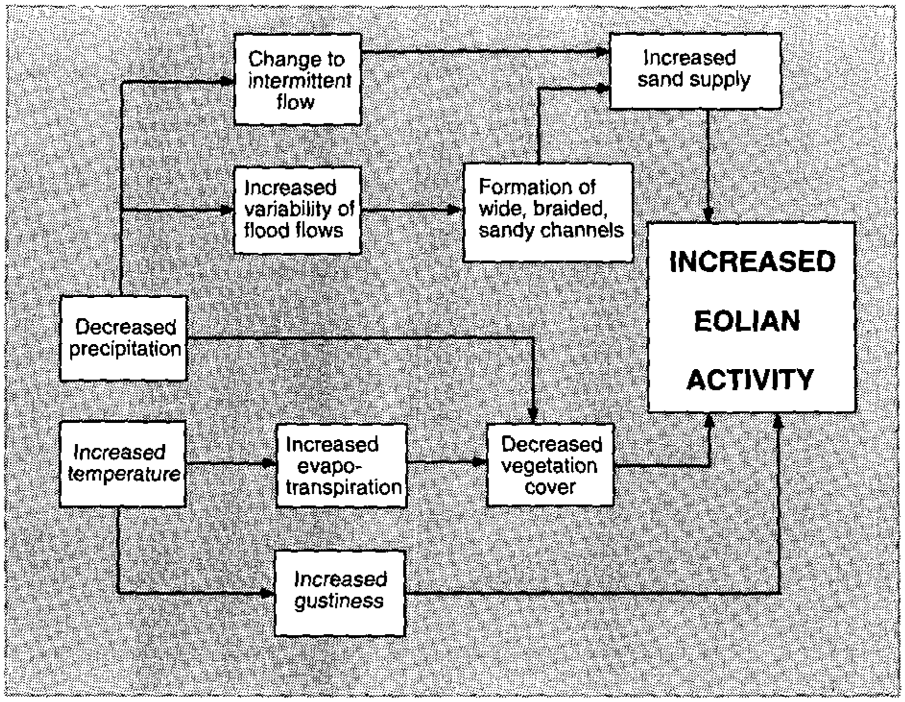


FIG. 6. Process-response model of climate change and fluvial and eolian activity in the Great Plains.

simulated conditions are correct, then they suggest that eolian sand can also accumulate under cold, arid conditions as well as warm, arid conditions in northeastern Colorado.

## CONCLUSIONS

Our investigations of early explorers' accounts indicate that eolian sand was active over at least parts of the Great Plains extending from northern Nebraska to southern Texas in the 19th century, as well as in parts of the Chihuahuan Desert to the southwest of the Great Plains. However, at present, dune fields dominated by active eolian sand are limited to the Chihuahuan Desert. Degree of dune activity appears to be roughly correlated with present *P/PE* values; thus, dunes of the central and northern Great Plains that were formerly active in the 19th century apparently had a climate that was more conducive to active eolian sand than is the case at present. This interpretation is supported by the tree-ring record, which indicates that there were several intense droughts in the 19th century, as well as evidence from Great Plains rivers, which had channel morphologies that were more conducive to eolian sand transport. The early explorers' accounts of their observations need to be interpreted with caution, however. Observations made by individuals often stress the unusual aspects of a landscape, rather than what is typical for a given terrain. Hence, it is particularly difficult to obtain even semiquantitative estimates of the extent of active sand on the Great Plains in the 19th century. Nevertheless, although models of a future greenhouse climate indicate significant increases in temperature and decreases in precipitation for regions such as the Great Plains (Rosenzweig and Hillel, 1993; Muhs and Maat, 1993), evidence of active eolian sand in the 19th century indicates that the potential for reactivation of dunes in the future is high, with or without a greenhouse climate.

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