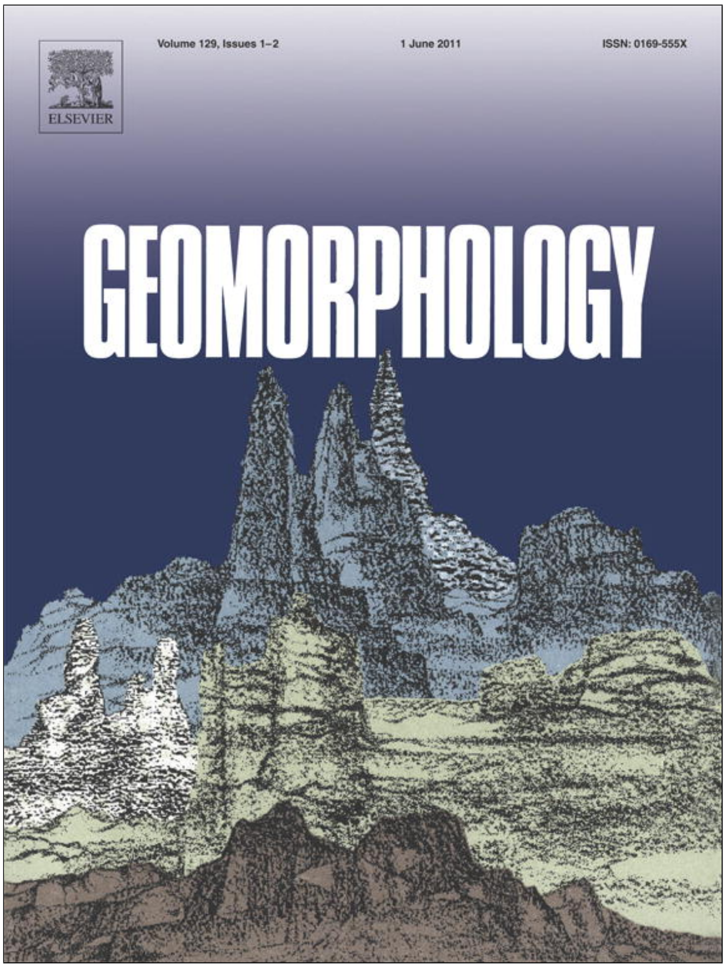
Volume 129, Issues 1–2
1 June 2011
ISSN: 0169-555X
ELSEVIER
GEOMORPHOLOGY

Geomorphology 129 (2011) 1–13

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Wind regimes and aeolian transport in the Great Basin, U.S.A.

Paul W. Jewell [a,*], Kathleen Nicoll [b]

[a] Department of Geology and Geophysics, University of Utah, Salt Lake City, UT 84112, United States
[b] Department of Geography, University of Utah, Salt Lake City, UT 84112, United States

ARTICLE INFO

Article history:
Received 23 April 2010
Received in revised form 4 January 2011
Accepted 11 January 2011
Available online 19 January 2011

Keywords:
Aeolian transport
Dunes
Climatology

ABSTRACT

The modern Great Basin of the interior western United States is characterized by surface winds with considerable spatial and temporal variabilities. Wind records from the second half of the 20th century for 12 Great Basin localities, analyzed with standard aeolian-sediment transport methods developed elsewhere in the world, reflect this complexity. The drift potential (DP) for aeolian deposits is generally moderate (DP 200–400) in the western Great Basin and weak (DP<200) in the central Great Basin where winds are predominantly west-southwesterly. DP is relatively high (DP>300) at the eastern edge of the Great Basin where the dominant prevailing wind direction is south-southwesterly. Both DP and resultant drift direction (RDD) are consistent with synoptic meteorological observations of the evolution of cold fronts in the Great Basin. Meteorological observations show that effective winds to produce dunes are most commonly the result of late winter–early spring cyclogenesis. There has been considerable temporal variability of DP in the latter half of the 20th century. Most of the Great Basin has experienced decreasing wind strength since 1973, consistent with recent studies of wind strength in North America and elsewhere. Dune morphology matches both localized RDD and temporal variations in DP reasonably well in the Great Basin. The results demonstrate that local topography can have an important influence on wind directionality, thus providing a cautionary note on the interpretation of dune morphology in the paleoclimatic and stratigraphic record.

1. Introduction

Aeolian sediment transport is important for the evolution of modern desert landscapes as well as the formation of sedimentary deposits in the geologic record. Aeolian transport and the formation of sand dunes is a function of the availability of transportable sediment, the net evaporation–precipitation of a given region, and the magnitude and variability of surface wind fields (e.g., Lancaster, 1990; Tchakerian, 1994). Interpretation of the climatic control of modern aeolian deposits thus has a direct relationship to the paleoclimatic interpretation of ancient aeolian sedimentary sequences.

Surface wind regimes and their associated aeolian deposits have significant spatial and temporal variabilities (e.g., McKee, 1979). While numerous studies have related specific aeolian dune fields and deposits to localized wind fields, fewer studies have integrated long-term (decadal) wind records over a large and complex geographic area and interpreted them within the context of aeolian transport (e.g., Bullard et al., 1996; Wang et al., 2005; Zu et al., 2008).

The interior of the western United States presents a particular challenge for the analysis of wind fields and aeolian deposits. While much of the region has low precipitation and abundant potential aeolian material (much of it derived from pluvial lakes of the last glacial maximum), its diverse geographic terrains and locally extreme topographic gradients exert tremendous influence on surface winds (Stewart et al., 2002; Cairns and Corey, 2003; Shafer and Steenburgh, 2008). Previous work documenting aeolian transport and areas of dune formation in the western U.S. includes the Mojave desert (Muhs et al., 1995; Tchakerian and Lancaster, 2002; Lancaster and Tchakerian, 2003), lower Colorado River basin (Muhs et al., 1995), northern Mexico (Lancaster et al., 1987), Wyoming (Alhlbrandt et al., 1983; Gaylord and Dawson, 1987; Mayer and Mahan, 2004) and New Mexico (Wells et al., 1990). Comparatively less attention has been paid to the Great Basin region.

For the purpose of this study, the Great Basin follows the classic physiographic definition as the area of interior drainage between the Sierra Nevada–Cascade Mountains to the west and the Rocky Mountains to the east. The Great Basin encompasses most of the state of Nevada, the western half of Utah, and small portions of eastern California, southern Idaho, and southeastern Oregon. This study also encompasses the southern tip of Nevada, which is actually a part of the Colorado River drainage (Fig. 1). The Great Basin is characterized by regularly spaced north–south trending mountain ranges separated by wide valley bottoms. The climate of the Great Basin is semi-arid; Nevada and Utah are the two driest states in the United States. Annual precipitation averages 20 cm and falls predominantly in the late winter and early spring (e.g., Knapp, 1994).

The meteorological records of the second half of the 20th century and their relationship to aeolian transport in the Great Basin will be

* Corresponding author.
E-mail address: paul.jewell@utah.edu (P.W. Jewell).

0169-555X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2011.01.005

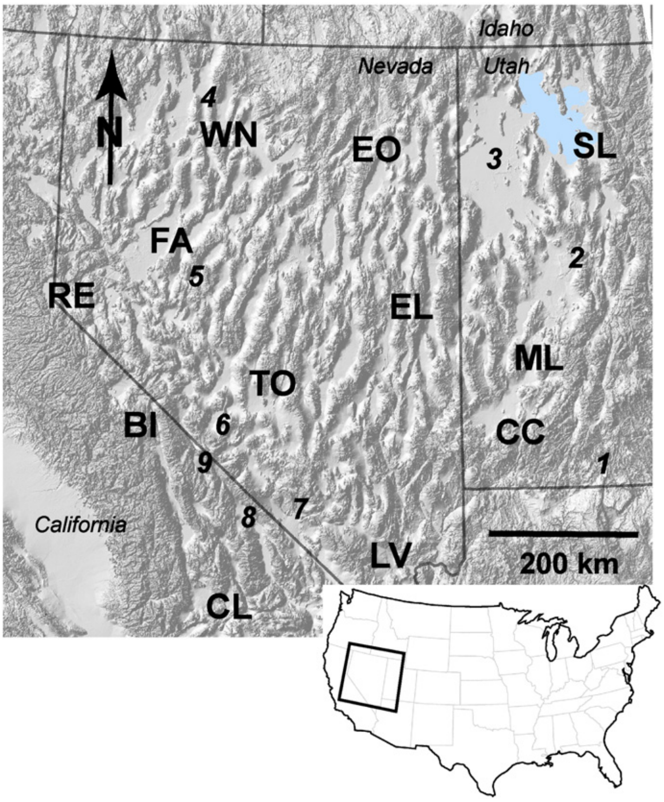

Fig. 1. Location diagram of the meteorological stations used in this study. RE — Reno, BI — Bishop, CL — China Lake, WN — Winnemucca, EO — Elko, RE — Reno, FA — Fallon, EL — Ely, TO — Tonopah, LV — Las Vegas, SL — Salt Lake City, ML — Milford, CC — Cedar City. Dune fields considered in this study include (1) Coral Pink, (2) Little Sahara, (3) Knolls, (4) Winnemucca, (5) Sand Mountain, (6) Clayton Valley, (7) Amargosa, (8) Stovepipe Wells, and (9) Eureka Valley.

the focus of this study, undertaken to address three issues: (1) the spatial variability of surface winds throughout the Great Basin and its relationship to physiographic features of this area and the late 20th century climatology of the Great Basin, (2) the temporal variability of winds in the Great Basin, and (3) the relationship between specific dune deposits and wind regimes of the Great Basin.

2. Methods

2.1. Wind data

Digital meteorological records are now widely available for much of the United States and other industrialized countries. For this study, the wind records of 12 meteorological stations (Fig. 1; Table 1) were purchased in digital form for the 55-year period 1945–2000 from EarthInfo, Inc., which in turn were derived from National Climate Data Center (NCDC) data sets TD-1440 and TD-3280. Quality control analysis of these data demonstrates that errors occur in fewer than 0.1% of the NCDC (Deganto, 1997).

Until the mid-1960s, wind direction was recorded as one of 16 coordinate sectors after which compass direction to the nearest 10° was recorded. The majority of wind records are hourly. Some stations' winds were recorded at 3- or 4-hour intervals and in some cases, winds were not recorded in the late evening or early morning hours. Data bias due to the absence of nocturnal winds is not considered to be an issue in this study since sand transport is believed to take place for wind velocities >6 m/s (Bagnold, 1941). Diurnal wind velocities in the Great Basin and Rocky Mountain region are in the 2–4 m/s range (Stewart et al., 2002).

The 12 stations provide a relatively uniform geographic distribution across the Great Basin (Fig. 1) in addition to having nearly continuous records for the 1945–2000 time period. Meeting these criteria necessitated employing data from airports of three relatively large metropolitan areas (Reno, Las Vegas, and Salt Lake City) where urban growth adjacent to the airport may have influenced wind characteristics over time. Salt Lake City International Airport is still located ~10 km from the major urban center and urban development probably has not influenced strong surface winds. Diurnal winds from the Great Salt Lake were observed in the wind data, but had magnitudes of less than 5 m/s. Some caution must be used in considering the temporal evolution of winds in Reno and Las Vegas due to urbanization near their respective airports. The other nine stations in this study are airports near small towns or military installations (i.e., Fallon Naval Air Station and China Lake Naval Airfield).

In addition to possible urban interference, there is a recognition that anemometer height has changed with time for many meteorological stations, which may cause irregularities of wind measurement records (e.g., Klink, 2002). This complication has been addressed by employing NCDC Data Set 6421 (DSI-6421) which documents post-WWII changes in anemometer heights for 1655 stations in the continental U.S. Anemometer height changes and wind velocity corrections for the 12 stations of this study were made by normalizing all wind speeds to a 10-m reference elevation according to the relationship:

$$V_R = Vz\frac{ln(z_R / z_o)}{ln(z / z_o)} \quad (1)$$

where V(z) is wind speed at elevation z, V_R is wind speed at a 10-m reference elevation, z_R is 10 m, and z_o is the roughness length (assumed to be 0.1; Archer and Jacobson, 2003). In general, the wind velocity correction to the 10-m reference elevation was <10%.

Table 1
Summary of wind records for meteorological stations of the Great Basin.

Station (WBAN no.)	Period of wind records	Total records	Records >6 m/s (% of total)	DP	RDP	RDP/DP	RDD
Bishop Airport, California (23157)	1948–2000	214,980	44,731 (20.8%)	419	91	0.22	358°
China Lake Naval Airfield, California (93104)	1945–2000	328,092	53,271 (16.2%)	364	254	0.70	59°
Reno–Tahoe International Airport (23185)	1949–2000	361,899	52,206 (14.4%)	264	155	0.59	43°
Fallon Naval Air Station, Nevada (93102)	1945–1998	384,172	30,277 (7.9%)	158	89	0.56	78°
Winnemucca Municipal Airport, Nevada (24128)	1949–2000	326,412	42,276 (13.0%)	144	71	0.45	76°
Elko Regional Airport, Nevada (24121)	1948–1995	355,314	32,686 (9.2%)	106	65	0.61	66°
Ely Yelland Field Airport, Nevada (23154)	1953–2000	320,141	82,549 (25.8%)	385	222	0.57	10°
Milford Municipal Airport, Utah (23176)	1948–1989	164,015	44,971 (27.4%)	687	477	0.69	27°
Tonopah Airport, Nevada (23153)	1952–2000	317,715	75,134 (23.6%)	370	133	0.39	85°
Las Vegas McCarren Airport (23169)	1949–2000	385,893	90,958 (23.6%)	475	251	0.53	53°
Salt Lake City International Airport (241127)	1948–2000	464,562	85,286 (18.4%)	282	157	0.55	4°
Cedar City Municipal Airport, Utah (93129)	1945–2000	360,258	78,844 (21.9%)	419	302	0.72	28°

Changes in anemometer height appear to have had little effect in other wind studies as well (e.g., Klink, 1999; Pryor et al., 2009).

For each station, a total of 1.6–4.6 $\times$ 10^5 wind records were studied of which 8–27% exceeded the 6 m/s threshold believed needed to transport sand (Bagnold, 1941) (Table 1). Records after 1989 for Milford, Utah, 1995 for Elko, Nevada, and 1998 for Fallon, Nevada were not available. At a number of stations, wind records between 1945 and 1950 were unavailable, so for the sake of comparison, plots comparing individual stations only encompass the 1950–2000 time period.

2.2. Sand transport calculations

For each wind record >6 m/s, the following relationship was used to calculate the "drift potential", DP, (Fryberger and Dean, 1979):

$$DP \propto V^2(V - V_t) * t. \tag{2}$$

V is the recorded velocity, V_t is the "impact threshold velocity" (6 m/s in this case), and t is the time increment relative to the total time for all measurements expressed as a percentage. DP is the value of Eq. (2) summed over all wind directions in a given amount of time (e.g., yearly or monthly). Metric velocity is used in applications of Eq. (2) in some recent publications (e.g., Bullard et al., 1996) and has been the source of subsequent confusion (Bullard, 1997). Knots were used by Fryberger and Dean (1979) in their landmark study as well as others (e.g., Lancaster et al., 1987; Saqqa and Atallah, 2004; Wang et al., 2005) and this convention is retained in this study so that direct comparisons of DP can be made with these earlier studies. The Fryberger and Dean (1979) categories are: low, DP<200; intermediate, 200<DP<400; and high, DP≥400.

The wind direction and DP for each wind record in the multi-decadal dataset was assigned to one of the 16 compass directions. This conforms to the practice of previous investigations, although it has been criticized because thirty six, 10° wind direction data bins cannot be distributed evenly into 16 compass directions (Pearce and Walker, 2005).

Since wind records express the direction that the wind is blowing from, aeolian drift direction is 180° from the resultant of DP. Using the terminology of Fryberger and Dean (1979), the direction and magnitude of this vector are known as the resultant drift direction (RDD) and the resultant drift potential (RDP), respectively (Fig. 2). The RDP/DP is thus a measure of the directional consistency of winds capable of moving aeolian material.

3. Results

3.1. Spatial variability of Great Basin winds and transport variables

The irregular topography and large topographic gradients of the mountain ranges such as those in the Great Basin can cause surface winds to be extremely complex and variable (e.g., Stewart et al., 2002; Cairns and Corey, 2003). In spite of this, a generalized picture of Great Basin winds and associated aeolian deposits appears to fit recent meteorological studies of how frontal systems behave in the Great Basin (Shafer and Steenburgh, 2008).

The spatial distribution of DP for the 16 compass directions is known as "a sand rose diagram" (Fryberger and Dean, 1979). Spatial variability of the ~50 year sand rose records across the Great Basin is clearly evident (Fig. 2, Table 1). In the western Great Basin (Reno, Fallon, Winnemucca, and Elko), DPs (106–264) are predominantly a function of winds that are relatively weak and predominantly west-southwesterly (Fig. 2). The somewhat stronger DP in Reno (264) may be the result of increased leeward wind energy from the Sierra Nevada Mountains to the west (Cairns and Corey, 2003). The DP of Bishop (419) is relatively strong, but bi-directional, as might be expected of its location in the steep Owens Valley of eastern California. The DP of

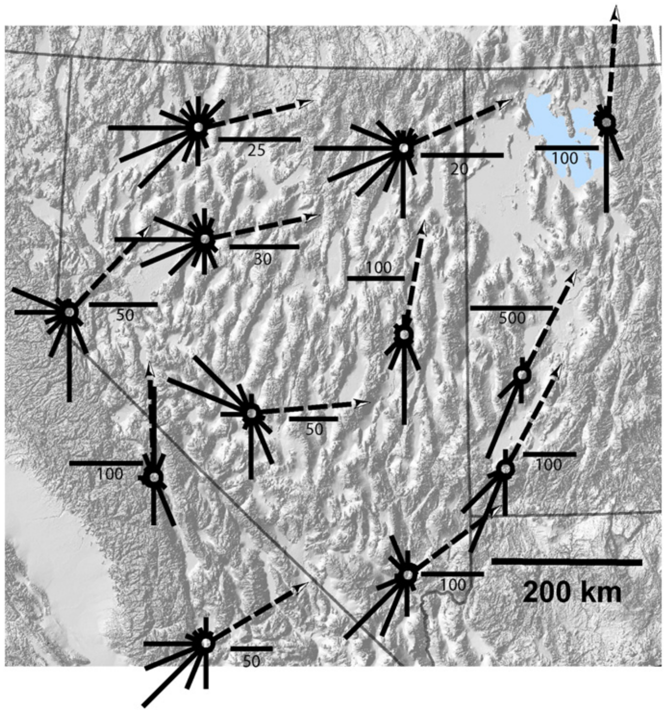

Fig. 2. Sand roses generated for the Great Basin, 1950–2000. Numbers next to the roses are scale bars for the adjacent sand rose of a given locality (criteria of Fryberger and Dean, 1979). Dashed lines represent the resultant drift direction (RDD); for the sake of an uncluttered diagram the magnitude of the dashed vectors is not the same as the resultant drift potential (RDP) (Table 1).

Tonopah (370) is much greater than stations to the north, but predominantly westerly.

DPs of eastern and southern portions of the Great Basin (China Lake, Las Vegas, Cedar City, Ely, Milford, and Salt Lake City) are more south-southwesterly and considerably stronger (282–687) (Fig. 2). Milford (DP = 687) is in a class by itself, a fact that has been noted before and given rise to the "Milford Corridor" designation as an important potential wind power area (Renewable Energy World, 2009). RDP/DP ratios (representing the consistency of prevailing strong wind directions) are modest and quite consistent (0.45–0.61) throughout the northern Great Basin and higher (0.53–0.72) in the southern Great Basin. Bishop and Topopah have lower RDP/DP values (0.22 and 0.39 respectively) that reflect the bi-directional nature of their sand roses (Fig. 2).

This general picture of aeolian transport is in agreement with a recent model of frontal development and associated Great Basin wind patterns outlined by Shafer and Steenburgh (2008). These authors note that cold fronts tend to be relatively rare along the west coast of North America yet relatively common east of the continental divide and the Rocky Mountains (Fig. 4). The Great Basin is thus considered a breeding ground for cold fronts since the number of these events greatly increases going from west to east. In the Great Basin, fronts reach a maximum near the Wasatch Front, which marks the westernmost boundary of the Rocky Mountains physiographic division. The cause of this phenomenon is believed to be the blockage of considerable energy in eastward-moving low-pressure systems by the Sierra Nevada Mountains (Shafer and Steenburgh, 2008). A portion of this energy is funneled south of the Sierra Nevada where it serves to energize eastward-moving cyclones in the eastern Great Basin. The passage of cold fronts in the eastern Great Basin are thus characterized by initially very strong southerly winds in advance of the front and relatively weak westerly winds on the back side of the front the passage of the cold front (Fig. 4).

3.2. Seasonal variability of wind fields and aeolian transport

For all stations examined in this study, winds >6 m/s are most common during the late winter–early spring as is typical of mid-latitude extratropical cyclogenesis (e.g., Whittaker and Horn, 1982; Shafer and Steenburgh, 2008) (Fig. 5). Stations in the western Great Basin show this characteristic most prominently (Fig. 5A, B, D). This seasonal signal is less pronounced in eastern Great Basin localities such as Salt Lake City (Fig. 5C) as well as Milford and Cedar City (not shown). The model of Shafer and Steenburgh (2008) (Fig. 4) attributes the most significant winds to late winter–early spring extratropical cyclones. Southerly monsoon winds during the summer months are observed in Las Vegas (Fig. 5D), but do not appear to be a significant factor in most winds of the Great Basin stations.

3.3. Decadal variability of wind fields and aeolian transport

The DP of the Great Basin for the latter half of the 20th century shows considerable temporal variation. In the extreme cases (e.g., Bishop and Las Vegas) annual DP over the last 50 years of the 20th century varies by four-fold (Fig. 6). Likewise, temporal trends of RDP/DP are extreme at some stations (e.g., Bishop) while remaining relatively constant at others (e.g., Reno and Elko).

Interpretation of these trends within the context of climate observations in the second half of the 20th century is a challenge. Studies of cyclogenesis of North America during this time period have produced a consensus that the annual frequency of cyclogenesis throughout North America decreased during the 1950s, remained low during the 1960s and early 1970s, after which cyclogenesis began to intensify again (Zishka and Smith, 1980; Whittaker and Horn, 1982; Parker et al., 1989; Ebbesmeyer et al., 1991). Assuming that most dune-producing winds are associated with cyclogenesis (Fig. 5A–D), a number of stations in the western Great Basin (China Lake, Reno, Winnemucca, Elko, and Tonopah) track the initial part of this scenario while the eastern Great Basin for the most part does not (Fig. 6). The 1960–1970s lull in cyclogenesis is not readily apparent in any of the DP time series presented here. It is interesting to note that the eastern California stations of Bishop and China Lake show temporal DP patterns that are out of phase with each other (Fig. 6A, B), although a specific explanation for this observation is beyond the scope of this investigation.

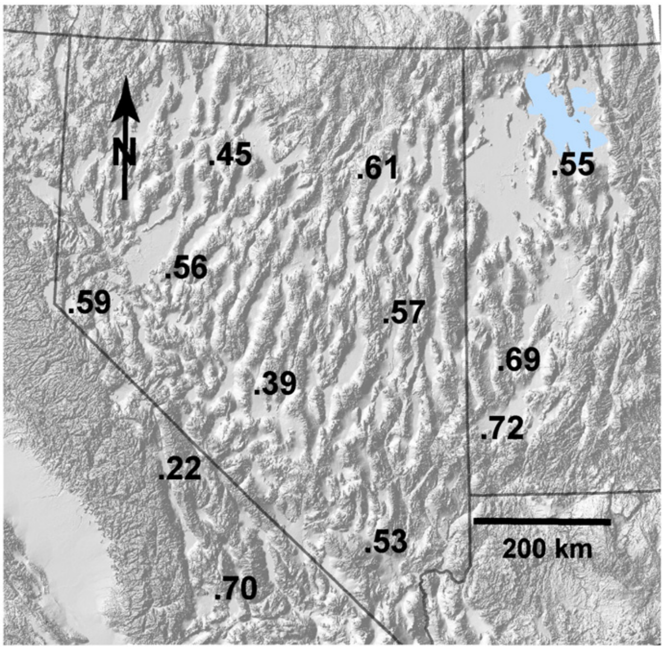

Fig. 3. RDP/RD values in the Great Basin, 1950–2000.

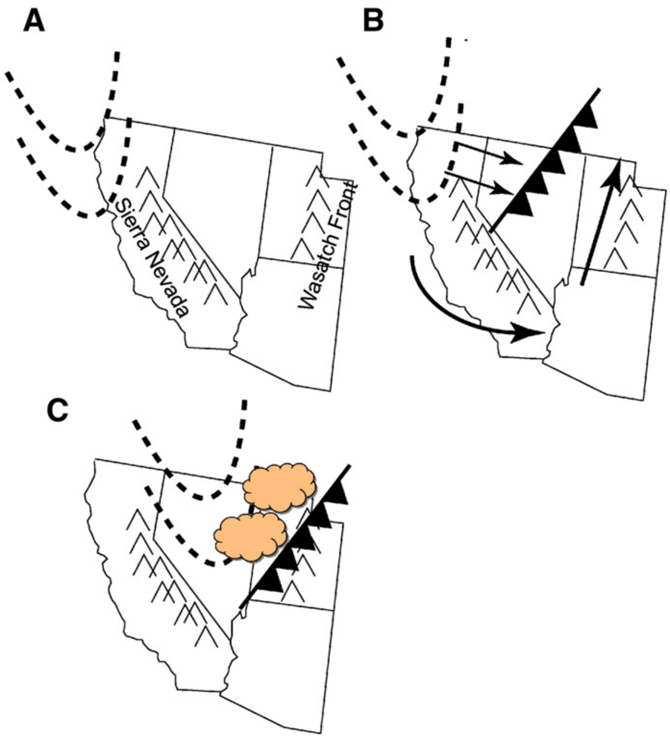

Fig. 4. Cartoon showing cyclogenesis and the development of cold fronts in the Great Basin (from Shafer and Steenburgh, 2008). (A) A upper-level, low-pressure trough (represented as dashed curved lines) approaches the west coast of the U. S. (B) Energy from the low pressure is stalled by the Sierra Nevada Mountains, resulting in strong wind energy developing from the south in the eastern Great Basin. A cold front develops in the central Great Basin. (C) The cold front intensifies along the Wasatch Front and the eastern Great Basin with precipitation formation by frontal strengthening and orographic lifting.

Comprehensive, statistically rigorous studies of North American winds for the latter half of the 20th century have recently been published (Pryor et al., 2007, 2009). This work suggests that for the 1973–2000 period, winds in the eastern and midwestern U.S. showed statistically significant declines whereas the results were more mixed for the western U.S. DP in the Great Basin declines for this same time period for 8 of the 12 stations, although some of the correlations are weak (Fig. 6).

3.4. Great Basin dune fields

The source of saltation loads (which can form dunes) and dust flux to the atmosphere in arid climates of the western U.S. has been traced to alluvial fans, river systems, playas, and defunct pluvial lakes (e.g., Reheis and Kihl, 1995; Muhs et al., 2003; Reynolds et al., 2007; Reheis et al., 2009). While the source of sediment comprising many Great Basin dune fields has not been definitely established, it is most likely derived from these same sedimentary environments. During the Last Glacial Maximum (LGM) there may have been as many as 100 pluvial lakes in the Great Basin (Snyder et al., 1964), suggesting this may have been a primary source of modern dune material. The largest of the pluvial lakes were Lake Bonneville in the eastern side of the Great Basin and Lake Lahonton in the western side. The dry, warm climate of the Holocene dried these lakes out, allowing lacustrine material to become mobilized into sand dunes. Dune formation elsewhere in the western U.S. appears to have peaked from about 8 to 5 ka (Tchakerian and Lancaster, 2002).

Minor aeolian material is ubiquitous throughout the Great Basin (e.g., Morrison, 1964; Dean, 1978) although large dune fields are not

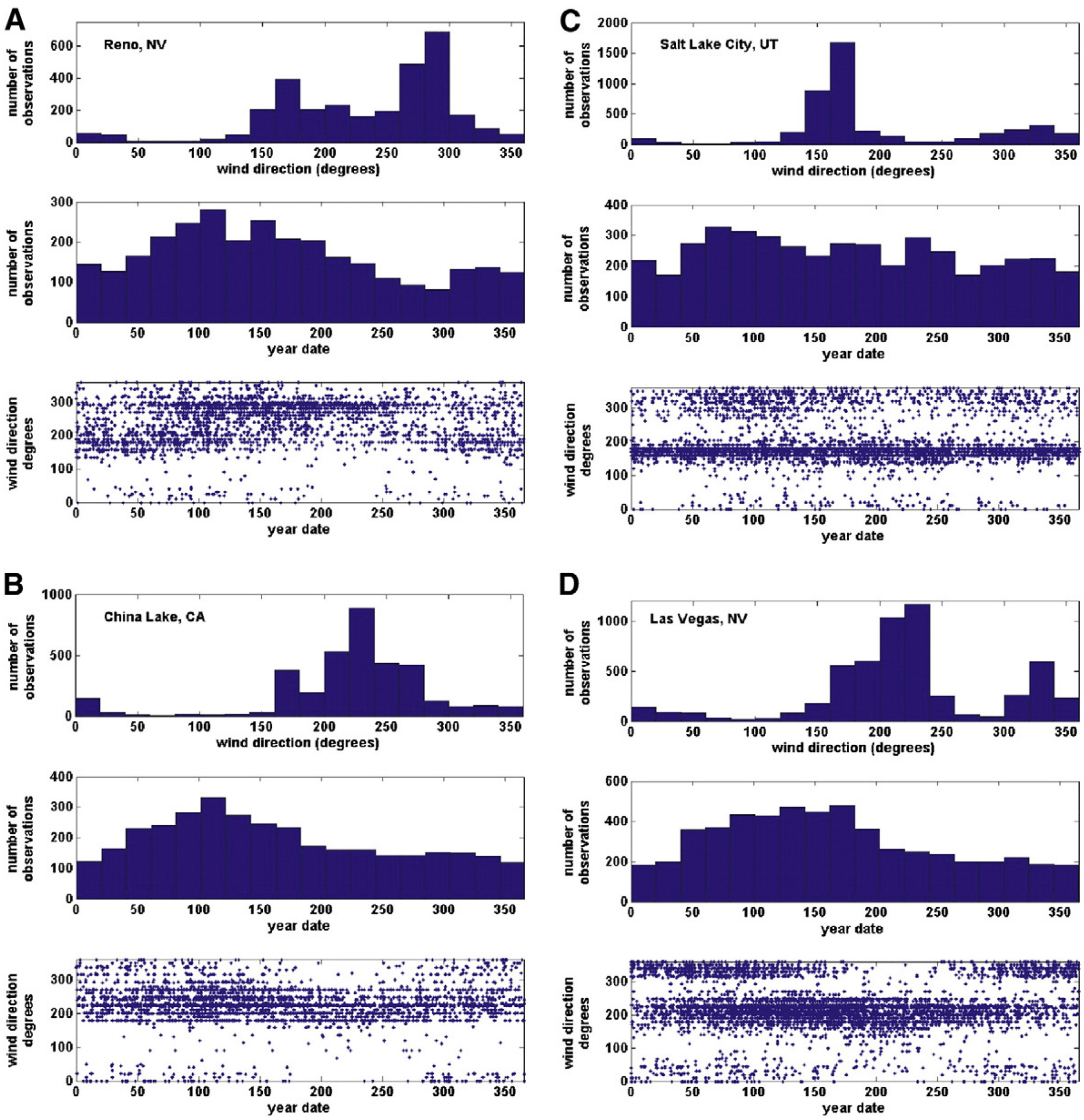

Fig. 5. Summary of seasonal variation of winds >6 m/s for selected meteorological stations of this study. Due to the very large number of data points, a random number generator was used to select ~10% of the total number of measurements shown here. (A) Reno, NV. (B) China Lake, CA. (C) Salt Lake City, UT. (D) Las Vegas, NV.

common as in the Mojave and Sonora regions of North America. For this study, eight significant dune complexes in the Great Basin were identified and characterized (Figs. 7–12; Table 2). An additional dune field (Coral Pink) located in the Great Basin–Colorado Plateau transition zone is included due to its proximity to one of the climate stations (Cedar City) used in this study.

3.4.1. Coral Pink dunes, Utah

The Coral Pink dunes of southwest Utah have a northeast-southwest alignment that parallels the calculated direction of sand motion (Fig. 7). Predominant dune types are traverse and barchanoid ridges (southern half of the dune field) and parabolic dunes (northern half of the dune field) (Ford et al., 2010). The dune sediment appears to be reworked material from nearby Mesozoic sandstones (Smith, 1982; Ford et al., 2010). The direction of dune migration corresponds to the RDP of nearby Cedar City (Fig. 3). Furthermore, the dune material has clearly stabilized between the mid-20th century and 2003 (Wilkins and Ford, 2007), although this trend is only weakly reflected in temporal DP trends at Cedar City (Fig. 6K).

3.4.2. Lynndyl (Little Sahara) dunes, Utah

A major dune complex of the Great Basin is the field known both as Little Sahara (Smith, 1982) and Lynndyl (Sack, 1987) located in west-central Utah. This dune field is derived from sediments left behind by the Sevier River delta of Pleistocene Lake Bonneville in the southern portion of the basin (Sack, 1987). The dune field consists of two separate lobes of accumulated sand that are elongate in a northeast–southwest direction. Barchan and parabolic ridges are the most common dune form (Sack, 1987) (Fig. 8). The north-northeast drift direction corresponds reasonably well with sand roses of Milford and Salt Lake City to the south and north, respectively (Fig. 2). The barchan dune forms are also consistent with high RDP/DP values for the area (Fig. 3). Reduction in the amount of dune material between 1953 and 1997 is apparent on the repeat photos (Fig. 8B, C), which is consistent with the temporally evolving wind pattern of Salt Lake (Fig. 6L), but not Milford (Fig. 6J).

3.4.3. Great Salt Lake Desert dunes, Utah

A series of diverse, widely scattered dune fields is found in the broad Bonneville playa west of the Great Salt Lake in west-central Utah. The most consistent dune area is south of Knolls, Utah (Fig. 9) with smaller dune accumulations common to the north and south of Interstate 80 (Eardley et al., 1957; Eardley, 1962). The dunes are composed of gypsum (Jones, 1953) as well as siliciclastic material and oolites (Dean, 1978). The oolitic material is derived from shorelines of the modern Great Salt Lake, while much of the rest of the material is from Pleistocene Lake Bonneville sediments. Parabolic and traverse morphologies are most common (Dean, 1978) (Fig. 9). Dune drift direction varies considerably over the diverse and widespread dune field, but seems to be predominantly from the southwest (Dean, 1978) matching the drift direction of Salt Lake City.

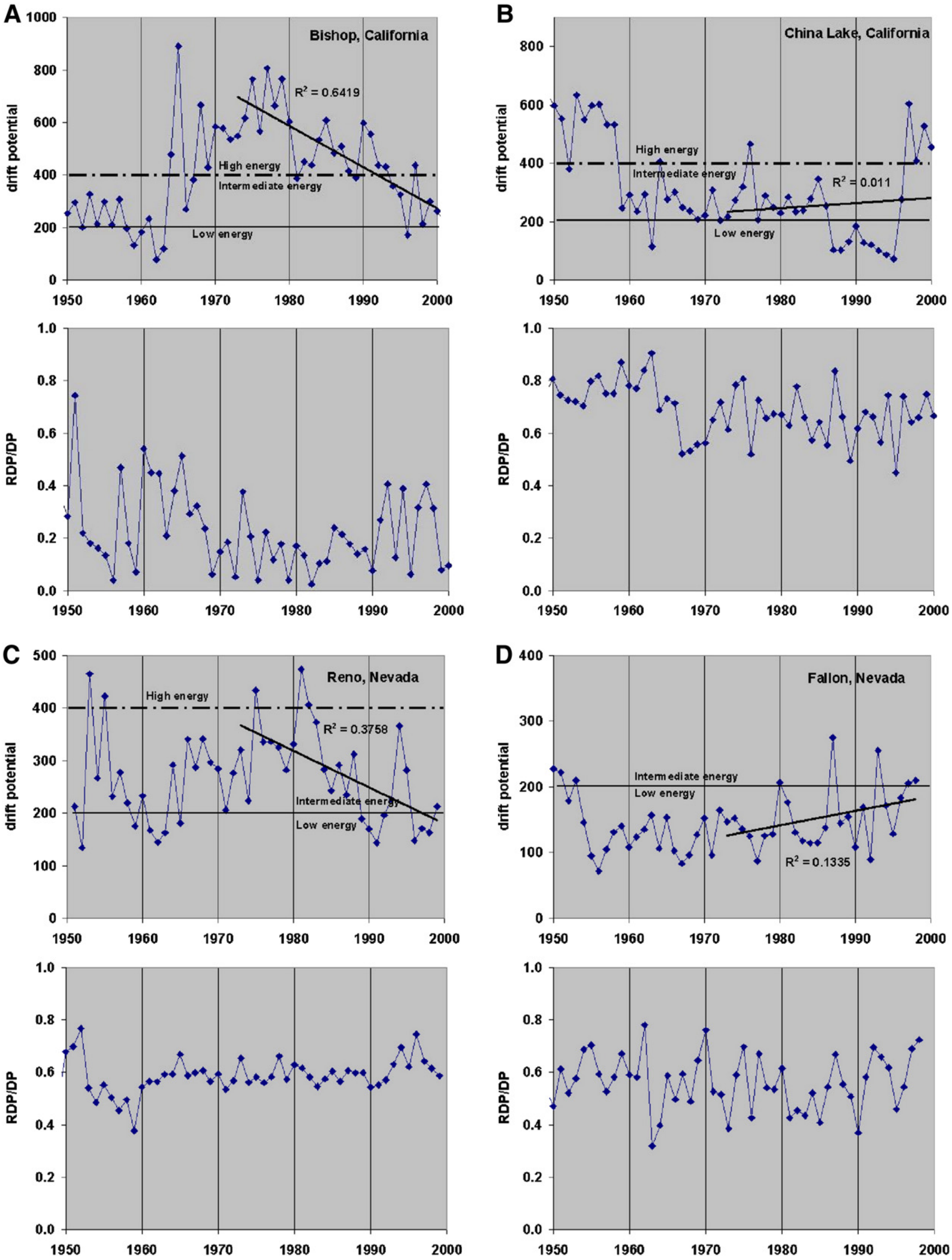

Fig. 6. Decadal variation in DP and RDP/DP for the 12 stations (A–L) of this study. Trendlines for 1973–2000 are shown on all diagrams as a way of evaluating the hypothesis of Pryor et al. (2007, 2009) that wind strength in North America has decreased since 1973.

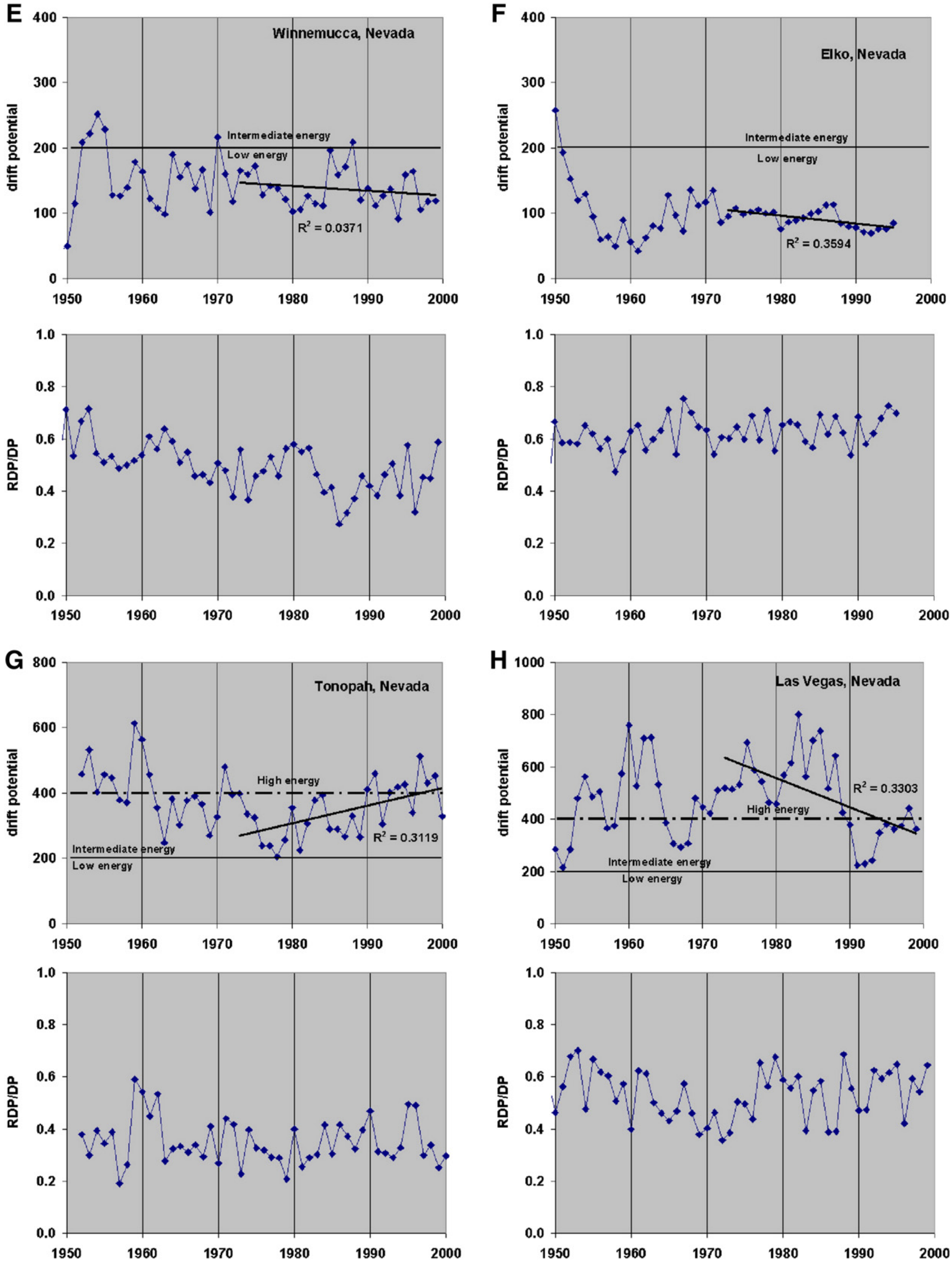

Fig. 6 (*continued*).

3.4.4. Winnemucca dunes, Nevada

An aerially extensive, discontinuous dune field extends across 100 s of square kilometers in an open valley immediately north of Winnemucca, Nevada (Fig. 10) (Smith, 1982). Barchans and some traverse dunes to the north and west transition into individual parabolic dunes spanning a considerable area in the east. The overall area of the dune field is 60 km by 10–15 km, with portions of the area covered by dunes (Smith, 1982). The Winnemucca dunes show very good correspondence with the drift direction of the meteorological station at the Winnemucca Airport (Fig. 2). Like the Little Sahara/Lynndyl

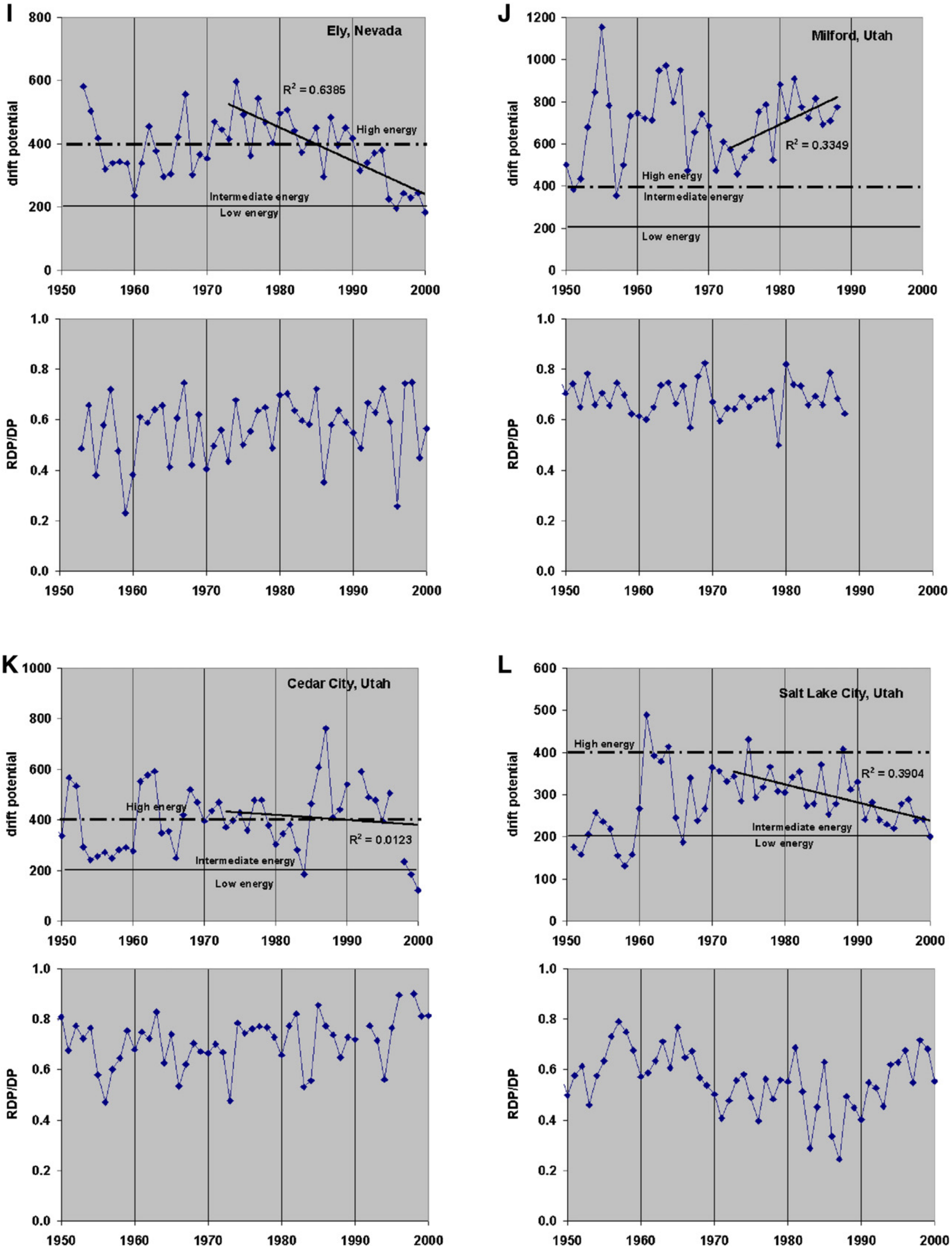

Fig. 6 (*continued*).

dunes, the decrease in DP of northern Nevada (Fig. 6E, F) corresponds with a decrease in observed dune material between 1958 and 2008 (Fig. 10B, C).

3.4.5. Sand Mountain, Nevada

The Sand Mountain deposit east of Fallon features a prominent high topographic dune that is a reversing dune with barchanoid ridges

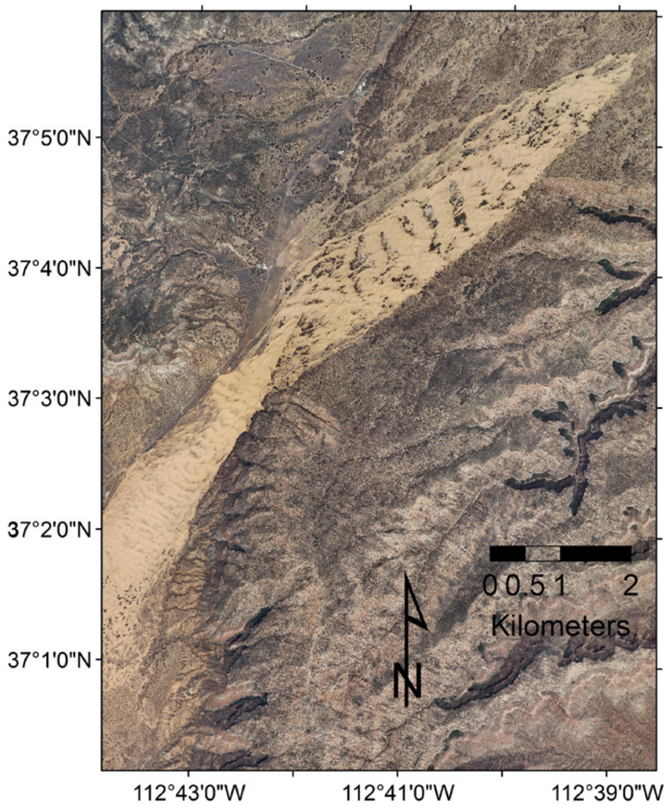

Fig. 7. National Agricultural Imagery Program (NAIP) image of Coral Pink Sand Dunes, Utah.

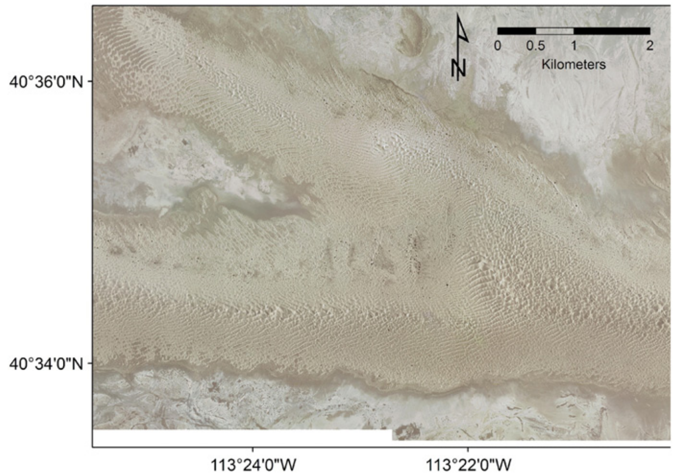

Fig. 9. NAIP image of Great Salt Lake Desert sand dunes near Knolls, Utah.

to the north (Fig. 11). Dune material is probably derived from the remnant Walker River delta of Lake Lahonton (Trexler and Melhorn, 1986). Sand Mountain has been studied from the standpoint of its notable acoustic emissions (Lindsay et al., 1976). The reversing-dune morphology reflects bimodal wind directions that are approximately equal in terms of intensity or duration (McKee, 1979). The dune features of the Sand Mountain area do not correspond particularly well with the sand rose or RDP/DP values for this portion of Nevada, which indicate largely consistent westerly flow (Figs. 2, 3). The dune deposits are immediately south of the prominent Stillwater Range that may exert a local influence on strong winds.

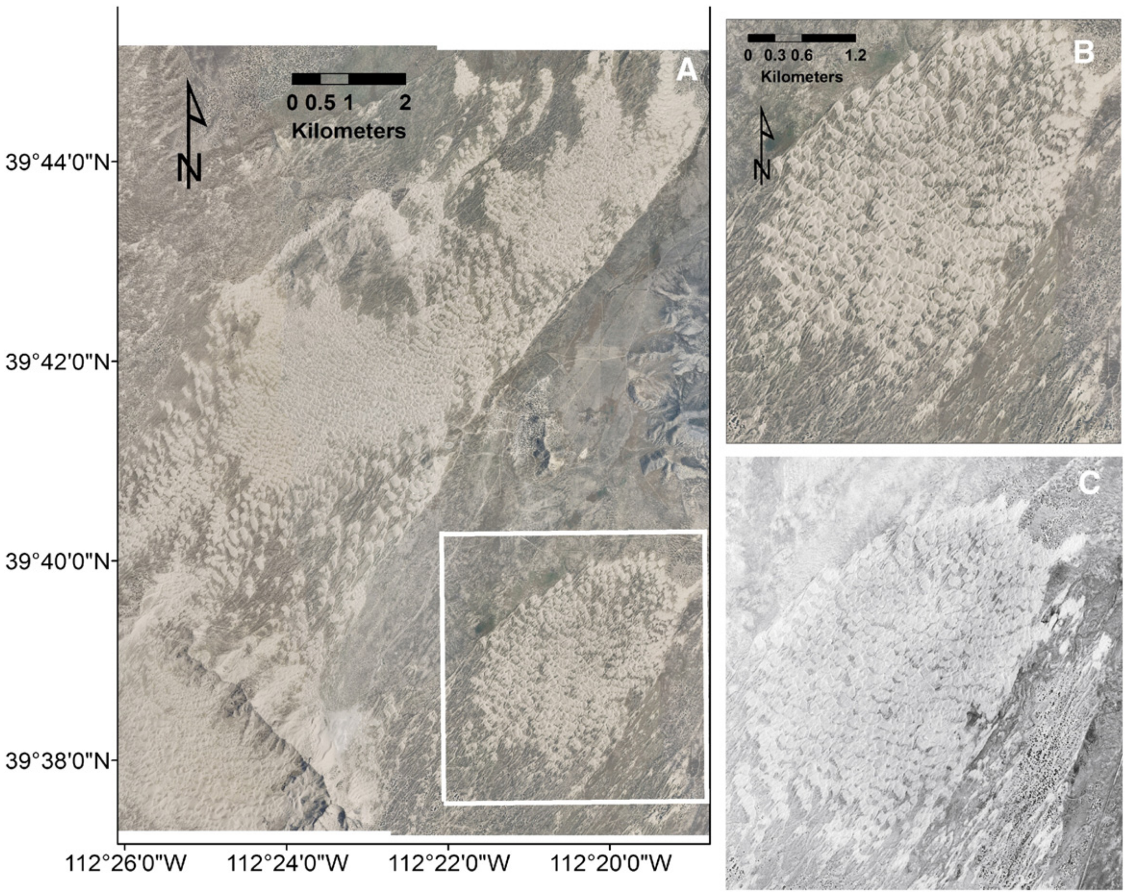

Fig. 8. NAIP image of Lynndyl (Little Sahara) sand dunes, Utah. (A) Overall view. (B) Close-up view of sand dunes in southeastern portion of the field. (C) 1953 image of the same area of (B) (photo from EROS Center of the U. S. Geological Survey).

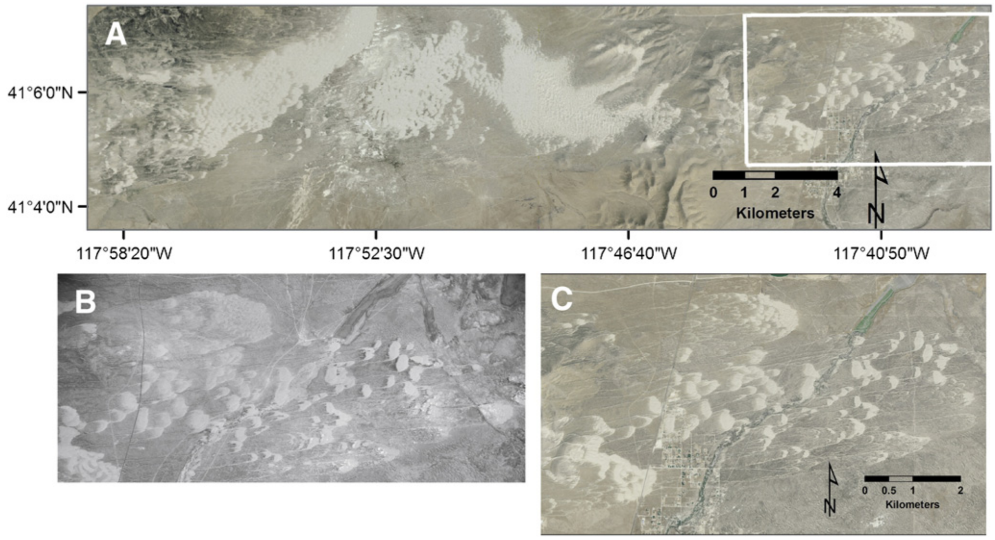

Fig. 10. NAIP image of Winnemucca sand dunes, Nevada. (A) Overall view. (B) 1954 image of the area of parabolic dunes outlined in the southeastern portion of (A) (photo from EROS Center of the U. S. Geological Survey). (C) 2009 close-up view of southeastern portion of the Winnemucca dune field.

3.4.6. Death Valley area dunes

A number of relatively small dunes are found in the Las Vegas–Death Valley area of southern Nevada and southeastern California. The Big Dune (Amargosa) and Clayton Valley sand deposits of southwestern Nevada and the Eureka Valley and Stovepipe Wells deposits of eastern California are all relatively small and have star dunes with minor linear features (Fig. 12, Table 2), reflecting highly variable strong wind directions (McKee, 1979). This is consistent with the low RDP/DP values of the nearby Tonopah and Bishop sand roses, while being less consistent with RDP/DP values at Las Vegas and China Lake (Fig. 3).

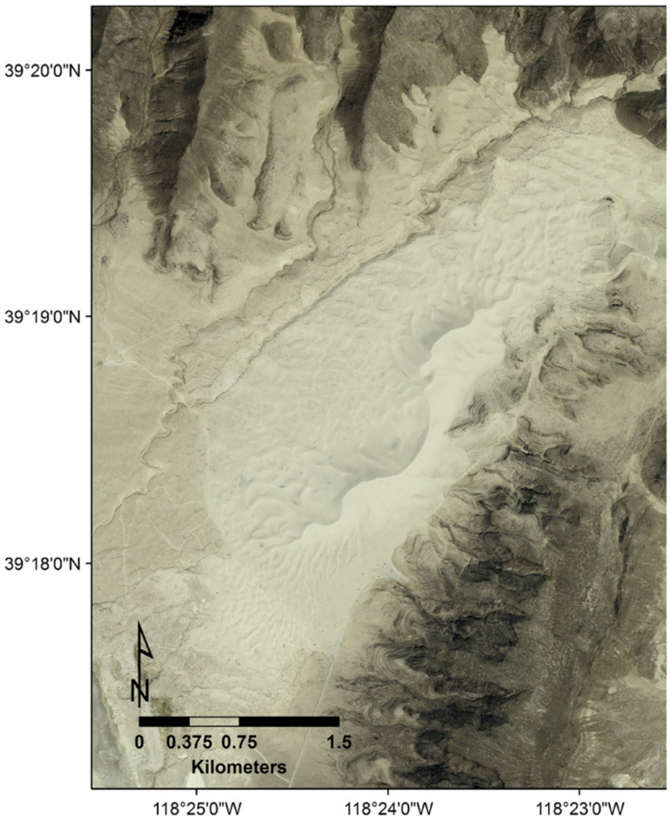

Fig. 11. NAIP image of Sand Mountain, Nevada.

4. Discussion

It is worthwhile placing this preliminary study of Great Basin winds and dunes within the context of other western U.S. dune fields as well as ancient aeolian deposits. Previous studies of sand dunes in western North America include the immense Gran Desierto sand sea of northwestern Mexico (Lancaster et al., 1987; Lancaster, 1990), the Algodones, Kelso, Cadiz, Danby, and Parker dunes of southeastern California and western Arizona (Muhs et al., 1995, 2003; Lancaster and Tchakerian 2003), the Chaco dune field of New Mexico (Wells et al., 1990), the Killpecker dunes of southwestern Wyoming (Mayer and Mahan, 2004), and the Sand Hills of Nebraska (Ahlbrandt and Fryberger, 1980). In general, these dune fields are very large (the order of 10^3–10^4 km^2). By contrast, dune fields in the Great Basin and surrounding areas are 1–2 orders of magnitude smaller, despite having DP values that are roughly equivalent.

The formation of sand dunes is dependent on a supply of sediment, absence of anchoring vegetation, and winds that are sufficiently strong to transport the sediment. Drift potentials (DP) calculated for the Great Basin in this study are not significantly different from published values of other North American localities (Table 3), and are the first for the Great Basin. The drying of numerous pluvial lakes formed during the Last Glacial Maximum in the Great Basin presumably provided plenty of sediment for dune formation. Furthermore, the Great Basin is a region of significant evapotranspiration (e.g., Shevenell, 1999). Thus the lack of Great Basin dune fields of comparable size as found elsewhere in western North America is somewhat puzzling but could be the result of mountain ranges blocking the accumulation of significant amount of sand. The fact that the largest Great Basin dune fields (i.e., Lynndyl, Knolls, and Winnemucca) are found in the lee side of relatively wide, unobstructed valleys (the Sevier Desert, Great Salt Lake Desert, and the 40 km-wide Desert Valley of northwestern Nevada respectively) supports this idea.

Aeolian deposits in the geologic record are often used to infer paleoclimate (e.g., Kocurek, 1999; 2003) and paleowind direction for specific paleogeographic and paleoclimate settings (e.g., Hoque, 1975; Glennie, 1982; Wells, 1983; Tchakerian, 2009). Understanding the direction, duration, and intensity of winds in the geologic record represents a tremendous challenge for paleoclimatologists. Direct evidence of ancient winds is seldom incorporated into the geologic record in a reliable fashion (Allen, 1993). In the past, interpretation of dune deposits in the sedimentary record has led to inferences about

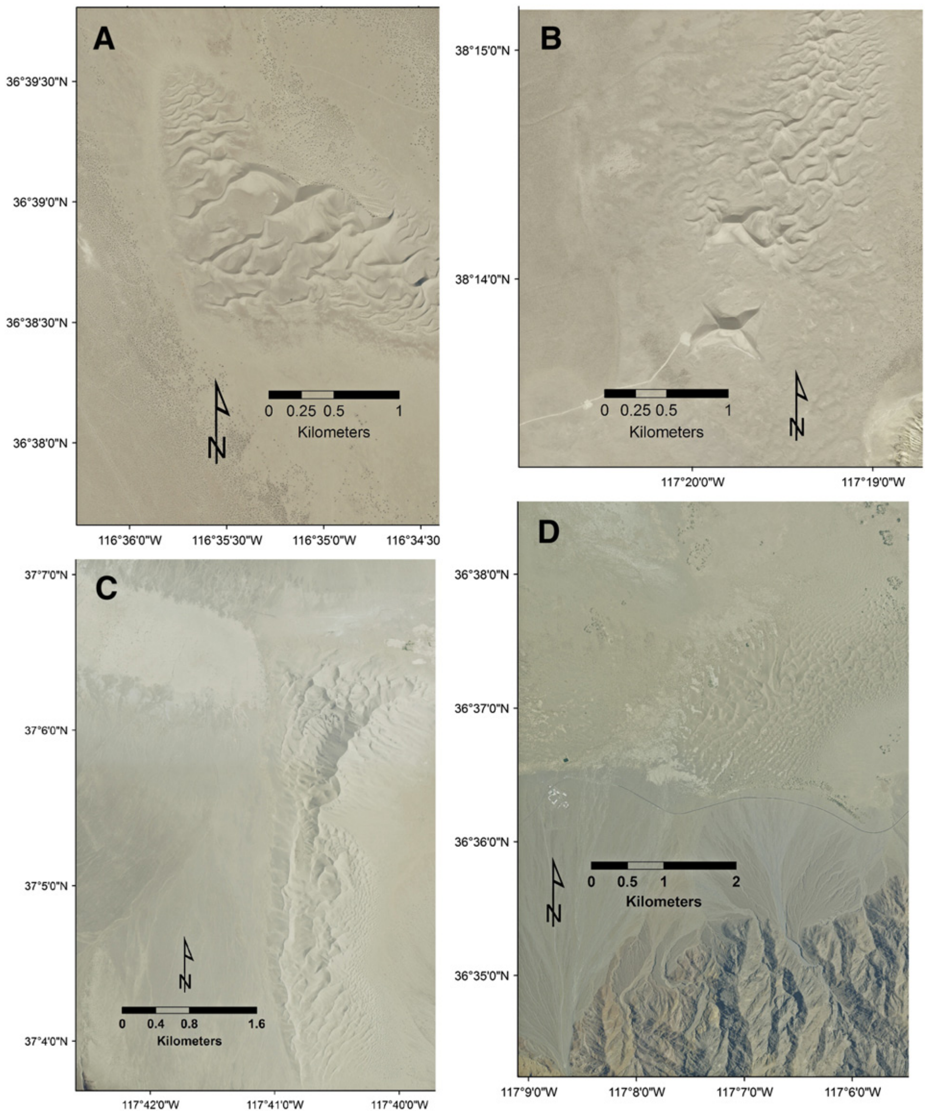

Fig. 12. NAIP image of southern Nevada–eastern California dune fields. (A) Big Dune (Amaragosa), Nevada. (B) Clayton Valley, Nevada. (C) Eureka Valley, California. (D) Stovepipe Wells, Nevada.

Table 2
Summary of dune deposits in the Great Basin.

Dune complex (latitude, longitude)	Approx. size (km^2)	Adjacent meteorological station (50-year ave. DP)	Dune type (RDP/DP)	Sediment source	Reference
Coral Pink, Utah (37°3.5′, 112°42′)	15	Cedar City (413)	Parabolic, transverse (0.73)	Sandstones (Mesozoic)	Wilkins and Ford (2007); Ford et al. (2010)
Lynndyl (Little Sahara), Utah (39°22′, 112°22′)	100	Salt Lake (279); Milford (943)	Parabolic, traverse (0.55, 0.69)	Lake Bonneville (Pleistocene) delta	Smith (1982); Sack (1987)
Great Salt Lake Desert, Utah (40°34.5′, 113°22′)	70	Salt Lake (279)	Parabolic, traverse	Lake Bonneville/Great Salt Lake (Pleistocene–Recent)	Jones (1953); Dean (1978)
Winnemucca, Nevada, (41°6′, 117°, 51.5′)	250	Winnemucca (143)	Parabolic (0.50)	Lake Lahonton (Pleistocene)	Smith (1982)
Sand Mountain Nevada, (39°19′, 118°24′)	10	Fallon (171)	Star, linear (0.53)	Lake Lahonton (Pleistocene) delta	Lindsay et al. (1976); Smith (1982); Trexler and Melhorn (1986)
Big Dune (Amargosa), Nevada (36°39′, 116°34′)	5	Las Vegas (480); Tonopah (385)	Star (0.53, 0.34)	Local alluvial system?	Smith (1982)
Clayton Valley, Nevada, (36°39.5′, 117°37′)	3	Tonopah (385)	Star, linear (0.34)	Local playa/alluvial system	Smith (1982); Trexler and Melhorn (1986)
Eureka Valley, California, (37°6′, 117°41′)	13	Bishop (331); Tonopah (385)	Star, linear (0.11, 0.34)	Local alluvial system?	Smith (1982); Trexler and Melhorn (1986)
Stovepipe Wells/Mesquite Flat, California, (36°37′, 117°7′)	8	China Lake (401); Las Vegas (385)	Star, linear (0.69, 0.53)	Local alluvial system?	Smith (1982)

Table 3
Summary of dune size and drift potentials of the three largest Great Basin dune fields and adjacent dune fields of western North America.

Dune complex	Adjacent meteorological station	Size (km^2)	Drift potential	Reference
Algodones, southern California	El Centro, California	3200	392, 525	Fryberger and Dean (1979); Muhs et al. (1995)
Algodones, southern California	Yuma, Arizona	3200	87	Muhs et al. (1995)
Gran Desierto, northern Mexico	Yuma, Arizona	5500	87	Muhs et al. (1995)
Coral Pink	Cedar City, Utah	15	413	This study
Little Sahara, Utah	Milford, Salt Lake City, Utah	310	687, 279	This study
Winnemucca, Nevada	Winnemucca, Nevada	~750	143	This study

prevailing wind directions and ancient wind fields (e.g., see summary in Kocurek, 1989). The modern drift directions in the modern Great Basin reflect the prevailing westerly winds in the western portion of the basin, as would be expected in temperate latitudes. However, the modern drift direction and dominant dune orientation is north to northeasterly in the eastern portion of the Great Basin. These are a result of the peculiar geography of the Great Basin–Sierra Nevada mountain system and not simply a function of the prevailing zonal wind patterns. This heretofore undocumented observation has implications for interpreting paleooclimates: if ancient aeolian systems were similarly influenced by local geographic attributes, their paleoclimatic interpretations may be entirely too simplistic.

5. Conclusions

As mentioned previously, Fryberger and Dean (1979) classify the annual DP>400 to represent a high wind environment, DP between 200 and 400 to be an intermediate wind environment, and DP<200 to be a low wind environments. Using these criteria, most of the Great Basin and surrounding areas is considered to be a modest to somewhat high wind energy environment over a 50-year period from 1950 to 2000 (Fig. 2; Table 1).

The results of this study fit the general conclusions of other studies of synoptic meteorology, decadal climate patterns, and aeolian sedimentology of western North America, while at the same time pointing out the need for more detailed studies of both local wind regimes and individual dune deposits. In general, winds capable of moving sand deposits in the Great Basin are relatively rare in the western portion where there is a prevailing east-northeast drift direction. Sand deposits in this portion of the Great Basin reflect this wind pattern. In the eastern portion of the Great Basin, surface winds intensify and the sand drift direction becomes more persistent in a north to northeasterly direction. The general features of strong winds and dune generation presented here are consistent with current understanding of meteorologists regarding cold front generation and evolution in the Great Basin. Extratropical cyclones entering the Great Basin have a portion of their energy deflected to the south around the southern end of the Sierra Nevada Mountains where that energy eventually intensifies storms in the eastern portion of the Great Basin and produces very strong southerly flow (Shafer and Steenburgh, 2008).

This study represents one of the first efforts to study dune fields within a large, geographically diverse area in the context of an extended period (50 years) of wind records. While drift potentials have varied considerably over this length of time, it is difficult to relate these changes to specific climate changes suggested for North America between 1950 and 2000. Results of this study demonstrate that a region of complex topography can alter drift directions and dune morphology, confounding the interpretation of paleowind directions in ancient aeolian sedimentary deposits. Hence, a measure of caution is essential to the accurate interpretation of ancient aeolian strata; reconstructions should consider how regional physiographic contexts may have influenced climate-controlled geomorphic surface processes.

Acknowledgments

Jim Steenburgh challenged our initial thoughts of winds in the Great Basin and greatly increased our understanding of regional meteorology of the Intermountain West. John Horel read the manuscript and offered helpful suggestions. An initial version of this manuscript and the present version benefited from the suggestions of four anonymous reviewers. Initial support for the work on this paper was provided by the National Science Foundation Grant EAR-9809241.

References

Ahlbrandt, T.S., Fryberger, S.G., 1980. Aeolian deposits in the Nebraska Sand Hills. U.S. Geological Survey Professional Paper 1120-A 24 pp..
Alhlbrandt, T.S., Swinehart, J.B., Maroney, D.G., 1983. The dynamic Holocene dune fields of the Great Plains and Rocky Mountain basin, U.S.A. In: Brookfield, M.E., Ahlbrandt, T.S. (Eds.), Aeolian Sediments and Processes. Elsevier, New York, pp. 379–406.
Allen, J.R.L., 1993. Paleowind: geological criteria for direction and strength. Philosophical Transactions of the Royal Society of London B341, 235–242.
Archer, C.A., Jacobson, M.Z., 2003. Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements. Journal of Geophysical Research 108 (D9), 4289. doi:10.1029/2002JD002076.
Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Chapman and Hall, London.
Bullard, J.E., 1997. A note on the use of the "Fryberger Method" for evaluating potential sand transport by wind. Journal of Sedimentary Research 67, 499–501.
Bullard, J.E., Thomas, D.S.G., Livingston, I., Wiggs, G.F.S., 1996. Wind energy variations in the southwestern Kalahari desert and implications for linear dune field activity. Earth Surface Processes and Landforms 21, 263–278.
Cairns, M.M., Corey, J., 2003. Mesoscale model simulations of high wind events in the complex terrain of western Nevada. Weather and Forecasting 18, 249–236.
Dean, L.E., 1978. Eolian dunes of the Great Salt Lake basin. Utah Geology 5, 103–111.
Deganto, A.T., 1997. A quality control routine for hourly wind observations. Journal of Atmospheric and Oceanic Technology 14, 308–317.
Eardley, A.J., 1962. Gypsum dunes and evaporite history of the Great Salt Lake Desert. Utah Geological and Mineralogical Survey Special Studies 2, 3–27.
Eardley, A.J., Gvosdetsky, V., Marsell, R.E., 1957. Hydrology of Lake Bonneville and sediments and soils of its basin. Geological Society of America Bulletin 68, 1141–1201.
Ebbesmeyer, C.C., Cayan, D.R., McLain, D.R., Nichols, F.H., Peterson, D.H., Redmond, K.T., 1991. 1976 step in the Pacific climate: forty environmental changes between 1968–1975 and 1977–1984. Proceedings of the 7th Annual Pacific Climate (PACLIM) Workshop. California Department of Water Resources, pp. 115–126.
Ford, R.L., Gillman, S.L., Wilkins, D.E., Clement, W.P., Nicoll, K., 2010. Geology and geomorphology of Coral Pink Sand Dunes State Park. In: Sprinkel, D.A., Chidsey, T.C., Anderson, P.B. (Eds.), Geology of Utah's Parks and Monuments: Utah Geological Association Publication, 28, pp. 379–406.
Fryberger, S.G., Dean, G., 1979. Dune forms and wind regime. U.S. Geological Survey Professional Paper 1052-F, 137–169.
Gaylord, D.R., Dawson, P.J., 1987. Airflow terrain interactions through a mountain gap, with example of aeolian activity beneath an atmospheric hydraulic jump. Geology 15, 789–792.
Glennie, K.W., 1982. Early Permian (Rotliegendes) paleowinds of the North Sea. Sedimentary Geology 34, 245–265.
Hoque, M., 1975. An analysis of cross-stratification of Gargaresh Calcerenite (Tripoli, Libya) and Pleistocene paleowinds. Geological Magazine 112, 393–401.
Jones, D.J., 1953. Gypsum-oolite dunes, Great Salt Lake desert, Utah. American Association of Petroleum Geologists Bulletin 37, 2530–2538.
Klink, K., 1999. Climatological mean and interannual variance of United States surface wind speed and velocity. International Journal of Climatology 19, 471–488.
Klink, K., 2002. Trends and interannual variability of wind speed distributions in Minnesota. Journal of Climate 15, 3311–3317.
Knapp, P.A., 1994. Seasonal associations between mid-tropospheric pressure patterns and precipitation in the western Great Basin. Climate Research 4, 75–78.
Kocurek, G.A., 1989. Desert aeolian systems. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, Oxford, pp. 125–153.

Kocurek, G.A., 1999. The aeolian rock record (Yes, Virginia, it exists, but it is really rather special to create one). In: Goudie, A.S., Livingstone, I., Stokes, S. (Eds.), Aeolian Environments, Sediments, and Landforms. New York, Wiley and Sons, pp. 239–259.
Kocurek, G.A., 2003. Limits on extreme eolian systems: Shara of Mauritania and Jurassic Navajo Sandstone examples. In: Chan, M.A., Archer, A.W. (Eds.), Extreme depositional environments: mega end members in geologic time: Geological Society of America Special Paper, 370, pp. 43–52.
Lancaster, N.R., 1990. Paleoclimatic evidence from sand seas. Paleoceanography, Paleoclimatology, Paleoecology 76, 279–290.
Lancaster, N.R., Tchakerian, V.P., 2003. Late Quaternary aeolian dynamics, Mojave Desert, California. In: Enzel, Y., Wells, S.G., Lancaster, N. (Eds.), Paleoenvironments and paleohydrology of the Mojave and southern Great Basin deserts: Geological Society of America Special Paper, 368, pp. 231–249.
Lancaster, N., Greelely, R., Christensen, P.R., 1987. Dunes of the Gran Desierto sand-sea, Sonoro, Mexico. Earth Surface Processes and Landforms 12, 277–288.
Lindsay, J.F., Criswell, D.R., Criswell, T.L., Criswell, B.S., 1976. Sound-producing dune and beach sands. Geological Society of America Bulletin 87, 463–473.
Mayer, J.H., Mahan, S.A., 2004. Late Quaternary stratigraphy and geochronology of the western Killpecker dunes, Wyoming, U.S.A. Quaternary Research 61, 72–84.
McKee, E.D., 1979. Introduction to a study of global sand seas. U.S. Geological Survey Professional Paper 1052-F, 1–19.
Morrison, R.B., 1964. Lake Lahontan—geology of the southern Carson Desert, Nevada. U.S. Geological Survey Professional Paper, 401. 156 pp.
Muhs, D.R., Bush, C.A., Cowherd, S.D., Mahan, S., 1995. Geomorphic and geochemical evidence for the source of sand in the Algodones dunes, Colorado desert, southeastern, California. In: Tchakerian, V.P. (Ed.), Desert aeolian Processes. Chapman and Hall, London, pp. 37–74.
Muhs, D.R., Reynolds, R.L., Been, J., Skipp, G., 2003. Eolian sand transport pathways in the southwestern United States: importance of the Colorado River and local sources. Quaternary International 104, 3–18.
Parker, S.S., Hawes, J.T., Colucci, S.J., Hayden, B.P., 1989. Climatology of 500 mb cyclones and anticyclones, 1950–1985. Monthly Weather Review 117, 558–570.
Pearce, K.I., Walker, I.J., 2005. Frequency and magnitude biases in the 'Fryberger' model, with implications for characterizing geomorphically effective winds. Geomorphology 68, 39–55.
Pryor, S.C., Barthelmie, R.J., Riley, E.S., 2007. Historical evolution of wind climates in the U.S.A. Journal of Physics: Conference Series 75, 1–8.
Pryor, S.C., Barthelmie, R.J., Young, D.T., Takle, E.S., Arritt, R.W., Flory, D., Gutowski Jr., W.J., Nunes, A., Roads, J., 2009. Wind trends over the contiguous United States. Journal of Geophysical Research 114, D14105.
Reheis, M.C., Kihl, R., 1995. Dust deposition in southern Nevada and California, 1984–1989: relations to climate, source area, and source lithology. Journal of Geophysical Research 100, 8893–8918.
Reheis, M.C., Budahn, J.R., Lamothe, P.J., Reynolds, R.L., 2009. Compositions of modern dust and surface sediments in the Desert Southwest, United States. Journal of Geophysical Research 114, F01028.
Renewable Energy World, 2009. 200-MW of Milford Wind Project Completed.
Reynolds, R.L., Yount, J.C., Reheis, M., Goldsein, H., Chavez Jr., P., Fulton, R., Whitney, J., Fuller, C., Forester, R.M., 2007. Dust emission from wet and dry playas in the Mojave Desert, USA. Earth Surface Processes and Landforms 32, 1811–1827.
Sack, D., 1987. Geomorphology of the Lynndyl dunes, west-central Utah, in Cenozoic geology of western Utah — sites for precious metal and hydrocarbon accumulations. Utah Geological Association Publication 16, 291–299.
Saqqa, W., Atallah, M., 2004. Characterization of the aeolian terrain facies in Wadi Araba Desert, southwestern Jordan. Geomorphology 62, 63–87.
Shafer, J.C., Steenburgh, W.J., 2008. Climatology of strong intermountain cold fronts. Monthly Weather Review 136, 784–807.
Shevenell, L., 1999. Regional potential evapotranspiration in arid climates base in temperature, topography, and calculated solar radiation. Hydrology Processes 17, 577–596.
Smith, R.S.U., 1982. Sand dunes in the North American deserts. In: Beder, G.L. (Ed.), Reference Handbook on the Deserts of North America. Greenwood Press, London, pp. 481–524.
Snyder, C.T., Hardman, G., Zdenek, F.F., 1964. Pleistocene lakes in the Great Basin. U. S. Geological Survey Misc. Geol. Investigations, Map I-416.
Stewart, J.Q., Whiteman, C.D., Steenburgh, W.J., Bian, X., 2002. A climatological study of thermally driven wind systems of the U. S. Intermountain West. Bulletin of the American Meteorological Society 83, 699–708.
Tchakerian, V.P., 2009. Paleoclimatic interpretations from desert dunes and sediments. In: Abrahams, A.D., Parsons, A.J. (Eds.), Geomorphology of Desert Environments. Chapman and Hall, London, pp. 757–772.
Tchakerian, V.P., Lancaster, N., 2002. Late Quaternary arid/humid cycles in the Mojave desert and western Great Basin of North America. Quaternary Science Reviews 21, 799–810.
Trexler, D.T., Melhorn, W.N., 1986. Singing and booming sand dunes of California and Nevada. California Geology 39, 147–152.
Wang, X., Dong, Z., Yan, P., Zhang, J., Qian, G., 2005. Wind energy environments and dune field activity in the Chinese deserts. Geomorphology 65, 33–48.
Wells, G.L., 1983. Late-glacial circulation over central North America revealed by aeolian features. In: Street-Perott, A. (Ed.), Variations in the Global Water Budget. D. Reidel Publishing Company, pp. 317–330.
Wells, S.G., McFadden, L.D., Schultz, J.D., 1990. Aeolian landscape evolution and soil formation in the Chaco dune field, southern Colorado Plateau, New Mexico. Geomorphology 3, 517–546.
Whittaker, L.M., Horn, L.H., 1982. Geographical and seasonal distribution of North American cyclogenesis, 1958–1977. Monthly Weather Review 109, 2312–2322.
Wilkins, D.E., Ford, R.L., 2007. Nearest neighbor methods applied to dune field organization: the Coral Pink Sand Dunes, Kane County, Utah, USA. Geomorphology 83, 48–57.
Zishka, K.M., Smith, P.J., 1980. The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950–77. Monthly Weather Review 108, 387–401.
Zu, R., Xian, X., Mingrui, Q., Bao, Y., Jianjun, Q., Kecun, Z., 2008. Characteristics of near-surface wind regimes in the Taklimakan Desert, China. Geomorphology 96, 39–47.