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Regional and climatic controls on seasonal dust deposition in the southwestern U.S.

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ABSTRACT

Vertical dust deposition rates (dust flux) are a complex response to the interaction of seasonal precipitation, wind, changes in plant cover and land use, dust source type, and local vs. distant dust emission in the southwestern U.S. Seasonal dust flux in the Mojave–southern Great Basin (MSGB) deserts, measured from 1999 to 2008, is similar in summer–fall and winter–spring, and antecedent precipitation tends to suppress dust flux in winter–spring. In contrast, dust flux in the eastern Colorado Plateau (ECP) region is much larger in summer–fall than in winter–spring, and twice as large as in the MSGB. ECP dust is related to wind speed, and in the winter–spring to antecedent moisture. Higher summer dust flux in the ECP is likely due to gustier winds and runoff during monsoonal storms when temperature is also higher. Source types in the MSGB and land use in the ECP have important effects on seasonal dust flux. In the MSGB, wet playas produce salt-rich dust during wetter seasons, whereas antecedent and current moisture suppress dust emission from alluvial and dry-playa sources during winter–spring. In the ECP under drought conditions, dust flux at a grazed-and-plowed site increased greatly, and also increased at three annualized, previously grazed sites. Dust fluxes remained relatively consistent at ungrazed and currently grazed sites that have maintained perennial vegetation cover. Under predicted scenarios of future climate change, these results suggest that an increase in summer storms may increase dust flux in both areas, but resultant effects will depend on source type, land use, and vegetation cover.

1. Introduction

The generation, transport, and deposition of aeolian dust comprise an important set of geomorphic, atmospheric, and ecologic processes in the drylands of the southwestern U.S. (Belnap et al., 2000, 2009; Field et al., 2009; Reheis et al., 2009; Reynolds et al., 2001). However, the significance of dust for landscapes and ecosystems has been less well studied at the regional scale compared to the recognition of global effects of Saharan and Asian dust sources, which are much larger (Mahowald et al., 2007; Prospero et al., 2002). Globally, atmospheric dust affects climate through its influence on radiation (Tegen, 2003), and may suppress rainfall (Han et al., 2008). Regionally, dust storms impact economies by obscuring visibility, causing health problems, and stripping agricultural soils.

Atmospheric modeling based on forecasts of greenhouse gas emissions suggests that the southwestern U.S. and adjacent Mexico will be persistent future climate "hotspots" (Diffenbaugh et al., 2008; McAfee and Russell, 2008) with consequences for dust generation. Many studies have shown a close correspondence of drought years to increased dust generation (summarized in Pye, 1987), others noted that delivery of fresh sediment by runoff from enhanced precipitation yields increased dust flux (e.g., McTainsh et al., 1999; Bullard and Livingstone, 2002; Mahowald et al., 2007), and some showed that dust flux from shallow groundwater sources increased during wet years (Okin and Reheis, 2002; Reheis, 2006). Land use policies may exacerbate the effects of projected future warming. Sediment cores recovered from alpine lakes downwind of southwestern drylands show strong evidence for large increases in dust flux during the past ~150 years due to land use impacts, especially grazing (Neff et al., 2008) and industrialization (Reynolds et al., 2009b), and other studies document similar effects (Belnap et al., 2009; Lee et al., 1993; Schlesinger et al., 1990). Thus, it is increasingly important to understand the conditions that influence dust emissions in the southwest in order to forecast future emissions and to provide input to land management decisions that mitigate or exacerbate emissions. Long-term dust monitoring at sites that show the different responses of dust sources to climatic events is needed to evaluate these complex responses.

In this study, seasonal vertical deposition rates (dust flux) are measured by marble traps in the Mojave and southern Great Basin Deserts (MSGB) and the eastern Colorado Plateau (ECP) from 1999 to 2008. We explore the relations among dust flux, seasonal precipitation, periods of drought, wind, land use, and dust source type.

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2. Study sites, materials, and methods

2.1. Site characteristics

The study areas exhibit a range of vegetation types, including exotic invasive annual plants. The annual extent of these plants in areas previously characterized by extensive bare ground (e.g., CM6 and CM7) or by perennial grasses (ECP sites) has greatly increased the variability in susceptibility to local wind erosion at some sites. At most of the MSGB sites, all at elevations below 1350 m and mostly below 1000 m (Table 1), vegetation is predominantly scattered creosote bush (*Larrea tridentata*) and desert saltbush (*Atriplex* sp.) with an understory of annual and perennial forbs and grasses, and subordinate amounts of invasive annual plants, mainly cheatgrass (*Bromus* sp.). Three sites are located at higher elevations in sparse to lush joshua tree-yucca (*Yucca brevifolia–Yucca* sp.) woodlands: T18, T23, and T29. Most sites are located on gravelly alluvial fans or colluvium with well-developed desert pavement.

The CM sites around Soda Lake (Fig. 1) are distinguished by their proximity to Soda Lake and the aeolian sand transport corridor to the south. This east–west corridor is dominated by sand sheets and dunes and provides a continuous pathway for delivery of aeolian sand derived from the Mojave River Sink on the west to the Kelso Dunes to the east (Sharp, 1966). The plant community of CM5, in a playa-fan marginal setting, is saltbush scrub. At CM6, on sandy alluvial and aeolian deposits, a former creosote-bush community has died, and the site is now dominated by invasive annual plants, mainly Mediterranean grass (*Schismus barbatus*). Site CM7, with many small dunes anchored by saltbush and creosote bush, has also been invaded, mainly by Mediterranean grass and tumbleweed (*Salsola* sp.) (Urban et al., 2009; R. Fulton, Calif. State Univ. Fullerton, http://esp.cr.usgs.gov/info/sw/clim-met/, accessed 11/05/2010).

The ECP sites, at higher altitudes (Table 1), are located in formerly perennial grasslands with scattered shrubs (mainly Mormon tea, *Ephedra viridis*; blackbrush, *Coleogyne ramosissima*; and winterfat, *Ceratoides lanata*) and nearby stands of pinyon–juniper (*Pinus edulis–Juniperus osteosperma*) woodland. ECP sites have been affected more or less by the historic arrival of invasive annual plants, including cheatgrass (*Bromus tectorum*), tumbleweed (*Salsola kali*), and at CM4, musk mustard (*Chorispora tenella*) (M. Miller, National Park Service, Moab, Utah, http://esp.cr.usgs.gov/info/sw/clim-met/, accessed 11/05/2010). CM4 is the most severely invaded site, with CM3 second. More shrub cover is present at sites CM8 and CP3.

All sites in both areas were grazed in the past (Table 2), except that CM2 in Canyonlands National Park was never grazed due to inaccessibility. Land use histories are similar among the MSGB sites, most of which are not currently grazed by livestock. The ECP sites have undergone significant changes in land-use history. Overgrazing converted native perennial grassland at site CM3 into one now dominated by native and invasive annuals with mostly bare plant interspaces (Belnap et al., 2009). Site CP4, previously

Table 1
Site locations, nearest dust source, land use, and nearby weather stations (see Tables DR-2A and B for weather station data).

Site	Name	Latitude (N)	Longitude (W)	Altitude (m)	Nearest weather stations[a]	Source type or land use[b]
Mojave—southern Great Basin (MSGB) sites						
T1–5	Fortymile Wash	36.89	116.36	1235	4Ja-n, Beatty, Mercury, *SORD 26*	Alluvium
T9	Jackass Flat	36.79	116.46	952	4Ja-n, *Amargosa Valley*, Beatty, Mercury, *SORD 26*	Alluvium
T10	Amargosa Flat	36.52	116.11	805	4Ja-n, Amargosa Farms, *Amar. Valley*, Mercury, *Pahrump*	Dry playa
T11	Funeral Range East	36.63	116.74	903	Amar. Farms, *Amar. Valley*, Beatty, Death Valley, *SORD 26*	Alluvium
T12	Funeral R. crest	36.76	116.91	1098		Wet playa
T13	Amargosa Desert	36.67	116.67	793	4Ja-n, Amargosa Farms, *Amargosa Valley*, Beatty, Death Valley, *SORD 26*	Alluvium
T14	Crater Flat	36.73	116.56	851		Alluvium
T16	Lower Kyle Canyon	36.38	115.32	839	Desert NWR, Las Vegas, Mercury, Red Rocks Canyon, *Yucca Gap*	Alluvium
T18	Upper Kyle Canyon	36.31	115.44	1318		Alluvium
T23	McCullough Mtns.	35.54	115.07	1327	*Mid Hills*, Mtn. Pass, Searchlight	Alluvium
T28	Kelso Dunes	34.95	115.61	921	Baker, Mojave Sink, *Mid Hills*, Mitchell Caverns	Alluvium
T29	Cima Volcanics	35.26	115.73	1257		Wet playa
T30	Lower Silver Lake	35.32	116.12	290	Baker, *Mojave River Sink*, *CM5*	Dry playa
T31	Upper Silver Lake	35.31	116.14	366		Dry playa
T33	Tecopa South	35.82	116.20	512	Am. Farms, Am. Valley, Death Valley, *Horse Thief Springs*, Shoshone, *Tecopa*	Wet playa
T34	Tecopa East	35.97	116.23	525		Wet playa
T69	Eagle Mountain	36.23	116.36	613	Death Valley, *Pahrump*, Shoshone, *Tecopa*	Wet playa
CM5	North Soda Lake	35.22	116.07	282	Baker, *CM5*	Dry playa
CM6	Balch	35.03	115.97	353	*CM6*, *Mojave River Sink*	Alluvium
CM7	Crucero	35.05	116.15	308	*CM7*, *Mojave River Sink*	Alluvium
Eastern Colorado Plateau (ECP) sites						
CM2	Virginia Park	38.09	109.84	1716	The Needles, *CM2*	Never grazed
CM3	Needles Housing	38.16	109.76	1497	The Needles, *CM3*	Prev. grazed
CM4	Dugout Ranch	38.14	109.61	1542	The Needles, *CM4*	Grazed, prev. plowed
CM8	Corral Pocket	38.16	109.66	1520	The Needles, *CM8*	Pres. grazed
CP1	Beef Basin	37.98	109.87	1978	The Needles, *CM2*	Pres. grazed
CP2	Newspaper Rock	37.99	109.49	2025	The Needles, *CM4*	Pres. grazed
CP3	Arches	38.78	109.60	1599	Arches N.P., The Neck	Prev. grazed
CP4	ISKY	38.46	109.82	1803	Arches N.P., The Neck	Prev. grazed

[a] Stations that include wind data shown in italics.

[b] All sites in the Mojave–SGB area were grazed in the past (see Table 2). All Canyonlands sites have essentially the same dust source type—alluvium and sand plains.

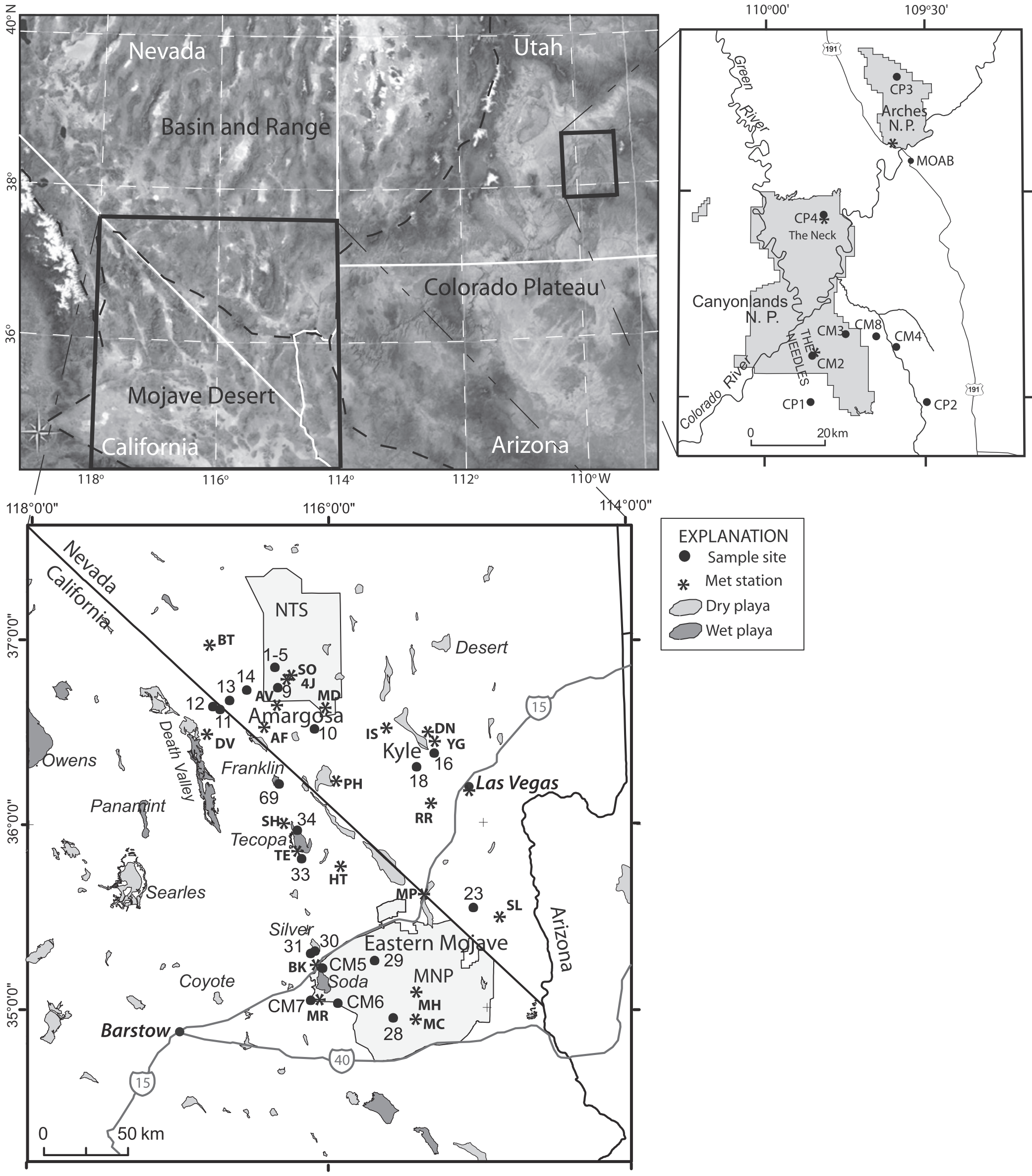

Fig. 1. Location map of study sites in the southern Basin and Range and Mojave Desert provinces of southern Nevada and California (MSGB sites), and in the eastern Colorado Plateau of Utah (ECP sites). Site location details are in Table 1. MNP, Mojave National Preserve; NTS, Nevada Test Site; N.P., National Park. Meteorological station abbreviations: 4J, 4Jan; AF, Amargosa Farms; AV, Amargosa Valley; BK, Baker; BT, Beatty; SO, SORD 26 (wind only); DNR, Desert National Wildlife Refuge; DV, Death Valley; HT, Horse Thief Spring; IS, Indian Springs; MC, Mitchell Caverns; MD, Mercury-Desert Rock; MH, Mid Hills; MP, Mountain Pass; MR, Mojave River Sink; PH, Pahrump; RR, Red Rock Canyon; SH, Shoshone; SL, Searchlight; TE, Tecopa; YG, Yucca Gap.

Table 2
Land use information for study sites.

Type of use	MSGB sites	ECP sites
Previous grazing	All	All except CM2
Year grazing ended	T1–5, T9—late 1940s T28—1998, T29—2002 CM5 and CM6—no leases current in 1994 Others rarely if ever grazed in past ~15 years	CM3, CP4—1974 CP3—1982
Current grazing	Feral burros and horses at most sites	Cattle at CM4, CM8, CP1, CP2
Plowed	None	CM4—2–5 years prior to 1960

Information sources: D. Hughson, Mojave National Preserve, written commun., 2009; V. Webster, National Park Service, written commun., 2009; Belnap et al., 2009.

grazed, is located on a narrow north-trending ridge, where active sand dunes testify to wind erosion and sand transport. The CM4 site, privately owned, was once perennial grassland but is now dominated by exotic annuals.

The study areas are characterized by different primary dust sources (Table 1). In the MSGB, dust sources are alluvial fans and plains, dry playas, and wet playas, and these sources respond somewhat differently to environmental changes (Reheis, 2006; Reheis and Kihl, 1995). On an annual basis, dust fluxes generally increase during drought periods at sites downwind of alluvial sources and dry playas (groundwater >10 m deep) due partly to the die-off of drought-stressed vegetation on alluvial sediments and to local intense rainfall events that deliver fresh sediment during runoff. Sites close to wet playas (groundwater <10 m deep) experience increases in fluxes of salt and silt–clay during El Niño and other cool-season rainfall events (Reheis, 2006). In the ECP, the local modern dust sources are sandy alluvial and aeolian deposits that have been variably disturbed by land use, such that soil crusts may be disturbed or absent and invasive annual plants may be dominant (Belnap et al., 2009).

2.2. Sampling and analysis of dust

Sample sites in the MSGB and ECP (Fig. 1) were selected to study the relations of dust deposition to soils, dust sources, climate, and land use. In the MSGB, T-sites (Table 1) specifically address the relations of dust to soil genesis, local sources, distance from source, and climate (Reheis et al., 1995; Reheis and Kihl, 1995). Additional criteria for location included accessibility, absence of disturbed areas upwind, and inconspicuousness. Four ECP dust trap sites (CM2, -3, -4, and -8) were co-located with instrumented CLIM-MET stations (Southwest CLIMate Impact METeorological stations: http://esp.cr.usgs.gov/info/sw/clim-met/), established by the U.S. Geological Survey beginning in 1998, to provide site-specific climate and dust transport and deposition information in areas with differing land-use histories. Three CLIM-MET stations (CM5, -6, and -7) were also constructed at Soda Lake in the Mojave Desert to examine conditions in an important dust emission area. In 2002, the four ECP sites were supplemented with four additional dust traps (CP designations) to allow a more regional analysis of dust deposition rates in eastern Colorado Plateau. Dust traps at all these sites were generally placed in flat, relatively open areas to mitigate wind-eddy effects created by tall vegetation or topographic irregularities.

For details on dust trap construction and sample collection, see Reheis and Kihl (1995) and Reheis (2003). The trap consists of a teflon-coated angel-food cake pan painted black on the outside and mounted on a post 2 m above the ground. Glass marbles rest on a circular piece of stainless steel mesh that is fitted into the pan to rest 3–4 cm below the rim. Samples were usually obtained in late April or early May and in October or early November and represent accumulation over 6-month periods, designated as winter–spring and summer–fall. Analytical procedures are described in Reheis (2003, 2006); analyses included total and inorganic carbon, soluble salts (mostly excluding $CaCO_3$), and particle size (Table DR-1). Silt and clay fluxes include carbonates, which were not removed prior to particle-size analysis. $CaCO_3$ flux is computed separately from inorganic carbon content. Because components of the $CaCO_3$ flux are included within silt and clay fluxes, we present the statistical results for $CaCO_3$ flux, but discuss it only where significant (mainly for ECP sites).

The principal sources of sampling error are the timing of sample collection and the dust trap construction. Variation in collection dates due to scheduling issues has noticeably affected some ECP sites (CM2, -3, -4, and -8), where in some years, the winter–spring samples were not collected until late May or June and thus could have included dust deposited under drier conditions in late spring. Dry dust that remains on the top layer of marbles can be deflated from the trap. Previous data from several sites with paired traps, one protected by a meteorological wind baffle, indicate that the true rate of dust deposition at sites with low scrubby vegetation may be at least 25–40% greater than measured (Reheis and Kihl, 1995). Calibration results using our dust trap in a wind tunnel also suggest these traps are relatively inefficient, compared to a water surface, in catching dust at wind speeds greater than 1 m/s (as low as 10% efficiency) (Goossens, 2007, 2010; Sow et al., 2006). However, efficiency is much higher for particle sizes $<20\ \mu m$ in diameter. We also note that the wind tunnel tests were performed at ground level, but dust traps are situated 2 m above the ground in the field, where sand flux is much lower at any wind speed. Nevertheless, the dust traps provide an internally consistent record of dust flux that can be compared to meteorological data. These traps were originally designed to provide a more accurate picture of silt and clay that is potentially added to or subtracted from the soil by wind erosion, and they do not record total deposition flux as does a perfect (water) trap, which includes a sand fraction that typically is in transit by saltation and does not infiltrate soils.

2.3. Climate data

We used monthly precipitation data for 1997–2008 for weather stations near dust trap sites, including NOAA stations (http://www.ncdc.noaa.gov/oa/climate/), Remote Automated Weather Stations (RAWS; Bureau of Land Management) and Community Environmental Monitoring Program (CEMP) stations (Western Regional Climate Center, http://www.wrcc.dri.edu/), stations within the Nevada Test Site (http://www.sord.nv.doe.gov/home_climate.htm), and CLIM-MET data (http://esp.cr.usgs.gov/info/sw/clim-met/). These data were used to calculate the sum of seasonal precipitation during the periods of sample accumulation, from May through October and November through September of the following year (Table DR-2A). Because many dust traps are not located at weather stations, the seasonal precipitation was estimated by averaging the values from two to five of the closest stations (Fig. 1 and Table 1), chosen to surround the site and bracket the site elevation. The 6-month sums of precipitation generally serve to equalize variation in the amount of precipitation received at different nearby sites from the same storm, but even the closely spaced CLIM-MET and other stations around Soda Lake show variation in some years (Urban et al., 2009). However, seasonal precipitation values at different stations are similar in the smaller ECP area through the study period (Table DR-2A).

To consider the effects of seasonal drought, we averaged the monthly Palmer Drought Index (PDI) values for each sub-region (southern Nevada, southeastern California, and southeastern Utah; http://www.cdc.noaa.gov/data/timeseries/). The PDI incorporates temperature and rainfall data, and is frequently used in dust emission studies (e.g., Lee et al., 1993; Mahowald et al., 2007; Reynolds et al., 2009a). PDI values may obscure weather differences between the two study areas because the values are normalized to local long-term averages. Temperature was not explicitly considered except as incorporated in PDI value.

Monthly wind data were obtained for several of the RAWS, CEMP, and SORD stations in the MSGB region from the above internet sources and combined with data for the CM stations that we maintain (Table DR-2B). Although all of these sources report and summarize hourly and monthly data for wind speed and direction, their dataloggers are programmed to record and store data in slightly different ways. Thus, average wind speed, even if identical between two sites during a given period, may vary slightly due to different data-storage protocols. Peak gust is probably less affected by the recording interval, as the maximum value measured is updated and stored regularly. We did not examine wind direction in this study.

Average monthly wind data, particularly wind speed, are likely to obscure high-wind periods that are most efficient at initiating saltation and dust transport, with presumed correlation to local dust deposition. The CLIM-MET stations provided continuous high-resolution wind data to examine the relation between average monthly data and high-wind periods. We summed numbers of hours over the 6-month sampling periods during which average wind speed exceeded specific thresholds, ranging from 2 to 12 m/s, and hours during which peak gust exceeded thresholds ranging from 2 to 20 m/s. Comparison of these variables with average monthly values showed expectably tight correlations of average wind speed with sums of hours above 2 m/s average wind speed (0.88–0.99 r values, Table 3). For the ECP sites, average wind speed was also well correlated with sums of hours with peak gust $\geqslant 6$–14 m/s (r values from 0.72 to 0.90 by season). Average monthly

Table 3
Correlation coefficients for wind variables by area and season.

Original wind variables	Sum hours average wind $\geqslant$2 m/s	Sum hours average wind $\geqslant$4 m/s	Sum hours average wind $\geqslant$6 m/s	Sum hours average wind $\geqslant$8 m/s	Sum hours average wind $\geqslant$10 m/s	Sum hours peak gust $\geqslant$6 m/s	Sum hours peak gust $\geqslant$10 m/s	Sum hours peak gust $\geqslant$14 m/s	Sum hours peak gust $\geqslant$18 m/s
Mojave–southern Great Basin (MSGB) sites (CM5, CM6, CM7)									
All seasons									
Ave. wind	**0.94**	**0.57**	x	x	x	**0.48**	x	x	x
Peak gust	x	0.36	x	x	x	**0.45**	x	x	x
Ave. mo. peak gust	x	**0.38**	**0.38**	**0.49**	**0.49**	0.33	**0.43**	**0.53**	**0.61**
Summer–fall season									
Ave. wind	0.93	0.62	x	x	x	x	x	x	x
Peak gust	x	x	x	x	x	x	x	0.46	x
Ave. mo. peak gust	x	x	x	0.48	x	x	x	**0.63**	0.55
Winter–spring season									
Ave. wind	**0.93**	0.43	x	x	x	x	x	x	x
Peak gust	x	0.46	x	**0.58**	**0.67**	0.43	x	**0.58**	**0.68**
Ave. mo. peak gust	x	**0.70**	**0.60**	**0.74**	**0.79**	**0.74**	**0.57**	**0.72**	**0.84**
Eastern Colorado Plateau (ECP) sites (CM2, CM3, CM4, and CM8)									
All seasons									
Ave. wind	**0.88**	**0.82**	**0.84**	**0.73**	0.60	**0.61**	**0.70**	**0.71**	**0.70**
Peak gust	**0.53**	**0.50**	**0.46**	**0.47**	x	**0.36**	**0.40**	**0.43**	**0.42**
Ave. mo. peak gust	**0.60**	**0.50**	**0.52**	**0.52**	x	**0.43**	**0.47**	**0.47**	**0.45**
Summer–fall season									
Ave. wind	**0.92**	**0.92**	**0.85**	**0.69**	0.62	**0.80**	**0.81**	**0.72**	**0.68**
Peak gust	**0.45**	x	x	x	x	x	x	x	x
Ave. mo. peak gust	**0.45**	**0.43**	x	x	x	0.39	0.37	0.35	x
Winter–spring season									
Ave. wind	**0.99**	**0.95**	**0.93**	**0.85**	**0.69**	**0.90**	**0.83**	**0.82**	**0.73**
Peak gust	**0.70**	**0.62**	**0.64**	**0.72**	x	**0.71**	**0.67**	**0.63**	**0.53**
Ave. mo. peak gust	**0.78**	**0.66**	**0.68**	**0.72**	x	**0.76**	**0.71**	**0.64**	**0.57**

x: correlation not significant at 0.05.
Bold font: significant at 0.01 or less.
Normal font: significant at 0.05–0.01.

peak gust is best correlated with sums of hours with peak gust $\geqslant$6 m/s ($r = 0.76$) and $\geqslant$16–18 m/s ($r = 0.84$) in winter–spring for ECP and Soda Lake sites, respectively. These results suggest that average wind speed and average monthly peak gust can be reasonable proxies for more high-resolution wind data at sites where such data are not available.

The most significant differences among the 15 wind speed stations are the heights at which wind data are measured and their environments (see Table DR-2B). Instrument heights ranged from 3 to 20 m. Some of the RAWS sites are located in hilly terrain and all are isolated from human constructions; in contrast, the CEMP sites are within small towns and are variably screened or buffered by buildings and trees. We rejected one CEMP site, Indian Springs, which was very sheltered from the wind, and one site, SORD 25 with a 20-m mast, which yielded unreasonably high values when corrected for height compared to data from a nearby site, SORD 26, only 20 km away. We standardized wind-speed values to a height of 3 m for eight stations that had anemometers at different heights using an equation (Zoumakis, 2006) that incorporated an estimated value for z_0, or roughness length, from published values (Brutsaert, 1982; Gipe, 2004; MacKinnon et al., 2002) in physical settings similar to our sites. The assigned z_0 value ranged from 0.1 to 0.2 m depending on terrain and shrub density. Vegetation change due to drought has little overall effect on roughness length for the desertscrub communities of the MSGB sites. Climate-driven changes in the ECP are more significant at some sites, but the CM stations required no correction for mast height. Varying z_0 values from 0.1 to 0.5 from a value of 0.3 changes the corrected wind speeds by only ±2.5%. We assigned wind speed data from the nearest station or the average of two stations to each dust trap location (Table 1).

2.4. Statistical analyses

Seasonal depositional dust flux (g/m^2/day for the winter–spring and summer–fall seasons; Table DR-1) was the response variable used in the statistical analyses. Daily dust flux is calculated using the sample weight and dividing by dust trap area and the number of days represented by each sample. Total dust is comprised of the organic-free, <2-mm diameter fraction, including $CaCO_3$ and salt. We also examined the sand (2000–53 μm; sand grains coarser than 250 μm were rare), silt–clay (<53 μm) and <10 μm fractions of dust to investigate particle-size effects, as well as the soluble-salt and $CaCO_3$ fractions.

Several types of statistical analyses were performed to investigate the relations among dust and climate variables using a standard software package (SPSS v. 11.0.1). Climate variables included seasonal precipitation sum and average monthly PDI, wind speed, peak gust, and monthly peak gust for winter–spring and summer–fall. To examine lag effects, we compared dust deposition rates to the previous season's average PDI, and to the previous seasonal precipitation and sums of the previous two and three seasons. In these analyses, sites were grouped on the basis of region (MSGP and ECP), on season (winter–spring and summer–fall), on primary dust source for MSGP sites (alluvium, wet playa, and dry playa), and on land use history for ECP sites (U, ungrazed; PG, previously grazed; G, currently grazed; and GP, currently grazed and previously plowed).

Tests showed that the primary flux variables (dust, sand, silt–clay, <10 μm, salt, and $CaCO_3$) converted to their logarithmic (base 10) values are normally distributed. However, these variables are co-dependent to some extent (i.e., when total dust deposition increases, flux rates of all components usually also increase).

Likewise, the variables representing sums of previous season precipitation are co-dependent. In addition, when subdivided by area, source type, and season, individual subgroups were not always normally distributed and their populations were not equal in size. Thus, two approaches were used to determine the influence of climate on dust deposition. (1) Populations of dust flux values of site groups were compared using both parametric analysis of variance and the non-parametric Kruskal–Wallis (three categories) and Mann–Whitney tests (two categories). Because these latter two tests do not require normally distributed populations, they provide a robust test of whether populations of different categories (i.e., different rainfall amounts) are statistically different. Results using both approaches were nearly identical with respect to statistical separation of the populations (not shown). (2) Climate and wind parameters, including sums of hours above wind-speed thresholds for some sites, and seasonal fluxes were compared using simple linear and multiple regression on logarithmic values of dust flux. To reduce collinearity in climate parameters, we used stepwise multiple regression, which automatically removes variables that do not contribute additional explanatory power.

3. Results

3.1. Regional precipitation and wind

Seasonal precipitation patterns are quite different in the two study areas (Fig. 2). Most of the MSGB sites receive moisture primarily from westerly storm systems during the winter and early spring; the easternmost three sites (T16, T18, and T23; Fig. 1), and occasionally sites T28 and T29, also receive southerly monsoon moisture during the summer (French, 1983). The MSGB area typically experiences distinct increases in winter and spring precipitation during El Niño events, and droughts during La Niña periods (ENSO cycle). No major El Niño events occurred during the 1999–2008 sampling period (the last significant event was in the winter and spring of 1997–1998; Fig. 2), although a moderate protracted El Niño marked the two winter–spring periods of 2002–2004. However, unusual Pacific winter storms produced very high rainfall in the MSGB area in the winter of 2004–2005. In contrast, westerly winter moisture is variable in the ECP and the influence of ENSO is subdued (Hereford et al., 2002), but the southwestern summer monsoon normally extends into southeastern Utah during the summer months.

The average 6-month seasonal PDI records for the two study areas are generally similar (Fig. 2). Both show an extended period of relative drought (negative values) from 2000 to 2004. The ECP experienced near-normal PDI conditions from 2005 to 2008, whereas values were distinctly negative in the MSGB.

Wind speeds and peak gusts show clear differences between the two study areas (Fig. 2). Both areas have higher average winds in the summer–fall season compared to the winter–spring, but the ECP area has slightly lower average wind and is more variable seasonally. In contrast, the average monthly peak gust (AMPG, monthly peak gust averaged over 6 months) is commonly much higher in the ECP than in the MSGB before 2006, and shows a much bigger seasonal range in values. Wind speed differences within the two areas are greater in some years than others, as shown by the standard deviations of average monthly peak gust (Fig. 2).

3.2. Seasonal dust flux by region, source, and land use

Measured dust fluxes during 1999–2008 were generally higher at ECP sites than at MSGB sites (Fig. 3). The boxplots show that most data have an approximately log–normal distribution, with a number of outliers (circles). Extreme values (stars) are nearly all from the most disturbed and annualized ECP sites (CM3 and CM4) and two MSGB sites in the sand-transport corridor south of Soda Lake (CM6 and CM7; Fig. 1). Two samples from two sites (T9 and T18, annotated in Table DR-1) gave extreme values due to contamination by bird roosting and deterioration of the pan; these two samples were eliminated from further statistical comparisons.

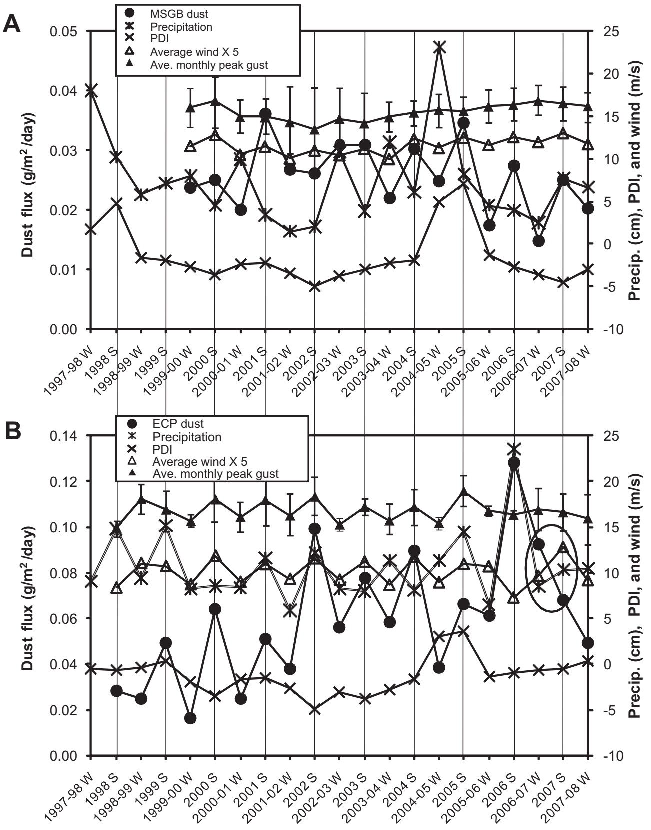

Fig. 2. Comparison of total seasonal dust flux (<2 mm fraction, including carbonate and salt) and precipitation, PDI, average wind, and average monthly peak gust for (A) MSGB and (B) ECP sites, 1998–2008. Note that average wind speed is multiplied by 5 for ease of plotting. Bars show 1 SD for average monthly peak gust. See Tables 1, DR-2A and B for station information. Precipitation and PDI shown for periods prior to the beginning of sample collection to evaluate antecedent moisture conditions. Circle around ECP dust flux values in winter–spring of 2006–2007 and summer–fall of 2007 indicates that some of these samples did not span the usual duration, because the winter–spring samples were collected in June rather than late April. Thus, the unusually low dust flux in the summer–fall of 2007 is likely due to part of the normal sample having been included in the previous winter–spring collection.

Dust source type and land use may have important effects on seasonal dust flux (Reheis, 2006; Belnap et al., 2009). In the following analyses, we use logarithmic flux values to compare populations of different groups (season, dust source, and land use) and to correlate dust flux with climate variables for the two areas separately, and then compare results. However, most figures show the same types of data for the two areas side-by-side for ease of comparison. To eliminate skewing by the extreme values, some of the statistical comparisons excluded all data from the grazed-and-plowed and sand corridor sites (CM4, CM6, and CM7).

3.2.1. Mojave–southern Great Basin sites

The MSGB sites on average had similar fluxes of dust components during the two seasons, except that soluble salt was statistically different, with higher values and a larger range of values in the winter–spring samples (Fig. 4). Summer–fall dust fluxes (total

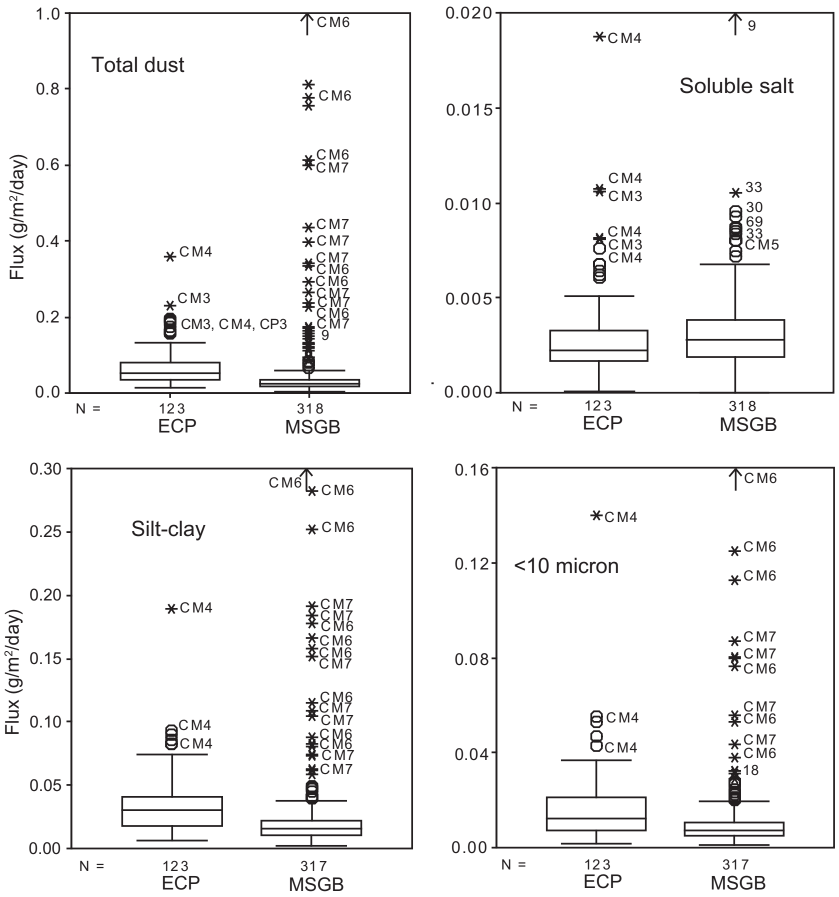

Fig. 3. Boxplots of dust deposition rates (dust flux) in g/m^2/day for total dust, soluble salt, silt–clay (<50 μm) fraction, and <10 μm fraction in the ECP and MSGB areas. Shown are the median (black bar within box), interquartile range (box), expected range (brackets, 1.5× interquartile range), and outlier values (circles, 1.5–3.0× interquartile range) and extreme values (stars, >3.0× interquartile range) annotated with sample location ("T" omitted from MSGB sites for simplicity).

non-organic <2 mm fraction) and average wind speeds are typically somewhat higher than those in winter–spring (Figs. 4 and 2A), but the largest fluxes are just after precipitation peaks (2000–2001 and 2004–2005), and one peak is coincident with precipitation during winter–spring of 2002–2003. Although rain may flush dust from the atmosphere into the trap and thus increase trapping efficiency, this does not account for all the variability since some dust peaks occur after precipitation peaks. Average MSGB dust flux does not seem directly correlated with PDI; note that the large dust flux in summer–fall 2005 coincided with the highest (wettest) PDI values during the period of study.

Simple correlations (*r* values; Table 4) yield results consistent with analysis of variance (Fig. 4). In the MSGB, winter–spring dust flux variables are negatively related to antecedent precipitation (sums of previous one, two, or three seasons), although correlations are relatively weak. However, salt flux in the winter–spring is correlated with same-season precipitation and in the summer–fall with the previous winter–spring, consistent with results of previous studies (Reheis, 2006; Reynolds et al., 2009a) that attributed salt flux to wind erosion of efflorescent salts produced in relatively moist, cool winter conditions. PDI is not generally correlated with dust flux components, although summer–fall PDI is negatively related to silt–clay and <10 μm flux. Silt–clay and <10-μm fluxes are not significantly related to average wind speed, and are only weakly correlated with average monthly peak gust. In site-specific studies, Bergametti and Gillette (2010) noted a similar lack of correlation with wind and lateral dust transport in the Chihuahuan Desert for all plant communities except mesquite. In general, average dust fluxes in the MSGB are not well explained by the climate and wind variables we considered.

Consistent with previous studies on annual dust flux (Reheis and Kihl, 1995; Reheis, 2006), seasonal dust flux is related to upwind dust source types (alluvium, dry playas, wet playas; Table 1). Silt–clay flux was commonly higher during the summer–fall at sites downwind of all sources (left columns, Figs. 5 and 6), except that fluxes were also high for dry playas in the winter–spring of several years (data from sites CM6 and CM7, in the sand-transport corridor south of Soda Lake, are omitted from these averages, being more than an order of magnitude greater in many seasons; see Fig. 3 and Table DR-1). Among the different sources during the summer–fall (bold capital letters along bottom of panels in Fig. 5), the only statistically significant difference was that sites near wet playas had less total dust than dry playas, mainly due to lower sand flux (upper left panel, Fig. 6). During the winter–spring (italic capital letters, Fig. 5), sites near dry playas had higher dust, silt–clay, and <10 μm fluxes than other sites, and sites near wet playas had higher soluble salt fluxes (Figs. 5 and 6).

Seasonally, sites with primarily alluvial dust sources exhibited significantly higher total dust, silt–clay, and <10 μm fluxes during the summer–fall than during the winter–spring (capital letters along tops of boxplots, Fig. 5). In contrast, dust fluxes at sites with dry playa sources were not statistically different between seasons. Soluble-salt flux was commonly highest and most variable in wet winter–spring seasons, especially downwind of wet playas.

MSGB sites grouped by geographic proximity generally have the same dust source types. Examination of such groups using weather

Table 4
Correlation coefficients for dust (log 10 values) and climate variables by area and season.

Dust component	PDI	PDI prev. season	Summed season precip.	Prev. season precip.	Prev. 2 seasons precip.	Prev. 3 seasons precip.	Ave. wind	Peak gust	Ave. monthly peak gust
Mojave–southern Great Basin (MSGB) sites (CM6, CM7)									
Summer–fall season									
Dust	x	x	x	x	x	x	x	x	x
$CaCO_3$	x	x	x	x	x	x	0.20	x	x
Salt	0.19	x	x	**0.22**	0.19	x	x	x	x
Sand	x	x	x	−0.19	−0.17	x	x	x	x
Silt–clay	x	x	x	x	x	x	x	x	0.17
<10 μm	x	x	x	x	x	x	x	x	x
Winter–spring season									
Dust	x	x	x	x	−0.22	−0.20	x	x	x
$CaCO_3$	x	x	x	x	x	x	0.22	x	x
Salt	x	x	**0.24**	−**0.31**	−0.20	−**0.24**	x	x	x
Sand	x	x	x	x	x	x	x	x	x
Silt–clay	x	x	x	x	−**0.23**	−**0.22**	x	x	0.16
<10 μm	x	(−0.196)	x	x	−**0.29**	−**0.30**	x	x	0.16
Eastern Colorado Plateau (ECP) sites (CM4)									
Summer–fall season									
Dust	x	x	0.27	−0.27	x	x	**0.56**	0.31	**0.36**
$CaCO_3$	−0.33	x	x	−0.28	x	x	0.30	x	x
Salt	x	x	x	**0.36**	x	x	x	x	0.30
Sand	x	−0.26	0.30	−**0.42**	x	x	**0.38**	x	x
Silt–clay	x	x	x	x	x	x	0.33	x	**0.41**
<10 μm	x	x	x	x	x	x	x	x	0.34
Winter–spring season									
Dust	x	x	x	0.24	x	x	**0.38**	x	x
$CaCO_3$	−**0.44**	x	−0.30	**0.37**	0.26	x	0.35	0.34	x
Salt	x	−0.29	x	x	x	x	x	x	x
Sand	x	x	x	x	x	x	x	x	x
Silt–clay	x	−0.31	x	x	x	x	**0.48**	x	**0.42**
<10 μm	x	−**0.36**	x	x	x	x	**0.52**	x	**0.46**

x: correlation not significant at 0.05.
Bold font: significant at 0.01 or less.
Normal font: significant at 0.05–0.01.
Parentheses: apparent significance invalid; usually undue weighting by one or two anomalous data points.

data only from stations close to each group yields better correlations with climate variables (Tables 5 and 6; see Table DR-3 for MSGB-wide correlations by dust source type). We analyzed the following groups (Fig. 1): the Amargosa group has sites with mainly alluvial dust sources; the East Mojave group is influenced by a mixture of sources; Soda Lake sites CM6 and CM7 are in the sand-transport corridor; and the Tecopa-Franklin group has mainly wet playa sources.

Few correlations are significant for dust flux during the summer–fall season except for sites CM6 and CM7. All of the MSGB groups show positive correlations for soluble salt flux with winter–spring precipitation (Table 5), and for dust and <10-μm flux at the Tecopa-Franklin sites with wet playa sources. These results demonstrate the close link between salt-rich dust production from wet playas and winter moisture, which produces efflorescent salts on playa surfaces that are easily deflated (Reheis, 2006; Reynolds et al., 2009a). The Amargosa and high-altitude East Mojave groups have negative correlations for <10 μm flux with previous PDI and, for East Mojave, sums of previous seasonal precipitation during the winter–spring (Tables 3 and 4). With respect to wind variables, Amargosa sites show weakly positive correlations of total dust, sand, and salt flux with average wind speed in the winter–spring. However, the high-altitude East Mojave sites actually show negative correlations of dust flux components with average wind and peak gust (Table 5).

Correlations are stronger for the southern Soda Lake sites, CM6 and CM7 (Fig. 1), which are located in the same geomorphic setting and have on-site climate data. In both seasons, total dust and sand fluxes are negatively related to antecedent precipitation, reflecting its control on growth and die-off of annual plants (Table 5 and Fig. 7A and B; Urban et al., 2009). This group also exhibits positive correlation of soluble and fine sediment fluxes with summer–fall precipitation (Fig. 7A). This could be a result of increased trapping efficiency of fine dust during rain events, but also may suggest distant dust sources. With respect to wind, the winter–spring particulate (non-salt) fluxes are well correlated with average monthly peak gust (Fig. 7C) and the summer–fall fluxes with number of hours having average wind $\geqslant 6$ m/s and peak gust $\geqslant 12$ m/s (Table 6 and Fig. 7D).

In summary, correlations with climate variables using geographic site groups are somewhat improved compared to the MSGB average (Table 4) and to region-wide dust source groups (Table DR-3), and especially improved for the south Soda Lake group with two sites close together and with on-site climate data. These improved correlations are likely due to the reduction in complexity of site variables within smaller, closely spaced sites and locally measured meteorological data. Note, for example, that increases in hours above certain wind-speed thresholds at the south Soda Lake sites do not correspond with region-wide dust fluxes (Fig. 6). However, the overall pattern of correlations in the MSGB does not change greatly. Dust flux is not well correlated with climate variables during the summer–fall, except at the south Soda Lake sites with same-season precipitation and wind hours. In the winter–spring, dust flux is correlated with drought. Relations to wind speed are variable among the groups, apparently being positive for the Amargosa and south Soda Lake groups and negative for the high-altitude East Mojave group, a non-intuitive result that requires explanation.

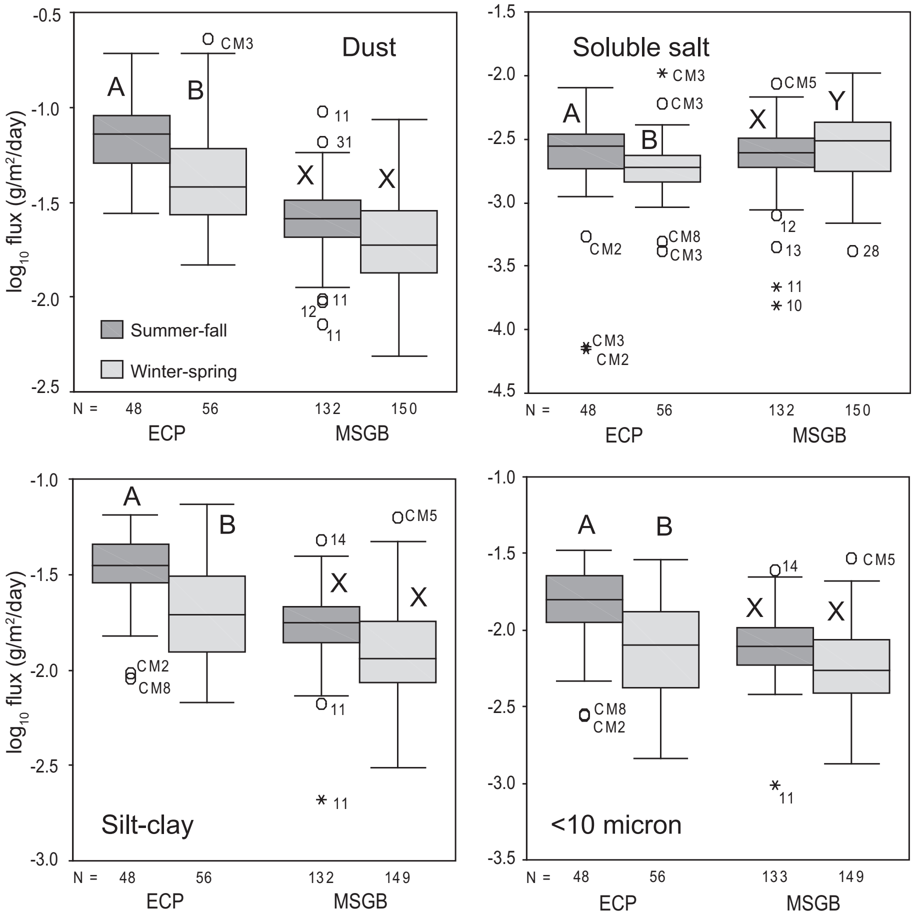

Fig. 4. Boxplots showing seasonal dust fluxes ($\log_{10}$ values) for the ECP and MSGB areas. Dark gray, summer–fall; light gray, winter–spring. Capital letters designate groups with statistically different or similar populations.

3.2.2. Eastern Colorado Plateau sites

Seasonal differences in dust flux are striking for the ECP sites, with summer–fall values significantly higher than winter–spring values (Figs. 4 and 2B). Average ECP dust fluxes are at least two times larger than MSGB dust fluxes, despite generally higher vegetation cover. Dust flux was relatively low in 1998–1999 during a period of normal rainfall. The lowest PDI values, during the drought period of 2000–2004, correspond with relatively high dust flux, and the highest PDI values during 2004–2005 with relatively low dust flux. In 2006, despite nearly normal PDI values and low wind speed, very high dust flux occurred during the wettest summer–fall period of the study interval. (*Note:* the low dust value in summer–fall of 2007 was due to a problem in the timing of sample collection.) This high flux is mainly due to a large influx of sand at several sites (Fig. 6 and Table DR-1), suggesting an unusual short-lived wind event, rather than an increase in fine dust flux by rainout. However, correlation between PDI and dust flux is not significant, except that high PDI appears to suppress $CaCO_3$ flux (Table 4).

ECP sites on average show positive correlations of all dust flux components except salt with average wind speed and average monthly peak gust in both seasons (Table 4). Expectably, some dust components are negatively related to same-season and previous-season PDI and precipitation. However, total dust and $CaCO_3$ flux during the winter–spring appears to be positively correlated with antecedent precipitation.

The ECP sites all have similar local dust sources (alluvial and aeolian sand plains and soils), but have experienced different levels of land use that have affected the physical surfaces and vegetation (Table 2) as well as the seasonal average daily fluxes (Fig. 5, right column). During the summer–fall, total dust flux is significantly larger and more variable at the grazed-and-plowed site (CM4) and at the previously grazed sites than at the never grazed site, and somewhat larger at the currently grazed sites (bold capitals). These disparities decrease with particle size, such that the <10 μm fluxes (not shown) are only larger at the grazed-and-plowed site. During the winter–spring, the differences are smaller.

All flux components at ECP sites reach maximum values in the summer–fall, regardless of land use (Figs. 5 and 6). Rare exceptions do occur, such as an increase in silt–clay flux at most sites in the winter–spring of 2006–2007. During the period from 1998 through 2000, dust fluxes are similar among sites with different land use histories (right column, Fig. 6), but this consistency ends with the onset of drought in 2000. Little difference exists between the never-grazed site CM2 and currently grazed sites CM8, CP1, and CP2, which have retained native perennial grass and shrub cover, and the similarity persists throughout the 10-year period except the grazed sites have higher total flux (Fig. 5). In contrast, sites CM3, CP3, and CP4 that were previously grazed prior to their incorporation into Arches and Canyonlands National Parks produced more dust than any but the highly disturbed site CM4 from 2003 to 2008. CM4 dust fluxes vary greatly from year to year, and in some years are 5 to more than 10 times greater than those at other sites. This variability can be directly related to the occurrence of sustained periods of higher winds at this site (Belnap et al.,

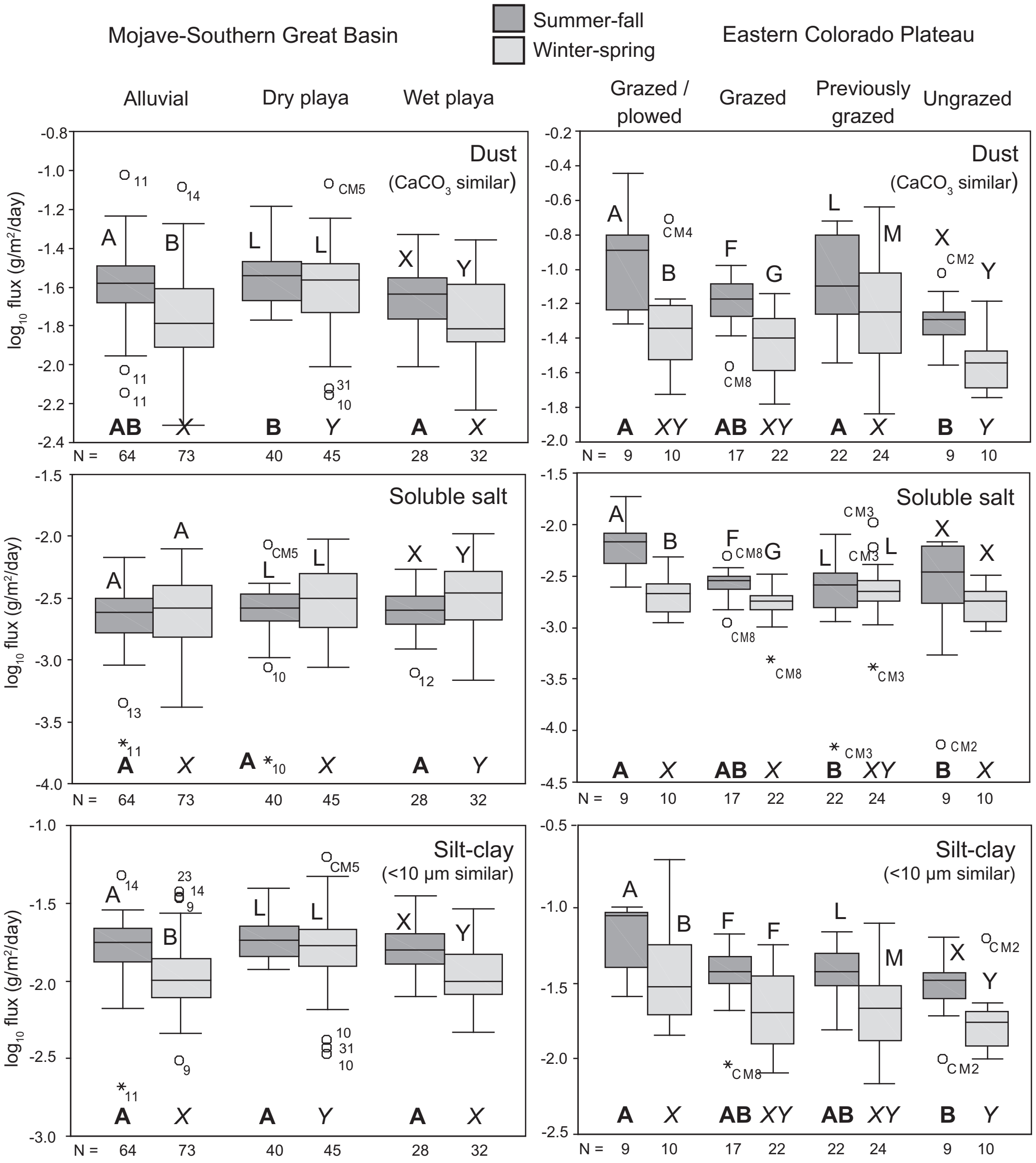

Fig. 5. Boxplots showing seasonal dust fluxes ($\log_{10}$ values) for the MSGB (left panel column) and ECP (right panel column) areas. Note that total dust and silt–clay dust are scaled differently for MSGB and ECP sites. $CaCO_3$ and <10 μm fluxes not shown, but have patterns similar to total dust flux and silt–clay flux, respectively. Dark gray, summer–fall; light gray, winter–spring. MSGB samples are divided into groups on the basis of primary upwind dust source type (alluvial, dry playa, wet playa). ECP sites are divided on the basis of land use history (see text for discussion). Capital letters designate groups with statistically different or similar populations. Normal fonts above boxes compare summer–fall vs. winter–spring flux within a dust source or land use group. Bold and italic fonts below boxes compare land use or dust source groups within the summer–fall or winter–spring season. Combined letters (AB) indicate population of group overlaps with other groups (A and B).

2009), and to plant cover through archives of repeat photography (http://esp.cr.usgs.gov/info/sw/clim-met/). The large standard deviations displayed in hours above threshold for Needles sites are due to high wind periods at CM4 and relatively low winds at CM2, the never-grazed site (Fig. 6 and Table DR-2B). In the severe drought of 2002–2003, plant cover at CM4 even in the springtime was only ~25%, and coppice dunes had formed where none were previously observed. The offset between the peaks of sand vs. silt–clay at CM4 (Fig. 6) may be due to progressive deflation and dune construction during this drought. These results suggest the importance of land-use management in areas of sandy substrates that are susceptible to wind erosion and invasion of exotic annual plants (Belnap et al., 2009).

Most correlations of climate variables by land use decreased to non-significant levels due to the smaller numbers of data points in each land use group caused by splitting the dataset (i.e., only one site has never been grazed and only one site was plowed; see Table DR-3). Restricting the dataset to the Needles area (all sites except the outlying CP3 and CP4) generally improved correlations with wind variables, but not necessarily with precipitation and PDI variables (Tables 4–6). Average wind speed and average monthly peak gust are positively correlated with most components of dust flux in both seasons. The numbers of hours having average wind and peak gust above certain thresholds are also significant (Table 6), although correlations are not much better than for average wind speed and monthly peak gust. Correlations indicate that some dust components, including $CaCO_3$, sand, and fine fluxes, are suppressed by locally moist conditions. Correlations excluding the most disturbed site CM4 do not change these relations or the r^2 values significantly (not shown). In summary, restricting the analysis to closely spaced sites does not change the overall pattern of correlation with climate variables in the ECP.

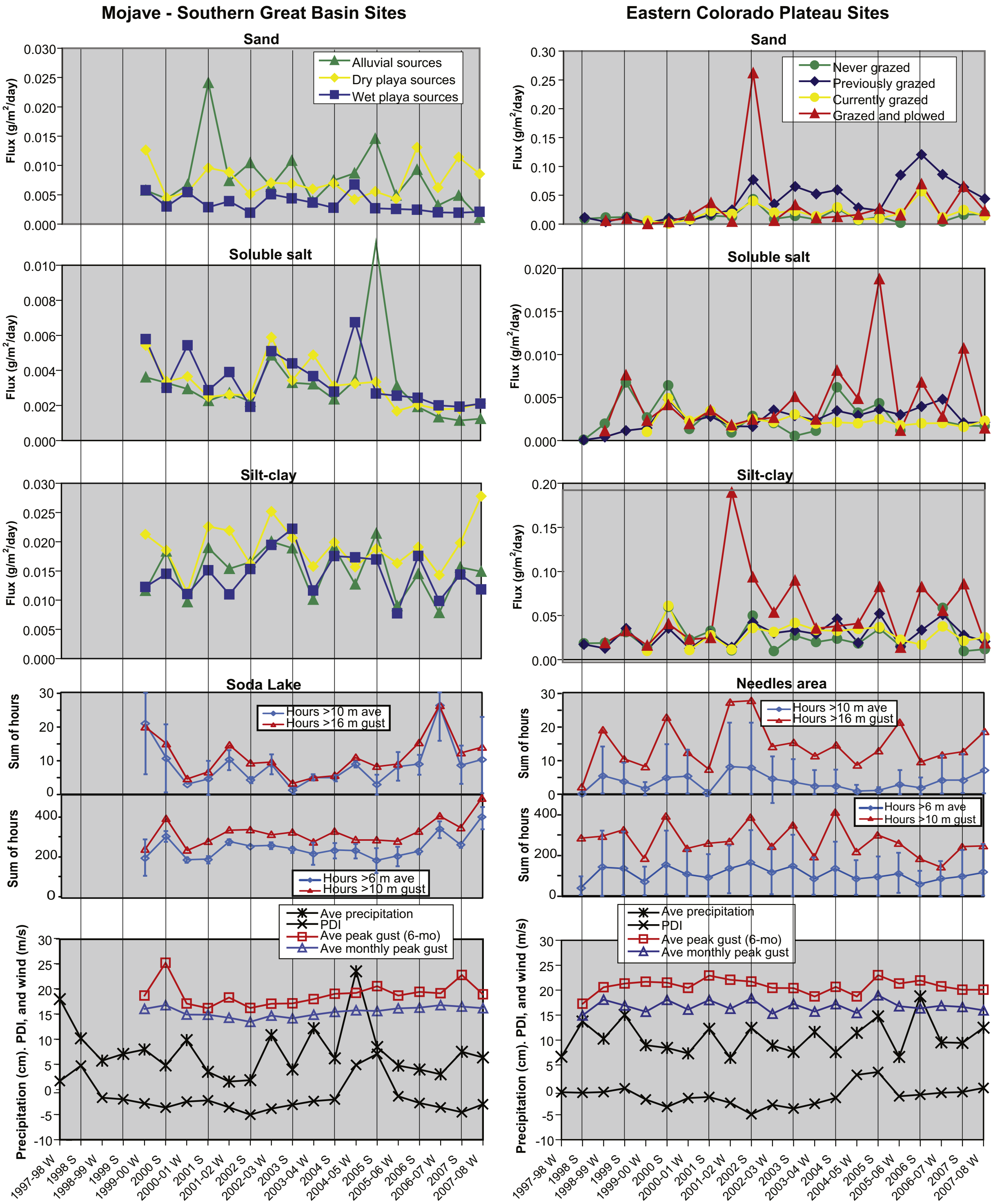

Fig. 6. Comparison of seasonal dust fluxes from 1998 to 2008 for MSGB sites by dust source type (left panel column) and ECP sites by land use history (right panel column) with climate parameters. Note that all fluxes are scaled differently for the two areas. "Soda Lake" and "Needles" plots are averages for CM stations showing number of hours during which average wind speed or peak gust exceeded stated value. Standard deviations (vertical bars) for hours ⩾6 and ⩾10 m/s average wind speed show much higher variability for Needles sites than for Soda Lake sites, due to significantly higher wind speeds at site CM4 than other sites and lower wind speeds at site CM2 (Table DR-2B).

4. Discussion

Dust deposition in the study areas responds to the interaction of local weather, seasonal and decadal climate cycles such as ENSO and the summer monsoon (Okin and Reheis, 2002; Reheis, 2006), wind speed (Stout, 2001), changes in plant cover (Belnap et al., 2009), nature of dust source (Reheis, 2006), and land use (Belnap et al., 2009; Holcombe et al., 1987). Vegetation in many parts of the southwest is increasingly invaded by annual plants (Bradley, 2009; Brooks and Berry, 2006). The cycle of growth and dieoff of such plants, accompanied by potential increases in disturbance by burrowing rodents, make dust emission and deposition even more variable and difficult to predict (Belnap et al., 2009; Urban et al., 2009).

Table 5

Correlations (*r* values) of dust flux and climate variables[a] for different geographic groups of sites by season (see text and Fig. 1 for locations).

Dust component	Summer–fall season									Winter–spring season								
	PDI	PDI prev. season	Summed season precip.	Prev. season precip.	Prev. 2 seasons precip.	Prev. 3 seasons precip.	Ave. wind	Peak gust	Ave. monthly peak gust	PDI	PDI prev. season	Summed season precip.	Prev. season precip.	Prev. 2 seasons precip.	Prev. 3 seasons precip.	Ave. wind	Peak gust	Ave. monthly peak gust
Mojave–southern Great Basin																		
Amargosa sites T1–5, T9, T10, T11, T12, T13, T14 (mainly alluvial sources)																		
Dust	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	**0.39**	x	x
$CaCO_3$	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Salt	x	x	x	**0.42**	0.33	x	x	x	x	x	x	**0.39**	−0.29	x	x	**0.62**	x	x
Sand	x	x	x	x	x	x	x	−0.31	x	x	x	x	x	x	x	0.28	x	x
Silt–clay	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<10 µm	x	x	x	x	x	x	x	x	x	x	−0.27	x	x	x	−0.32	x	x	x
East Mojave sites T23, T28, T29 (higher altitude, mixed alluvial and playa sources)																		
Dust	x	x	x	x	x	x	x	x	x	−0.51	**−0.66**	x	x	**−0.54**	**−0.54**	−0.47	**−0.57**	−0.47
$CaCO_3$	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Salt	x	x	x	x	x	x	−0.46	x	x	x	x	0.38	x	x	x	x	x	x
Sand	x	x	x	x	x	x	x	(−0.66)	x	x	x	x	−0.42	x	x	−0.47	−0.44	−0.43
Silt–clay	x	x	x	x	x	0.43	x	x	x	−0.47	−0.62	x	x	**−0.54**	**−0.52**	x	−0.47	x
<10 µm	x	x	x	0.40	x	x	x	x	x	x	−0.60	x	x	**−0.53**	**−0.54**	x	−0.42	x
East Mojave sites T30, T31, CM5 (lower altitude, mixed alluvial and playa sources)																		
Dust	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
$CaCO_3$	x	x	**−0.68**	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Salt	x	x	x	x	x	x	x	−0.41	x	x	(−0.41)	0.41	**−0.62**	x	−0.46	x	x	x
Sand	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Silt–clay	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<10 µm	x	x	x	x	x	x	x	−0.45	x	x	x	x	x	x	x	x	x	x
South Soda Lake sites CM6, CM7 (sand-transport corridor)																		
Dust	x	x	x	**−0.72**	**−0.72**	**−0.67**	x	x	x	**−0.62**	x	−0.51	x	−0.51	x	x	x	**0.71**
$CaCO_3$	x	x	0.59	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Salt	x	x	**0.65**	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Sand	−0.58	x	x	**−0.84**	**−0.78**	**−0.66**	x	x	x	**0.66**	x	−0.50	x	−0.58	x	x	x	**0.71**
Silt–clay	x	x	**0.64**	x	x	−0.60	x	x	x	(−0.50)	x	−0.50	x	x	x	x	x	**0.65**
<10 µm	x	x	0.55	x	x	**−0.65**	x	x	x	x	x	x	x	x	x	x	x	**0.60**
Tecopa-Franklin sites T33, T34, T699 (mainly wet-playa sources)																		
Dust	x	x	x	x	x	x	x	x	x	x	x	0.41	x	x	x	x	x	x
$CaCO_3$	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Salt	x	x	x	x	x	x	x	x	x	x	x	0.44	x	x	x	x	x	x
Sand	x	x	0.50	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Silt–clay	x	x	x	x	x	x	x	x	x	x	(−0.47)	x	x	x	x	x	x	x
<10 µm	x	x	x	x	x	x	x	x	x	x	(−0.49)	0.42	x	x	−0.42	x	x	x
Eastern Colorado Plateau																		
Needles area sites CM2, CM3, CM4, CM8, CP1, CP2 (soil and alluvial sources)																		
Dust	x	x	x	x	x	x	**0.52**	x	0.36	x	x	x	x	x	x	**0.38**	x	x
$CaCO_3$	−0.35	x	x	x	x	x	x	x	x	**−0.40**	x	−0.36	**0.42**	x	x	**0.50**	0.32	0.31
Salt	x	x	x	x	x	x	0.33	x	0.33	x	x	x	x	x	x	x	x	x
Sand	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Silt–clay	x	x	x	x	x	x	**0.46**	x	**0.46**	x	−0.31	x	x	x	x	**0.54**	x	**0.48**
<10 µm	x	x	x	x	x	x	0.35	x	**0.41**	x	−0.33	x	x	x	x	**0.57**	x	**0.51**

Bold font: significant at 0.01 or better.

Normal font: significant at 0.05–0.01.

x: correlation not significant at 0.05 level.

Parentheses: apparent significance invalid; usually undue weighting by anomalous data clusters.

[a] Climate variables are averaged from 2 to 5 weather stations closest to site groups.

Table 6
Correlations (r values) of dust flux and wind variables for different geographic groups of sites by season (see text and Fig. 1 for locations).

Dust component	Summer–fall season						Winter–spring season					
	Sum hours average wind ⩾6 m/s	Sum hours average wind ⩾8 m/s	Sum hours average wind ⩾10 m/s	Sum hours peak gust ⩾12 m/s	Sum hours peak gust ⩾14 m/s	Sum hours peak gust ⩾16 m/s	Sum hours average wind ⩾6 m/s	Sum hours average wind ⩾8 m/s	Sum hours average wind ⩾10 m/s	Sum hours peak gust ⩾12 m/s	Sum hours peak gust ⩾14 m/s	Sum hours peak gust ⩾16 m/s
Mojave–southern Great Basin												
South Soda Lake sites CM6, CM7 (sand-transport corridor)												
Dust	**0.70**	**0.72**	x	**0.71**	**0.70**	0.58	x	x	x	x	x	0.60
$CaCO_3$	x	x	x	x	x	x	x	x	x	x	x	x
Salt	x	x	x	x	x	x	x	x	x	x	x	x
Sand	**0.69**	**0.73**	x	**0.68**	**0.68**	0.59	x	x	x	x	x	0.59
Silt–clay	**0.59**	**0.56**	x	**0.63**	0.59	x	x	x	x	x	x	0.58
<10 µm	**0.58**	**0.50**	x	0.59	0.49	x	x	x	x	x	x	0.54
Eastern Colorado Plateau												
Needles area sites CM2, CM3, CM4, CM8, CP1, CP2 (soil and alluvial sources)												
Dust	**0.44**	**0.48**	**0.50**	**0.44**	**0.52**	**0.53**	0.27	0.34	**0.38**	x	x	0.32
$CaCO_3$	0.41	**0.46**	**0.46**	**0.41**	**0.47**	**0.54**	**0.46**	**0.48**	**0.56**	0.34	0.41	**0.49**
Salt	0.31	x	x	x	x	x	x	x	x	x	x	x
Sand	x	x	x	x	x	x	x	x	x	x	x	x
Silt–clay	**0.47**	**0.47**	**0.46**	**0.52**	**0.53**	**0.55**	0.30	**0.39**	**0.45**	x	x	(0.28)
<10 µm	**0.44**	**0.45**	**0.44**	**0.51**	**0.51**	**0.52**	0.33	**0.40**	**0.45**	x	x	x

Bold font: significant at 0.01 or better.
Normal font: significant at 0.05–0.01.
x: correlation not significant at 0.05 level.
Parentheses: apparent significance invalid; usually undue weighting by anomalous data clusters.

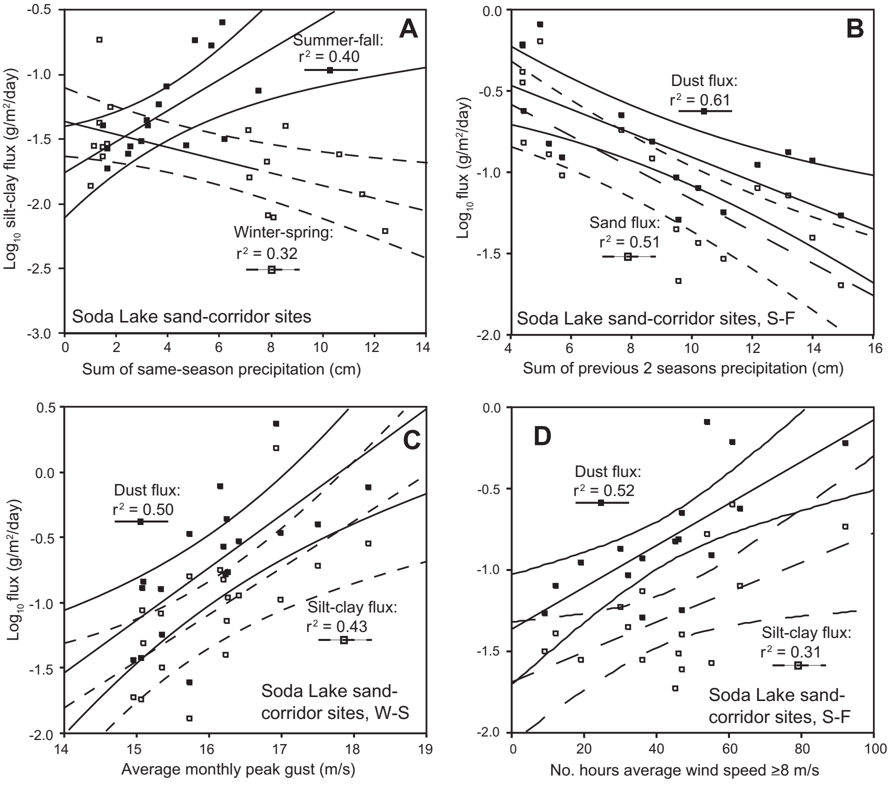

Fig. 7. Selected correlations of dust-flux components with precipitation and wind variables for south Soda Lake sand-corridor sites CM6 and CM7 (see Fig. 1 for location and Tables 5 and 6 for all correlations). W–S, winter–spring; S–F, summer–fall. (A) Summer–fall and winter–spring silt–clay flux vs. same-season precipitation. (B) Total dust and sand flux vs. sum of precipitation during previous two seasons. (C) Total dust and silt–clay flux vs. average monthly peak gust. (D) Total dust and silt–clay flux vs. number of hours with average wind speed ⩾8 m/s.

4.1. Regional contrasts in seasonal climate and dust flux

Seasonal precipitation and wind patterns are different in MSGB and ECP areas (Figs. 2 and 6), and produce different patterns of dust emission and deposition. MSGB sites experience wetter conditions in the winter and early spring, especially during El Niño events and unusual Pacific winter storms. In contrast, southeastern Utah has a biannual pattern with southerly monsoon moisture during the summer months and westerly moisture in the winter (Hereford et al., 2002). Both areas have higher average wind speeds in the summer–fall season compared to the winter–spring, but the ECP has greater seasonal contrast. In addition, although variability among sites is very high, with wind speeds highest at site CM4 and lowest at CM2, the number of hours with wind gusts exceeding 16 m/s in the Needles area of the ECP commonly exceeded those of the Soda Lake area (Fig. 6). Hours of high winds were equally common in both seasons at the Needles sites but were typically greatest during winter–spring at the Soda Lake sites. The strongest winds typically occur in March through May in both areas (Belnap et al., 2009; Reheis, 2006; Urban et al., 2009); thus, our sampling periods (November–April, May–October) essentially divide this windy interval. Summer monsoonal thunderstorms in the ECP produce gusty winds (Nickling and Brazel, 1984), and differential heating in the summer in both areas causes convective winds that can generate substantial dust plumes and dust devils (Gillette and Sinclair, 1990; Koch and Renno, 2005). Summer–fall dust fluxes were higher than winter–spring fluxes in the ECP, likely as a result of these factors plus higher summer temperature. ECP dust fluxes and especially summer–fall fluxes were at least two times larger than MSGB dust fluxes, despite generally greater vegetation cover (Figs. 3 and 4). Additional factors that may have contributed to higher ECP fluxes are the abundance of sand available for saltation in the ECP, and suppression of locally derived dust by gravel desert pavements in the MSGB.

The ECP sites are positively correlated with average wind, average monthly peak gust, and sums of hours with wind speed above certain thresholds in both summer and winter (Tables 4–6). Engelstaedter and Washington (2007) showed with satellite data that gustiness is better correlated with dust emissions than average wind speed in global "hotspots", and our study provides some support for this observation. Previous studies have shown that extreme wind events account for a large proportion of total dust emission over a longer measurement period (e.g., Holcombe et al., 1987; Stout, 2001; van Donk et al., 2003). That the correlations we measured are not significantly improved for hours above threshold vs. peak gust vs. average wind speed may be caused by the reduced efficiency of the dust traps at higher wind speeds (Goossens, 2007, 2010). The correlations tend to be stronger with total dust and sand flux in the summer–fall, and with the finer silt–clay and <10 μm flux in the winter–spring. Such relations suggest that locally generated, coarse dust may account for a higher proportion of dust flux in the summer, when convective storms and dust devils are common, and farther-traveled fine dust may be more significant in the winter. In this regard, other studies have demonstrated the presence of far-traveled dust, in part from the Mojave Desert, in ECP soils (e.g., Goldstein et al., 2008; Reynolds et al., 2006). The positive correlation between total dust and sand fluxes and same-season precipitation in the summer–fall suggests that intense rainfall may mobilize local sediment through runoff (Bullard and Livingstone, 2002). In addition, convective summer storms may raise dust directly. The positive correlation of dust and $CaCO_3$ flux in winter with previous-season precipitation may also reflect sediment availability. On the other hand, dust flux in the summer decreased with increasing previous-season precipitation, and in the winter with previous-season PDI, likely reflecting the lag effect on vegetation cover due to increased prior moisture (Holcombe et al., 1987; Mackinnon et al., 1990; Musick, 1999).

Seasonal differences in wind are much smaller in the MSGB and some dust sources such as wet playas tend to be more active in the winter–spring (Reynolds et al., 2009a), thus average seasonal dust production is balanced (Fig. 4). In contrast to the ECP, correlations with climate and wind variables tend to be significant in the winter–spring rather than in the summer–fall and explain less of the variability in seasonal dust flux (Tables 4 and 5); however, south Soda Lake sites are well correlated with hours of wind above thresholds in summer–fall. Total dust, sand, silt–clay, and <10-μm fluxes in the winter–spring are suppressed by antecedent precipitation and presumably, associated vegetation growth. Soluble salt flux is clearly correlated with winter–spring precipitation, as suggested previously (Reheis, 2006). The generally weaker relations of dust flux and climate variables in the MSGB compared to the ECP are likely a result of the averaging of data from sites across a larger region with greater diversity in elevation, climate, and principal dust sources that respond differently to climate forcing.

Dust trap sites in the MSGB span ∼1000 m in elevation (Table 1) and consequently a range of vegetation communities as well as precipitation. Local site relief varies considerably, from gentle alluvial plains and distal fans to moderately dissected fan slopes to highly dissected piedmonts and hilly terrain. In contrast, most of the ECP sites are in similar vegetation and terrain. Dust deposition is known to be affected by the flow and eddying of wind through irregular terrain (Goossens, 1988; Goossens and Offer, 2005). Reheis and Kihl (1995) noted that wind baffles constructed around selected dust traps increased dust deposition rates at sites with short desert-scrub vegetation, but had little effect on rates at sites with tall vegetation (pinyon–juniper and Joshua trees). Overall, dust flux increases with decreasing elevation of the sites (Fig. 8A; r^2 value significant at <0.01); the relationship is still significant if the high-flux data points from sites CM6 and CM7 (the sand transport corridor) are removed.

To explore the effects of vegetation height and relief, we assigned qualitative rankings to each dust trap site ranging from 1 to 3 for short to tall vegetation, and 1 to 3 for low to high relief. Interestingly, dust flux increases with average wind speed and average monthly peak gust at sites with low relief and short vegetation (Fig. 8B), but decreases with wind speed at sites with high relief and tall vegetation (Fig. 8C) (both significant at <0.01). We speculate that irregular terrain and tall vegetation may cause eddying that reduces dust trap efficiency. These relations may help explain the conflicting results obtained above (Table 5), in which Amargosa and south Soda Lake sites, in low to moderate-relief terrain with short desert scrub, exhibited a positive relation with wind speed whereas the high-altitude East Mojave sites, mainly in moderate to high-relief terrain with taller vegetation, had a negative relation with wind speed.

4.2. Effects of dust source and land use

Previous studies using most of the same dust trap sites in the MSGB (Reheis and Kihl, 1995; Reheis, 2006) showed that annual dust flux is related to source type as dust sources respond to yearly changes in precipitation amount, unusual wetting events, extended drought, and the combined effects of these factors on surface condition and the growth and die-off of annual plants. In the ECP, Belnap et al. (2009) used the CM sites over a 4-year period to show that land use history exerts a strong control on local dust emissions and vertical dust inputs. The seasonal data in the present study allow examination of these relations in more detail.

The MSGB sites have different primary local dust sources; however, many sites are affected by more than one dust source type (alluvial sources are ubiquitous), so source effects are almost certainly mixed. The seasonal differences in dust flux in the MSGB are relatively small, regardless of source type (Figs. 5 and 6). Sites with wet playa sources exhibit higher fluxes of total dust and fines during the summer–fall, and higher fluxes of soluble salt during the winter–spring. Salt-rich dust storms on Franklin playa, a wet playa near site T69 (Fig. 1) are closely related to wet periods (Reynolds et al., 2009a). These results partly contradict an earlier study (Reheis, 2006), which showed that wet playas produced both more salt and silt–clay during El Niño episodes. However, the

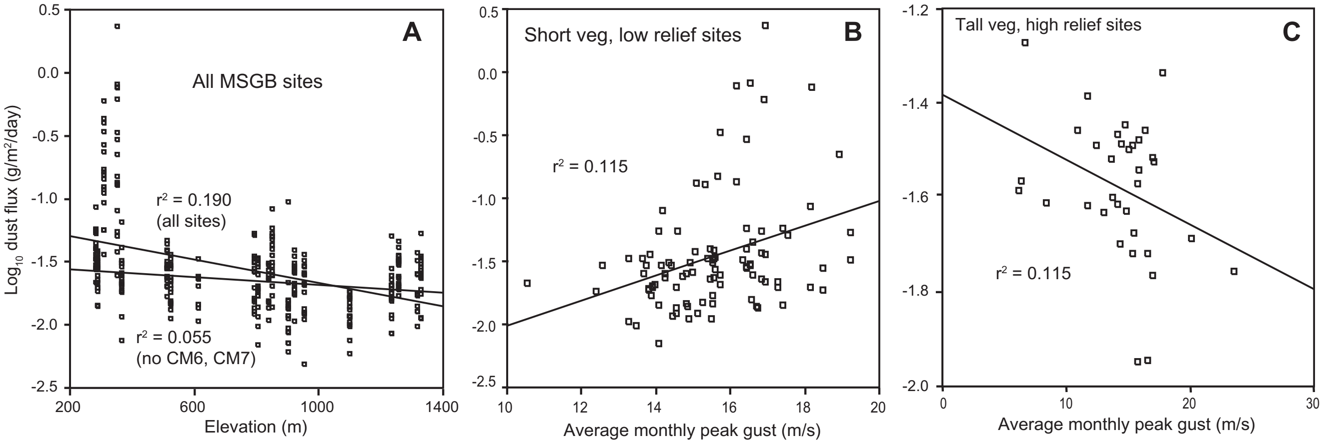

Fig. 8. Correlations of total dust flux in the MSGB area with elevation, relief, and vegetation height. (A) Dust flux with elevation; note separate correlations for all sites and omitting CM6 and CM7 (sand-transport-corridor sites). (B) Dust flux with average monthly peak gust at sites with low vegetation (~30 cm or less) and low relief (distal fans and sand plains). (C) Dust flux with average monthly peak gust at sites with high vegetation (>2 m) and high relief (hilly terrain).

present analysis used seasonal rather than annual fluxes over a different time period with no large El Niño events (Fig. 2). Dust fluxes from alluvial sources are inversely correlated with previous-season precipitation, a result that supports the significance of antecedent precipitation and consequent plant growth to dust suppression (Holcombe et al., 1987; Mackinnon et al., 1990; Musick, 1999; Musick and Gillette, 1990).

Previous studies have demonstrated the susceptibility of disturbed lands to wind erosion in the southwestern U.S. (e.g., Belnap and Gillette, 1997; Gillette et al., 1980; Nash et al., 2003). Although Tegen et al. (2004) suggest that agricultural land use is responsible for less than 10% of global dust loads, recent studies demonstrate large increases in dust flux due to historic land use on a regional scale (Lee et al., 1993; Neff et al., 2008; Reynolds et al., 2009b).

Belnap et al. (2009) showed that dust emissions in the Needles area of Canyonlands are strongly linked to previous land use, which has affected the vegetation structure and biological crust cover. Our results confirm this for a larger area of the Colorado Plateau. During the summer–fall season, and to a lesser extent in winter–spring, dust fluxes are significantly larger and more variable at the grazed-and-plowed site and at the previously grazed sites that have been invaded by annual plants than at the never grazed site. At site CM3 there is a large population of burrowing rodents that continually disturb the surface (Belnap et al., 2009) despite lack of grazing for the past 35 years. The previously grazed sites CP3 and CP4 are not completely annualized or burrowed, but both are located on west-facing slopes or ridge crests that are more exposed to wind than other ECP sites and show evidence of active aeolian sand. Thus, the higher amounts of total dust flux at the previously grazed sites are likely caused by saltating sand (Fig. 6). Our results also suggest that managed grazing in areas that have maintained perennial plant cover (sites CM8 and CP1) has not greatly increased vertical dust flux, in contrast to results for horizontal flux (Belnap et al., 2009).

4.3. Predicting dust flux in the southwestern U.S.

An important goal in this extended monitoring of dust deposition is to better understand the conditions that influence dust emissions in the southwest in order to better forecast and mitigate future emissions. As the preceding discussion demonstrates, many local (land use, localized storms, relief, vegetation) and regional (precipitation, wind) factors interact to influence dust emission and deposition. Further, some dust flux likely results from climate conditions in distant source areas (this study; Yu et al., 1992; Reynolds et al., 2001, 2006). Site groups yield better correlations with climate variables than regional groups (Tables 5 and 6), but correlation coefficients are generally lower than 0.5 and much variability in dust flux is unexplained by any one variable. In addition, some of the climate variables are co-dependent. To better evaluate these relations and account for collinearity, we performed stepwise linear regression on the geographic groups (Table 7). To ensure these are not used as predictive equations, we omit the coefficients. However, the results illustrate the most important climate variables and the combination of variables that induce or suppress dust emission.

Dust fluxes at all MSGB sites are poorly predicted by climate variables, especially in the summer–fall (Table 7). In the winter–spring, antecedent precipitation can have either a positive or a negative influence on dust flux due to the differing responses of local dust sources to rainfall (Figs. 5 and 6), in some cases stabilizing a source by increasing vegetation cover and in other cases destabilizing a source by runoff or surface efflorescence (Reheis, 2006; Reynolds et al., 2007, 2009a). When separated into more cohesive groupings, multiple regression is more successful at providing predictive relations. For example, nearly 60% of variability in soluble salt flux at Amargosa sites in the winter–spring can be explained by a combination of seasonal precipitation, average wind, and peak gust (positive) along with PDI (negative). Up to 50% of variability in winter–spring dust flux at high-altitude East Mojave sites is accounted for by antecedent and current wet conditions (high PDI values). In contrast, summer–fall dust flux at the lower Amargosa sites is related to a combination of wet seasons (causing runoff that delivers fresh sediment?) and average monthly peak gust (emission by convective winds).

Predicting dust flux using climate variables is most successful using the two south Soda Lake sites, the most cohesive group with on-site climate data (Table 6). In the summer–fall, as much as 90% of variability is explained by antecedent precipitation (negative) and present-season PDI and precipitation (positive). In the winter–spring, as much as 65% of variability in dust and sand flux is explained by PDI (negative) and sum of hours with peak gust ⩾16 m/s (positive; essentially equal to average monthly peak gust, Table 3). The closer relation of dust flux and wind at these sites, with dunes and vegetation aligned in the sand-transport corridor, may be analogous to the correlation of high wind and lateral dust transport in mesquite-dominated areas (Bergametti and Gillette, 2010). We caution that these sites are unusual within our dataset because of their location and the highly fluctuating nature of the invasive annual plant cover and sand substrate (Urban et al., 2009). Never-

Table 7
Multiple regression results for different geographic groups using climate variables.

Log of dependent variable	Summer–fall season				Winter–spring season			
	Significant variables[a] and sign	Adjusted r^2	Signif. level	Std. error of estimate	Significant variables and sign	Adjusted r^2	Signif. level	Std. error of estimate
All Mojave–southern Great Basin sites								
Total dust	x	x	x	x	−Prv2P	0.04	0.005	0.41
$CaCO_3$	+AvW	0.03	0.025	0.44	+AvW	0.04	0.027	0.69
Salt	+Prv1P	0.04	0.008	0.22	−Prv1P, +P, +PG	0.20	0.000	0.24
Sand	−Prv1P	0.03	0.025	0.55	x	x	x	x
Silt + clay	+AvMPG	0.02	0.039	0.24	−Prv2P, +Prv1P, +PG	0.09	0.001	0.37
<10 μm	x	x	x	x	+Prv3P, −Prv1P	0.14	0.000	0.36
All eastern Colorado Plateau sites								
Total dust	+AvW, −Prv2P	0.34	0.000	0.19	+AvW	0.13	0.002	0.26
$CaCO_3$	−PDI, +PG	0.18	0.005	0.27	PDI, +AvW, +Prv2P	0.35	0.000	0.28
Salt	+Prv1P, +AvMPG	0.18	0.004	0.37	−PrvPDI	0.07	0.026	0.21
Sand	−Prv1P, +AvW	0.26	0.000	0.39	x	x	x	x
Silt + clay	+AvMPG	0.15	0.003	0.20	+AvW, −PrvPDI, +Prv1P	0.36	0.000	0.22
<10 μm	+AvMPG	0.10	0.016	0.27	+AvW, −PrvPDI, +Prv1P, +P	0.44	0.000	0.26
Amargosa sites: T1–5, T9, T10, T11, T12, T13, T14 (mainly alluvial sources)								
Total dust	x	x	x	x	+AvW	0.14	0.002	0.22
$CaCO_3$	x	x	x	x	x	x	x	x
Salt	+Prv1P, −Prv3P, −P	0.31	0.000	0.25	+P, +AvW, −PDI, +PG	0.58	0.000	0.17
Sand	−PG	0.08	0.024	0.45	+AvW	0.06	0.032	0.48
Silt + clay	x	x	x	x	x	x	x	x
<10 μm	x	x	x	x	−Prv3P	0.08	0.015	0.25
East Mojave sites, low altitude: T30, T31, CM5 (mixed alluvial and playa sources)								
Total dust	x	x	x	x	x	x	x	x
$CaCO_3$	−P	0.44	0.001	0.31	x	x	x	x
Salt	−PG	0.13	0.047	0.17	−Prv1P	0.35	0.003	0.19
Sand	x	x	x	x	x	x	x	x
Silt + clay	x	x	x	x	x	x	x	x
<10 μm	−PG, −AvW	0.31	0.008	0.14	x	x	x	x
East Mojave sites, high altitude: T23, T28, T29 (mixed alluvial and playa sources)								
Total dust	x	x	x	x	−PrvPDI, −PDI	0.56	0.000	0.11
$CaCO_3$	x	x	x	x	x	x	x	x
Salt	−AvW	0.18	0.022	0.12	x	x	x	x
Sand	−PG, +AvMPG, −P1P	0.76	0.000	0.13	−AvW	0.19	0.014	0.32
Silt + clay	+P3P	0.15	0.036	0.09	−PrvPDI, −PDI	0.48	0.000	0.14
<10 μm	+AvP	0.20	0.021	0.12	−PrvPDI	0.33	0.001	0.22
South Soda Lake sites:[b] *CM6, CM7 (sand-transport corridor)*								
Total dust	A8W	0.48	0.002	0.27	−PDI, +P16W	0.60	0.001	0.32
$CaCO_3$	+P	0.29	0.032	0.42	x	x	x	x
Salt	+P	0.37	0.007	0.15	x	x	x	x
Sand	−PrvP, +P, −PrvPDI	0.91	0.000	0.13	−PDI, +P16W	0.65	0.000	0.35
Silt + clay	+P, −Prv3P, +P10W, −A6W	0.92	0.000	0.10	+P16W, −PDI	0.45	0.006	0.36
<10 μm	−Prv3P, +P	0.70	0.000	0.20	+P16W, −A2W	0.41	0.010	0.39
Tecopa-Franklin sites: T33, T34, T69 (mainly wet playa sources)								
Total dust	x	x	x	x	x	x	x	x
$CaCO_3$	x	x	x	x	x	x	x	x
Salt	x	x	x	x	+P	0.16	0.034	0.27
Sand	+P, −Prv2P, +PDI, +AvMPG, −PG	0.76	0.000	0.14	x	x	x	x
Silt + clay	x	x	x	x	−PrvPDI	0.18	0.025	0.16
<10 μm	x	x	x	x	−PrvPDI	0.20	0.018	0.20
Needles sites:[b] *CM2, CM3, CM4, CM8, CP1, CP2 (soil and alluvial sources)*								
Total dust	+P16W	0.27	0.000	0.19	+A8W, +P6W	0.24	0.001	0.21
$CaCO_3$	+P16W, −P6W	0.30	0.000	0.26	P16W, −P10W	0.31	0.000	0.25
Salt	+A2W	0.10	0.023	0.42	x	x	x	x
Sand	x	x	x	x	x	x	x	x
Silt + clay	+P16W	0.29	0.000	0.19	A8W, −P10W, −PrvPDI	0.36	0.000	0.23
<10 μm	+P16W	0.26	0.000	0.26	A8W, −P10W, −PrvPDI	0.37	0.000	0.30

[a] Variable acronyms: AvW, average wind speed; AvMPG, average monthly peak gust; PG, peak gust; PDI, average Palmer drought index; PrvPDI, average PDI of previous season; P, sum of season precipitation; Prv1P, Prv2P, Prv3P, sums of one, two, or three previous seasons' precipitation.

[b] These site groups regressed using wind variables that are sum of hours over wind speed thresholds: A(number)W is number of hours when average wind speed exceeded given threshold; P(number)W is number of hours when peak gust exceeded given threshold.

theless, the response of these sites to antecedent moisture, summer storms, and wind is similar to that of other site groups.

In summary for the MSGB, it appears that at sites not influenced by wet playas, antecedent and current moisture will suppress dust emission during the winter–spring, but summer storms may increase dust emission. This suggests that under most current scenarios of expected temperature change in the American southwest (Seager et al., 2007; Diffenbaugh et al., 2008; McAfee and Russell, 2008) and current vegetation, dust flux in most of the region will increase if winter moisture decreases and (or) summer storminess increases. Additional factors that we cannot assess here are the possible fertilization by increased CO_2 and the encroachment of exotic annual plants, as well as the possible influence of increased temperature on germination success. Models have suggested that vegetation growth due to doubled CO_2 may suppress dust globally (Mahowald et al., 2006), but the effect of such CO_2 increase on precipitation-limited desert vegetation may be small. In addition, increased CO_2 may favor propagation of invasive annual plants (Smith et al., 2000). Dry conditions in the winter–spring will increase perennial plant mortality (McAuliffe and Hamerlynck, 2010) and may suppress germination of annuals, which would enhance dust emission. Also, dust flux at relatively high altitude sites is more strongly dependent on PDI (Tables 5 and 7); thus, higher temperature and reduced PDI may significantly increase dust emissions from such areas. At sites influenced by wet playa sources, the effect of increasing drought on dust flux will depend on the type of playa and the change in depth to groundwater (Reynolds et al., 2007). With a decrease in groundwater table, whether caused by drought or pumping, some playas with very shallow groundwater may produce less dust, but others, especially those underlain by evaporate-rich sediment, may produce more dust.

Compared to averages of MSGB sites, average ECP dust fluxes are better predicted by climate variables (Tables 5 and 7). In the summer–fall, as much as 30% of the variability in most dust-flux components at Needles-area sites is accounted for by number of hours with wind speed $\geqslant 16$ m/s, with surprisingly little apparent influence by antecedent precipitation. In the winter–spring, as much as ~40% of variability in dust fluxes is accounted for by average wind speed combined with negative PDI (drought) of the previous summer. Because fine sediment, rather than locally derived sand, is dominantly deposited in the winter–spring season, and deposition rates overall are significantly lower than in the summer–fall (Figs. 4 and 5), it is also possible that long-distance transport is responsible for some of this dust.

In summary for the ECP, the majority of dust deposition is in the summer–fall and is most strongly influenced by wind speed among the climate variables we considered (Tables 4–6). Thus, a future increase in the intensity of the summer monsoon may increase dust flux on the eastern Colorado Plateau. However, both vertical dust flux and local dust emissions in this area are strongly related to surface disturbance (Figs. 5 and 6) (Belnap et al., 2009). Sites that have been grazed in the past and invaded by annual plants (CM3, CP3, and CP4) emit more dust even though they have been protected for decades. Possible increases in vegetative growth due to increased CO_2, which could decrease dust production, may be counterbalanced by a shift to invasive annual plant species as in the MSGB (Smith et al., 2000; Mahowald et al., 2006).

5. Conclusions

Dust fluxes in two study areas, the Mojave–southern Great Basin and the eastern Colorado Plateau, respond differently to changes in seasonal and antecedent precipitation, evaporation (PDI values), and wind. Dust fluxes in the MSGB are similar in the summer–fall and winter–spring and are closely linked to winter–spring precipitation as well as to summer convective storms. Antecedent precipitation tends to suppress dust flux in the winter–spring, especially at higher altitude, and dust flux is negatively correlated with altitude. Dust fluxes in the ECP are much larger in the summer–fall than in the winter–spring, and in general are twice as large as in the MSGB. ECP dust flux is more closely related to wind speed, and in the winter–spring to antecedent moisture; dust flux increases during periods of drought. The higher summer dust flux in the ECP is likely caused by gustier winds in the monsoon season when temperature and evapotranspiration are also higher. In both areas, monthly peak gust and hours above certain wind-speed thresholds are as well correlated to dust flux as average wind speed.

Source type and land use have important effects on seasonal dust flux. In the MSGB, wet playas produce salt-rich dust during wetter intervals. At sites downwind of alluvial and dry-playa sources, antecedent and current moisture suppress dust emission during the winter–spring, but summer storms appear to enhance dust emission through sediment mobilized by runoff or through direct dust emission by convective winds. In addition, fine dust flux may increase due to rainout in the summer–fall. In the ECP, land use history varies greatly among the study sites. Dust fluxes among the sites were fairly similar during the first 2 years of our study when conditions were relatively wet. However, with the onset of drought in 2000, dust flux increased and became much more variable at the grazed-and-plowed site and at three protected sites that had become dominated by annual vegetation due to previous grazing. Dust flux at the grazed-and-plowed site is as much as five times greater than at other sites in drier years. The ungrazed site, along with three currently grazed sites that have maintained perennial vegetation cover, have been much more resistant to drought and exhibited relatively consistent dust fluxes.

Finally, results of this study suggest that under predicted scenarios of future climate change, dust emission in most of the MSGB will likely increase if there is an increase in summer storms or a decrease in winter moisture, and drought conditions may also cause increased emission from higher-altitude areas. In addition, dust flux may be increased by a shift from perennial to annual plants, which are more sensitive to drought during germination periods. In the ECP, an increase in the effects of the summer monsoon or overall drought will increase dust flux, but this will be strongly dependent on land use and vegetation cover type. Although the southwestern U.S. is not considered an important source of dust globally (Mahowald et al., 2007; Prospero et al., 2002), increasing wind erosion and dust emissions may have significant local impacts on ecosystems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.aeolia.2011.03.008.

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