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Dust Emission at Franklin Lake Playa, Mojave Desert (USA): Response to Meteorological and Hydrologic Changes 2005–2008

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ABSTRACT

Playa type, size, and setting; playa hydrology; and surface-sediment characteristics are important controls on the type and amount of atmospheric dust emitted from playas. Soft, evaporite-rich sediment develops on the surfaces of some Mojave Desert (USA) playas (wet playas), where the water table is shallow (< 4 m). These areas are sources of atmospheric dust because of continuous or episodic replenishment of wind-erodible salts and disruption of the ground surface during salt formation by evaporation of ground water. Dust emission at Franklin Lake playa was monitored between March 2005 and April 2008. The dust record, based on day-time remote digital camera images captured during high wind, and compared with a nearby precipitation record, shows that aridity suppresses dust emission. High frequency of dust generation appears to be associated with relatively wet periods, identified as either heavy precipitation events or sustained regional precipitation over a few months. Several factors may act separately or in combination to account for this relation. Dust emission may respond rapidly to heavy precipitation when the dissolution of hard, wind-resistant evaporite-mineral crusts is followed by the development of soft surfaces with thin, newly formed crusts that are vulnerable to wind erosion and (or) the production of loose aggregates of evaporite minerals that are quickly removed by even moderate winds. Dust loading may also increase when relatively high regional precipitation leads to decreasing depth to the water table, thereby increasing rates of vapor discharge, development of evaporite minerals, and temporary softening of playa surfaces. The seasonality of wind strength was not a major factor in dust-storm frequency at the playa. The lack of major dust emissions related to flood-derived sediment at Franklin Lake playa contrasts with some dry-lake systems elsewhere that may produce large amounts of dust from flood sediments. Flood sediments do not commonly accumulate on the surface of Franklin Lake playa because through-going drainage prevents frequent inundation and deposition of widespread flood sediment.

INTRODUCTION

Dry lakes have been recognized as important sources of atmospheric dust (e.g., Goudie 1978, 1983; Young & Evans 1986; Shaw & Thomas 1989; Gill 1996; Prospero et al. 2002; Goudie & Middleton 2006; Washington et al. 2006). Concerns about the effects of dust on global and regional climate, air quality, human health, and ecosystems currently generate interest in the conditions responsible for dust emission from them (e.g., Gill 1996; Reheis 1997; Prospero et al. 2002; Bryant 2003; Washington et al. 2003; Goudie & Middleton 2006; Bryant et al. 2007; Reynolds et al. 2007). Bryant et al. (2007) summarized general associations between dust from dry-lakes and hydrologic change at the scale of basins and noted the need to document processes of dust emission and their underlying climatic controls at single dust sources, because large variability in these emissions remain difficult to explain (e.g., Mahowald et al. 2003; Luo et al. 2004; Zender & Kwon 2005).

At the outset, it is important to consider the types and sizes of dry lakes or playas (Shaw & Thomas 1989) along with their climatic and geologic settings, as factors that influence dust emission from them. Our study focuses on Franklin Lake playa (FLP) in the central Mojave Desert, USA (Figure 1), a small (about 14 km^2 in area), wet playa that intermittently produces dust plumes. Flood events on this playa are rare and limited to through-going channels and parts of the playa. In its small size, this playa differs from much larger ephemeral lakes elsewhere that can be globally significant dust sources (see Prospero et al. 2002; Goudie & Middleton 2006; Bryant 2003; Bryant et al. 2007). Nevertheless, the capacity to produce evaporite mineral dust at FLP (Reynolds et al. 2007) bears resemblance to significant dust producers, such as Owens (dry) Lake (California), parts of the desiccated Aral Sea, and many other dry saline lakes (Gill 1996).

Descriptions of playas, and the distinction between a wet and dry playa, are provided in several articles (e.g., Shaw & Thomas 1989; Smoot & Lowenstein 1991; Rosen 1994; Gill 1996). Wet playas are characterized by shallow depth to the saturated zone, typically less than about 4 m, thereby allowing vapor discharge through the surface. Evaporation of high-TDS ground water in wet-playa systems produces saline minerals at the surface and within sediment between the surface and ground water table (the capillary fringe zone). Wet playas may thus be closely related to saline lakes, representing conditions that span alternating states of lake expansion and drying to long-term desiccation. Surfaces of wet playas are commonly dynamic, changing over very short time spans (on the order of weeks to months) between soft and hard, having relatively thick (approximately > 5 mm) crusts. When soft and dry in the upper few cm, wet-playa surfaces may be vulnerable to wind erosion and dust emission (Saint-Amand et al. 1986; Gill & Gillette 1991; Cahill et al. 1996; Gill et al. 2002). In contrast, dry playas are characterized by greater depths to the saturated zone (> 4 m depth) and lack of evaporation of ground water at the surface, all of which lead to hard, stable surfaces of clastic sediment. Typically, dry playas do not produce much dust unless disturbed.

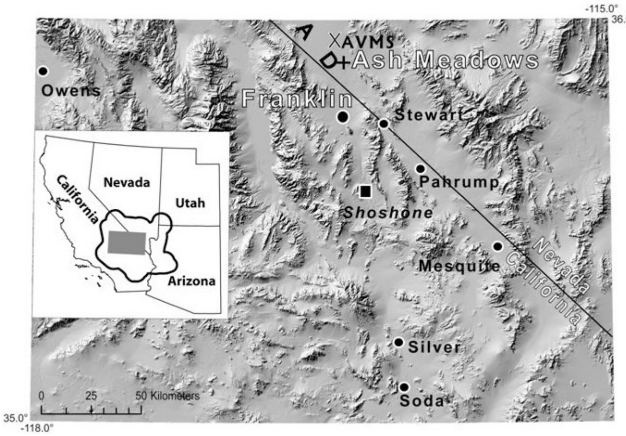

Figure 1–Location map of part of the Mojave Desert, which is indicated by the heavy line in the inset map. The map shows playas (filled circles), town (filled square), Amargosa Valley meteorological station (AVMS, denoted by X), and Ash Meadows (+). AD denote Amargosa Desert.

Many studies have characterized natural conditions of wind erosion at playas with respect to crust type, crust thickness, water content, and wind shear stress. In one set of approaches, wind erosion of natural surfaces is measured using wind tunnels or eolian sediment collectors with monitored meteorological conditions (e.g., Gillette et al. 1980, 1982, 2001; Reid et al. 1994; Cahill et al. 1996). Wind-tunnels and penetrometer tests have also been applied to samples collected in the field or prepared in the laboratory to simulate natural conditions, including varying concentrations of different salts (Nickling & Ecclestone 1981; Nickling 1984; Rice et al. 1996; Argaman et al. 2006).

Despite detailed understanding about eolian particle movement at playa surfaces, there are still gaps in understanding the many factors that promote or retard dust emission. This paper builds on previous studies, especially at nearby Owens (dry) Lake (Figure 1; Saint-Amand et al. 1986; Reid et al. 1994; Cahill et al. 1996; Gillette et al. 2001; Gill et al. 2002) and at FLP (Czarnecki 1990, 1997), to address some of the conditions that influence dust emission from FLP and their underlying causes.

Earlier work indicated that, at any one time, FLP supports many different types of surfaces varying greatly in mineral-crust properties (Czarnecki 1997; Reynolds et al. 2007). Moreover, some areas of the playa change rapidly in these properties, at times having high dust-emission potential and at other times low potential. Observations from our work (Reynolds et al. 2007) suggested important hydrologic influences on dust emission, leading to a hypothesis that relatively wet conditions, caused by high local or regional rainfall, promoted dust emission and that long-term dry conditions impeded emission. To test this hypothesis, we chose to examine the possible influences of precipitation and ground-water-depth levels on the frequency of dust emission. Precipitation and perhaps local flooding of the playa surface might enhance dust emissivity by providing new dust sources, such as clastic flood-sediment, or by temporarily removing saline-mineral crusts, thereby rendering the surface vulnerable to wind erosion before or as mineral crusts begin to re-form. A higher potentiometric surface might additionally promote development of wind-erodible saline-mineral fluff. We also considered variations in seasonal wind strength and temperature as factors that might influence dust emission (cf. Saint-Amand et al. 1986; Reid et al. 1994; Cahill et al. 1996).

SETTING

Franklin Lake playa is centered at 36.252° N, 116.375° W in the Mojave Desert of southeastern California (Figure 1). The playa covers 14.2 km^2 at about 610 m above mean sea level (Figure 2). The Mojave Desert receives most of its precipitation (50-125 mm annually) from winter frontal storms from the Pacific Ocean (Hastings & Turner 1965). Nevertheless, the frequency, seasonality, and amount of precipitation in the low-elevation parts of the Mojave Desert may vary considerably partly related to ENSO (El Nino-Southern Oscillation) states, monsoon strength, as well as tracks of winter frontal and tropical low-pressure systems.

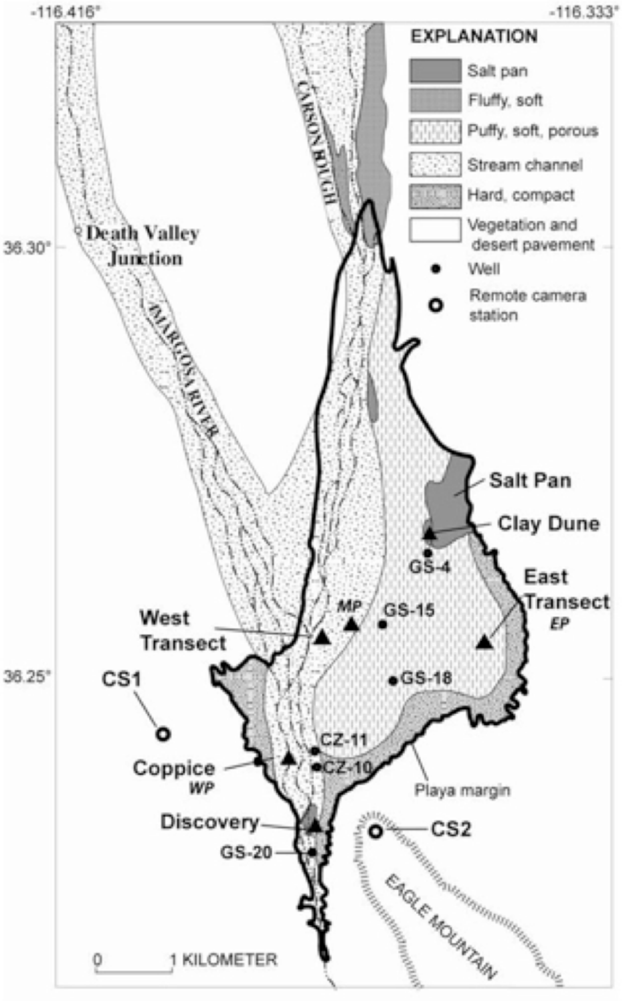

Figure 2–Distribution of surfaces at Franklin Lake playa, locations of camera sites (CS1 and CS2) and wells, and locations discussed in the text. Modified from figures 3 and 4 in Czarnecki (1997). Triangles mark the locations of study sites for erosion and crustal properties discussed in Reynolds et al. (2007): WP, west-playa at Coppice site; MP, middle-playa; EP, east-playa at East Transect site.

At FLP, as at other wet playas, the evaporative loss of large quantities of water may produce “fluffy” sediment composed of loose aggregates of evaporite minerals with a high pore-space volume (Czarnecki 1997; Reynolds et al. 2007). Some surfaces consist of more compact, but still friable, “puffy” sediment (Czarnecki 1997), having fewer evaporite minerals as a result of lower rates of evaporation and (or) lower salinity of evaporating ground water. On hot days at FLP, evaporite minerals crystallize in the capillary fringe zone within minutes of exposure of wet sediment to air. Thick saline-mineral crusts form periodically at FLP within areas that produce fluffy and puffy surfaces at other times. Common evaporite minerals at FLP include halite ($NaCl$), trona ($Na_3H(CO_3)_2\cdot 2H_2O$), thenardite (Na_2SO_4), and burkeite ($Na_6CO_3(SO_4)_2$) (Breit et al., this volume); mirabilite ($Na_2SO_4\cdot 10H_2O$) is probably ephemerally present. These minerals are derived primarily from ground-water solutes originating in ground water discharged into the basin and interaction of ground water with sediments in the valley-fill aquifer (Winograd & Thordarson 1975; Breit et al., this volume). Following heavy rain, local dissolution of evaporite minerals may also transfer solutes to the valley-fill aquifer. Reynolds et al. (2007) described surfaces at FLP and their temporal changes over two years (May 2003–May 2005) with respect to types of mineral crusts and their rheological properties that describe varying degrees of hardness.

Ground water flows southward from the Amargosa Desert to FLP (Figure 1), as described by the shallow ground-water potentiometric surface in the valley-fill aquifer (plate 1 in Winograd & Thordarson 1975). This flow is focused along the ephemeral Amargosa River and Carson Slough channels, thereby delivering solutes from throughout the valley to FLP. Ground-water salinities are relatively low in the confined flow of the valley-fill aquifer in the northern part of FLP, with TDS values of about 1000 to 5000 mg l^{-1} (Walker & Eakin 1963). Ground water from areas closer to the Amargosa River and Carson Slough, which provide most surface-water flow to FLP, have TDS levels ranging from 6000-20000 mg l^{-1}. In contrast, ground water samples from 11 sampling sites on the playa reveal enormous variations in salinity (McKinley et al. 1991), with highest salinities (TDS reaching about 70000-80000 mg l^{-1}) beneath parts of the playa to the east of the channels of the Amargosa River and Carson Slough (Figure 2). The elevated TDS in ground water at FLP reflects ground-water evaporation, with highest salinities produced in the ground water having relatively long residence times (Czarnecki, personal comm. 2006). Breit et al. (this volume) describe water-extractable solutes in the upper 2.8 m of sediment at central FLP, including depth concentrations of the trace elements, arsenic, molybdenum, tungsten, and uranium.

Unlike several other several playas (e.g., Silver Lake; Stewart Lake) in the region, FLP does not become a lake during times of heavy precipitation and runoff, although bank overflow may result in short-lived sheet flows. For example, FLP remained free of standing water during periods of heavy precipitation (238 mm near Pahrump Playa; http://www.wrcc.dri.edu/) between September 2004 and March 2005, as revealed by monitoring using MODIS and Landsat satellite images.

Dust emission from FLP has been documented previously (Czarnecki 1997) and is reported by many other observers, including nearby residents. The parts of FLP with fluffy sediments frequently emit dust under moderate winds; anecdotal information and infrequent on-site observations suggested that puffy, thinly crusted sediments are susceptible to dust emission in winds higher than about 22 m per second.

METHODS

The frequency of dust emission was determined by examining images taken by remote digital cameras triggered by wind speed at the camera site. The camera system is based on one described by Tigges et al. (2001). One camera operated between 10 March 2005 and 04 November 2006 at a height of 4 m on an abandoned telegraph pole about 200 m west of the western margin of FLP at an elevation of 610 m AMSL. Two cameras operated at a higher elevation (695 m AMSL) on a ridge near the south end of the playa between 05 November 2006 and 07 April 2008. The images acquired from the ridge cameras provided increased areal coverage of the playa, enhancing the ability to locate dust-source areas. The cameras began to acquire images when wind speed, which was sampled every 2 seconds, exceeded 4.9 m s^{-1} as a 10 minute average. Images were acquired every 10 minutes at and above the triggering wind speed.

“Dust days” were identified by examining > 14400 images downloaded from the remote cameras. A dust day was tabulated when considered significant and sustained on the basis of a series of images that showed multiple dust emissions. Cyclonic dust devils or other minor, shorter-lived events were not counted. The number of dust days reported here represents an undercount of dust emissions, primarily because nighttime dust events could not be detected. Nighttime dust emission is documented in another part of the Mojave Desert where sensors, which detect particle movement caused by wind, reveal nearly equal frequency of day and nighttime dust emission (F. Urban, written comm. 2008). Another source of undercounting is related to location of the cameras on the ridge. It is likely that this location was to some unknown degree sheltered from southerly winds and thereby that some dust plumes went unrecorded. Despite these uncertainties, the dust-day counts provide a measure of the frequency of dust emission from FLP that can be related to changing environmental conditions at FLP.

Precipitation, wind, and temperature records were obtained from the meteorological station at Amargosa Valley, Nevada (Amargosa Valley Meteorological Station-AVMS; http://www.wrcc.dri.edu/cgi-in/cemp_stations.pl?stn=amar &prod=5). This station is located at 36.5692 deg. N, 116.4589 deg. W and at 740 m elevation, 27 km north of FLP. We also obtained a partial record of wind at and near FLP (July 2005 to April 2008), using a cup anemometer at each camera station (used to trigger the cameras) and a cup anemometer at West Transect site on the playa (Figure 2).

Two separate sensor stations (Figure 2; see also Reynolds et al. 2007) were placed on the playa floor for the purpose of measuring wind speed and direction, as well as soil-moisture content using dielectric sensors placed at depths of 10, 20, and 30 cm. Hourly records began in May 2005 at Discovery site and in July 2005 at the West Transect site. Gaps in the data records occurred during March 2006 and from mid-April to mid-May 2006. The readings are recorded as a raw voltage output and have not been calibrated for the soil type to produce a true volumetric measure; however, the raw voltage readings produce a time-series record of infiltration and thus precipitation events.

Over an 18 month period from November 2006 through April 2008, we monitored ground-water depth from thirteen pre-established piezometers and wells using a steel tape, with 7-10 total measurements at each site.

RESULTS

Imaging

Over the 37 month period of record, camera images detected 71 days of dust emission. The distribution of these dust days over the sample period is uneven (Figure 3), with 33 dust days recorded within a seven-month period of the autumn of 2005 and the winter-spring of 2005/2006 and 18 more during a six-month period of autumn 2007 into spring 2008. In contrast, the period of autumn 2006 through winter-spring 2007 (spanning nearly nine months) was marked by a total of only four observed dust days. Eight dust days were noted during March 2005, the first month of camera operation, but this dusty period was followed by only one detected dust day (in July 2005) until November 2005.

Precipitation at Amargosa Valley and Soil Moisture at Franklin Lake Playa

Precipitation at the Amargosa Valley meteorological station (AVMS) was highly variable over the period of record (Figure 3). Within the 48 month period, 13 months had more than 1 cm rainfall, and 24 months had less than 0.2 mm, of which 14 had no rain. The most prolonged wet spell was from October 2004 through February 2005, with rainfall more than 2 cm per month for five consecutive months that culminated in 6.73 cm of rain during February 2005. July through September 2005 brought four consecutive months of rainfall between 0.94 and 2.45 cm per month. Another four consecutive months of rain occurred between January and April 2006, with highest amount during March (2.54 cm). A 15 month interval from May 2006 through August 2007 marked the driest period of this record. This dry spell was broken by 7.37 cm of rain during September 2007, the highest monthly amount of the record and resulting in flooding of the Amargosa River through FLP.

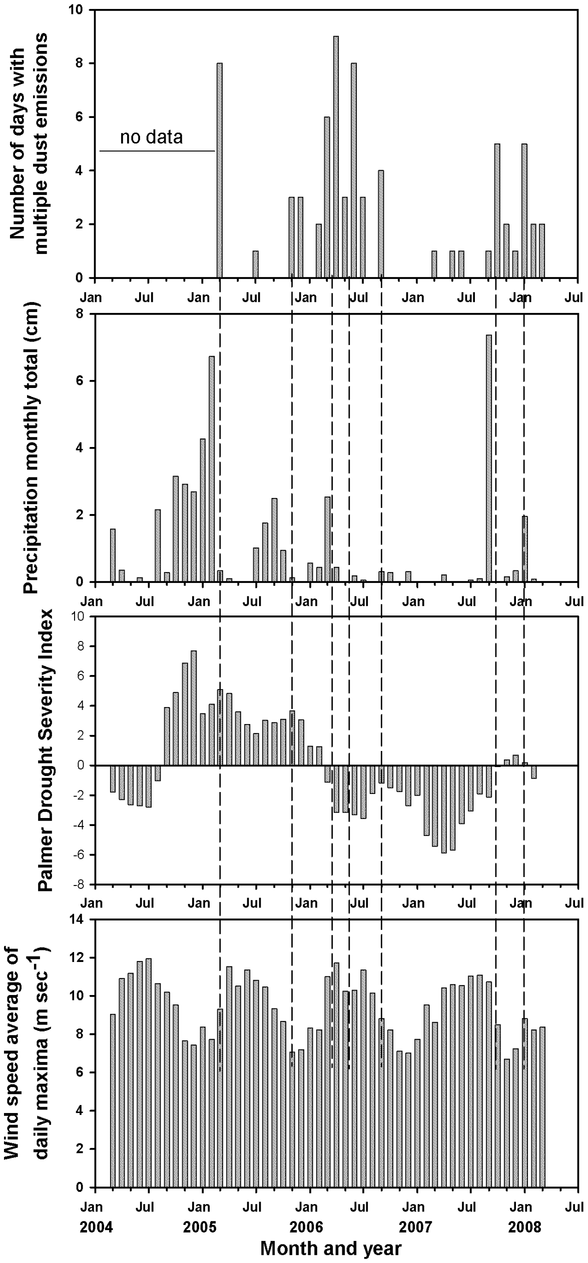

Figure 3–Plots of monthly dust days at Franklin Lake playa from examination of digital images taken by automatically triggered cameras beginning March 2005 (described in text); meteorological data (precipitation, wind) from the Amargosa Valley meteorological station (AVMS); and a modified Palmer drought index (unitless values) for the region of southern Nevada (26-04). Vertical dashed lines indicate most of the months during which a high number of dust days were detected.

Most large rainfall events recorded at AVMS are expressed by sharp changes in soil moisture at FLP. For these associated changes, we conclude that rainfall also occurred at FLP. This association is observed for all rain events > 2 mm at AVMS. These comparisons and soil moisture data at FLP indicates that rainfall at Amargosa Valley is a reliable proxy for the major rain events at FLP. As expected, some smaller rain events at Amargosa Valley are not expressed in soil moisture at FLP, highlighting the spatial variability of some smaller rain events.

Periods of sustained rainfall or drought are reflected in the Palmer Drought Index for southern Nevada (PDI; Nevada region 4; ftp://ftp.cpc.ncep.noaa.gov/htdocs/temp2/), thereby providing a general record of moisture for the study site. The PDI is a hydrological drought index used to assess the severity of dry or wet spells on the basis of the principles of a balance between moisture supply and demand (see Palmer 1965; PDI values < -1 reflect drought, < -3, severe drought). Over the period of record, the study region alternated among an initially dry period to an 18 month-long wet period, a return to a 19 month-long drought, and most recently an abrupt positive shift to near-zero PDI values since the heavy rainfall of September 2007 (Figure 3).

Because soil moisture measurements likely reflect both water content and soil conductivity influenced by solid or dissolved salts, it is difficult to assess directly the effect of precipitation on water content in near-surface sediments. Nevertheless, the very high precipitation during September 2007 apparently led to long-term wetting of the uppermost capillary fringe zone. The soil moisture reading doubled and remained at this relatively high level for seven months (through April 2008) when data were last collected. This long-term condition coincides with a shift in PDI from negative to slightly positive.

Comparison among the number of dust days, precipitation, and PDI shows several long-term (multi-month) associations. For example, the very dry interval between August 2006 and late September 2007 was a period of only four dust days (Figure 3). The highest frequency of dust days (November 2005–July 2006) occurred during and immediately following frequent rainfall (precipitation during nine of 10 months between July 2005 and April 2006). Within this interval of frequent dust emission, PDI values shifted from relatively moist to dry conditions across February-March 2006. Dust-emission frequency additionally corresponds with positive or neutral PDI (after September 2007). The results further illustrate some apparent short-term responses of dust emission to heavy precipitation. Frequent emission in March 2005 followed heavy rainfall in February, as well as several preceding months having rain. Dusty conditions in October 2007 followed exceptionally high precipitation in late September, and similarly, dust emission in January 2008 followed heavy rain just a few days earlier.

Wind

Wind strength in the area is seasonal with uniformly weakest winds during November and December; relatively strong winds typically occur from March through September (Figure 3). To assess regional winds during the 71 observed dust days at FLP, we examined wind conditions from AVMS data between March 2005 and April 2008 (the period of imaging record). For these 71 days (4.6% of the record), the maximum winds ranged 6.4-22.3 m s^{-1}, and averaged 12.8 m s^{-1} (standard deviation, 3.1 m s^{-1}). By contrast, 264 days (17.1% of the record) had maximum winds in excess of 12.8 m s^{-1}. At AVMS, daily maximum winds ranged 2.9-23.3 m s^{-1}, and the average of the maximum wind each month was 16.8 m s^{-1} (standard deviation, 2.2 m s^{-1}). Moreover, the 12 month period with few dust days had six months during which the average daily maximum wind speed exceeded 10.0 m s^{-1} at AVMS. At FLP daily maximum winds during the 71 dust days ranged 10.5-26.6 m s^{-1}, averaging 17.9 m s^{-1} (standard deviation, 3.9 m s^{-1}).

Depth to Ground Water

The depth to ground water at FLP, and hence the thickness of the capillary fringe zone, is temporally variable in places and seemingly invariant in others. Water levels that were measured in piezometers by Czarnecki (1990) during a 16-24 month period (1983–1985) showed very little variation for wells in highly transmissive sediments and large variation, sometimes gradual and sometimes abrupt, for wells in less permeable sediments. Our results between November 2006 (or February 2007 for some wells) and April 2008 show a range of behavior that includes rises (to nearly 40 cm) and declines (by as much as ~80 cm) in water levels in most wells, and little change in other wells. These measurements spanned the driest interval until the heavy precipitation of September 2007. Several wells (GS-15, CZ10, CZ11, GS-4, GS-18) had water-level declines during the dry spell that might be related to regional aridity indicated by PDI values (Figure 4). Most wells (11 of 13) showed increase in water-table elevations at some time after September 2007, and seven of 13 wells had increases in the first measurement (in November) made after September 2007.

Air Temperature

As with other North American desert settings, seasonal air temperature ranges greatly. Monthly average temperatures for July exceed 30°C, whereas winter-month averages typically ranged from 5 to 8°C. Temperature might influence dust emission in several ways. Firstly, very high summer temperatures, combined with sustained low humidity, would stabilize salt crusts to suppress dust generation (see Saint-Amand et al. 1986; Reid et al. 1994). Secondly, daytime temperatures of autumn and spring might promote evaporation and evapotranspiration, where salt grass is common, to produce evaporite minerals at and near the surface. Thirdly, temperature might control the presence and absence of mirabilite ($Na_2SO_4{\cdot}10H_2O$), the stability of which is favored at relatively low temperature (at higher temperatures thenardite is favored). Mirabilite commonly forms acicular crystals that protrude slightly above the surface, preferentially exposing it to wind. We found no correspondence between temperature and dust emission on a monthly basis, except, perhaps, for the absence of detected dust days during August.

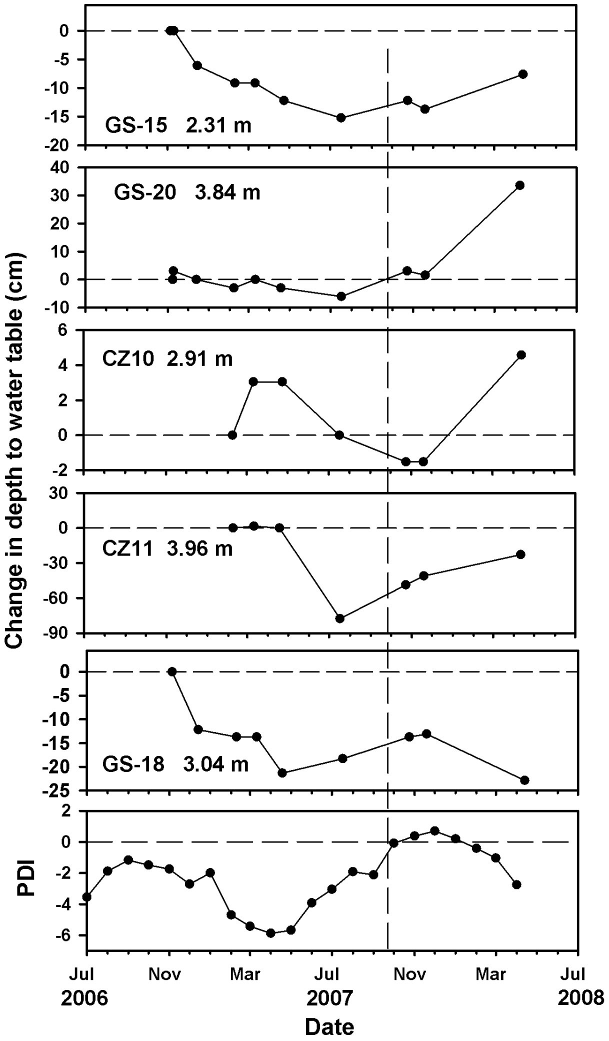

Figure 4–Plots showing changes in depth to the top of the water table beneath Franklin Lake playa over time for wells shown in Figure 2. Total well depth is given in meters after the well-site designation. Positive values indicate rises in the elevation of the water table, relative to the initial measurement in this study; negative values indicate drops in the elevation of the water table. Bottom plot shows monthly Palmer drought index (PDI; unitless values) from southern Nevada region 26-04. Vertical dashed line marks the time of the heavy rainfall during September 2007.

DISCUSSION

No single factor or condition can explain the pattern of dust emission during the study. Investigations at similar settings have demonstrated that, in addition to wind strength, properties of mineral crusts strongly control wind-erosion vulnerability of surfaces at wet playas. In the following discussion, we first consider the role of wind in observed dust emission. We do not describe here crustal properties (crustal hardness, thickness, and mineralogy; and surface moisture) but instead look beyond such factors to the temporal relations among dust emission and regional moisture balance (precipitation, ground-water levels) for clues to underlying controls on surface conditions and dust emission.

Observations at FLP and AVMS imply that wind is not a dominant control on observed dust days. The study area commonly has winds in excess of those required for eolian activity; however, many of the windiest days were not accompanied by dust emission, and emission is sometimes observed on days of only moderate wind. Most days (77%) in the area between March 2005 and April 2008 had sufficient maximum winds (> 6.7 m s^{-1}) to generate aeolian activity, but significant dust emission was observed on only about 5% of the days during imaging. Assuming that the camera system at FLP detected about half of the dust events, estimated dust emission at FLP still falls far short of the frequency and amounts expected if the surface were vulnerable to wind erosion much of the time. Nevertheless, plots of the number of dust days against monthly means for daily maximum wind speed and the average monthly wind speeds appear to indicate a very weak positive correlation between monthly dust days and monthly averages of daily maximum wind speed (Figure 5).

The results reveal an association between moisture and dust emission. For this general association, however, no single moisture condition can account for the observed wind-erosion history. At one end of the spectrum of conditions, long-term and severe aridity apparently created surface conditions that suppressed dust emission. In this respect, an important feature of the dust-emission record at FLP is the paucity of dust days from late September 2006 to late September 2007 within the very dry interval between May 2006 and late September 2007 (Figure 3). At the other end of the spectrum, periods of dust emission occurred during and as long as several months after prolonged intervals of precipitation. For example, the period having the highest frequency of dust days (November 2005 to September 2006) overlapped and immediately trailed an 18 month interval of positive PDI (Figure 3). Infrequently, dust emission closely followed high precipitation events, sometimes within a few days or weeks.

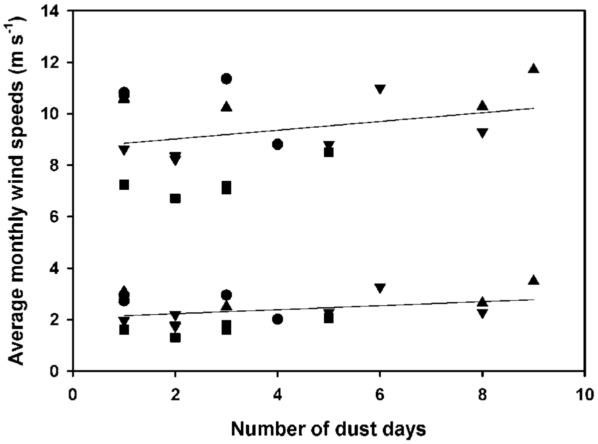

Figure 5–Plots of number of dust days against monthly wind speeds (upper plot, average of the daily maximum wind speed; lower plot, average monthly wind speed). Inverted triangles denote data for 2005; triangles for 2006; circles for 2007; squares for 2008. The regression line in the upper plot gives $r^2 = 0.08$ and in the lower plot gives $r^2 = 0.11$.

The infrequent rapid response of dust emission to precipitation may result from at least two conditions. Firstly, rainfall directly onto playa surfaces may initiate the development of soft surfaces vulnerable to wind erosion and (or) the production of loose aggregates of evaporite minerals that are easily entrained in wind. We surmise that heavy rainfall can initiate the following chain of events: (a) dissolution of saline-mineral crust, (b) movement of salts into the capillary fringe zone, (c) evaporation, and (d) rapid concentration of salts at and near the surface that are vulnerable to wind entrainment. Direct, on-site observations of the first and last links in this chain (Reynolds et al. 2007) lead us to conclude that heavy rainfall can sometimes promote dust emission shortly afterward by these mechanisms. This mode of dust generation would require sufficient rainfall to remove pre-existing evaporite-mineral crusts that previously resisted wind erosion.

Secondly, flooding might introduce fresh, fine-grained sediment into the playa area. Dust derived from flood sediments in dry lakes has been documented elsewhere. As examples, Bryant (2003) and Bryant et al. (2007) demonstrated that individual inundation events had both a rapid and lingering effect on dust emissions. Inundation suppressed dust emission but afterward had the effect of promoting dust plumes through emission of easily deflated flood sediment.

During the study period, FLP was not inundated, and, thus, the situation at this playa differs from those at large dry lakes in southern Africa that undergo occasional inundation (Bryant 2003; Bryant et al. 2007). Any flood sediment at FLP, therefore, would have been confined to channels or areas of brief overland flow that are primarily associated with the Amargosa River in the western and southern parts of the playa (Figure 2). Dust seen in the digital images can help determine the importance of flood-sediment vis-à-vis evaporite-mineral sources on the basis of dust-emission locations, whether from fluvial channels or from commonly salt-covered areas. In addition, the color of the dust would indicate whether it is derived from evaporite minerals, in which case the dust would be white, or from clastic sediment, in which case the dust would have a distinct brown or tan color by contrast. For these reasons, we examined images of dust emissions in March 2005 and October 2007 that followed heavy rainfall. In some of the March 2005 images, evaporite-mineral dust was observed likely emanating from the northeastern playa-Carson Slough area. Other March 2005 images appear to show dust composed of both evaporite and clastic minerals, but the locations of their sources could not be discerned. The October 2007 images reveal dominantly white dust, consistent with airborne evaporite minerals (Figure 6). If clastic mineral dust from channels is present, it is obscured by widespread, dense evaporite-mineral dust. Flood-derived sediment is likely a part of the dust load from FLP, but we did not see clear evidence for it during this study.

Figure 6–Digital image of Franklin Lake playa looking north from camera site 2 (CS2, Figure 2) showing widespread evaporite mineral dust. Image was taken on October 5, 2007, 13 days after heavy precipitation on September 21–22. On October 5, winds on the playa averaged 14.3 m s^{-1}, with a maximum of 20.6 m s^{-1}.

We lack evidence to document the fundamental controls on dust emission that occurred during and after prolonged intervals of precipitation, such as whether rising water-table depths increased wind-erosion by softening surfaces or increasing rates of vapor discharge. Water-well measurements indicate that heavy rainfall in and near the playa locally raised the potentiometric surface, perhaps caused by increased recharge and ground-water flow. The capillary fringe zone showed greatest thinning (relatively high water tables) in wells following the heavy rainfall of September 2007, illustrating that ground water under some parts of the playa can respond quickly (on the order of a few months) to heavy regional precipitation (Figure 4).

An indirect way to estimate possible effects of long-term moisture on dust emission is by comparing the monthly number of observed dust days to monthly PDI. For this exercise, we examined values for the same months and also with PDI shifted forward in time by one to seven months. These shifts were intended to account for time lags between soil moisture (PDI) and potential responses in ground water and then playa-surface conditions. Comparing the results for the same months, 25 dust days occurred during times of positive PDI, but most dust days (46, of 71 dust days observed during this study) occurred during months of positive PDI when it was shifted ahead by five and six months (Figure 7).

Despite lack of detailed and specific documentation about how the timing and amount of precipitation affect playa surfaces, higher frequency of dust emission appears to be related to relatively moist conditions over periods of months. This association may be related to higher moisture content in the capillary fringe zone leading to higher rates of vapor discharge and perhaps development of isolated evaporite minerals near the surface, all of which in combination may expand and soften playa surfaces. As evaporite-mineral crystals form, their mass physically displaces rock-derived clastic minerals, expanding the volume of sediment. Retention of water from direct precipitation and decreasing depth to the saturated zone are two factors that plausibly contribute to: (1) the development of soft surfaces, (2) the ephemeral development of very thin mineral crusts as well as the occasional production of loosely aggregated salt minerals at the surface, and (3) consequent dust emission with winds of varying strengths.

Our observations that changing surfaces at FLP correspond to varying hydrological conditions (Reynolds et al. 2007) are similar to observations made over many decades at wet playas and drying saline lakes in the Mojave Desert and elsewhere (e.g., Thompson 1929; Stone 1956; Neal 1965, 1972; Neal & Motts 1967; Saint-Amand et al. 1986). Recent dust emission at FLP, however, has apparently differed from the timing of dust events at Owens (dry) Lake that exhibited seasonality during the 1980s and 1990s (e.g., Saint-Amand et al. 1986; Reid et al. 1994; Cahill et al. 1996; Gillette et al. 2001; Gill et al. 2002). At Owens (dry)

Lake, efflorescent salt crusts vulnerable to wind erosion developed during late winter and spring following wintertime conditions of relatively high precipitation and low temperature. Hard, stable crust resistant to breakup by sand saltation dominated during late spring and summer under conditions of low humidity and high temperatures. This general cycle of saline crustal change can be discerned at FLP, but conditions for dust emission were possible nearly every month because rainfall and high wind have occurred over much of some years during the study period. August was the only month without significant dust emission at FLP between March 2005 and April 2008.

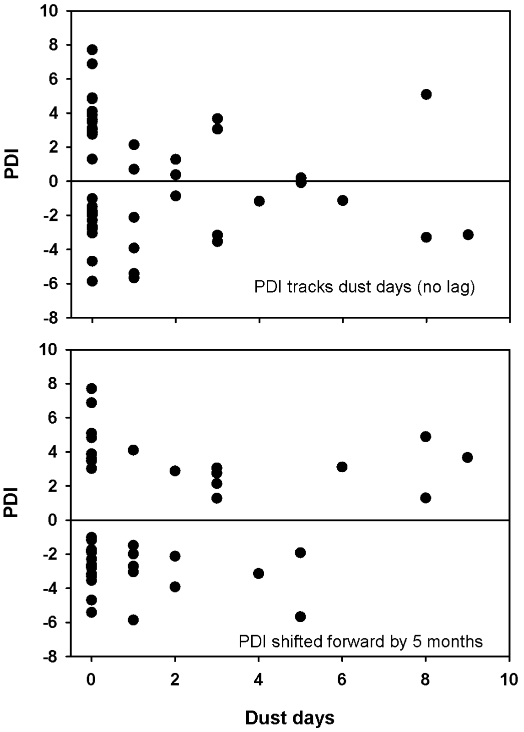

Figure 7–Number of monthly dust days plotted against monthly Palmer drought index (PDI) from southern Nevada region 26-04. In upper diagram, PDI tracks dust days for the same months. In lower diagram, PDI data (unitless values) are shifted forward in time by five months.

Dust emission in the Mojave Desert has generally occurred during the late winter and spring, as recorded by visibility data during the 1980s to the early 1990s from widely separated meteorological stations (Brazel & Nickling 1987; Bach, et al. 1996). High variations in interannual dust emission have been associated with antecedent precipitation (Brazel & Nickling 1987; Bach et al. 1996), with more dust during dry periods and less dust following heavy antecedent precipitation that encourages plant growth. This relation likely reflects the condition that sparsely vegetated landscapes dominate the Mojave Desert (see Wallace et al. 2008). Recent monitoring of dust emission from sparsely vegetated sites in the Mojave Desert reveal the importance of annual plant growth to suppression of dust emission after wet autumn, winter, or early spring (Urban et al. 2007). Wet playas, such as FLP, have a different, apparently opposite, response to precipitation. As subordinate dust sources in the Mojave Desert, wet playas in the past have not greatly affected regional dust patterns as identified from visibility analyses. Nevertheless, recent studies have detected increased wet-playa dust emission as a result of periodic heavy precipitation. By examining relations among El Niño-Southern Oscillation (ENSO) events, dust sources, and dust composition, Okin & Reheis (2002) and Reheis (2006) found that the fluxes of soluble-salt dust, and its amounts relative to silt-clay dust, increased at sites close to wet playas during regionally wet El Niño events.

CONCLUSIONS

Understanding controls on dust emission from dryland basins with dry lakes and playas remains a challenge. Comparison among recent investigations shows that different basins can have variable dust frequencies determined by responses to seasonal and inter-annual climate, sizes of basins, features of their drainage systems, and aspects of their land uses. Such variability has implications for the development of regional and global climate models, and for distinguishing between natural and anthropogenic causes of dust flux at local, regional, and global scales (Bryant et al. 2007).

Conditions at FLP are similar in some important respects to those at Owens (dry) Lake, California (e.g., Reid et al. 1994; Cahill et al. 1996) and parts of the margins of the Aral Sea that generate "white dust" (see Goudie & Middleton 2006). Conditions at FLP further appear to be similar to conditions at many other settings that emit evaporite-mineral dust, judging from the color of dust as well as the points of origins of the plumes on the basis of satellite images.

For other large and complex dust-producing areas (Etosha Pan, Namibia; the Makgadikgadi Pans, Botswana, as examples), Bryant (2003) and Bryant et al. (2007) demonstrated that atypically large inundation events had both a rapid and lingering effect on increasing dust emissions. Inundation initially suppressed dust emission but afterward promoted emission of easily deflated flood sediment. Overall, unusually heavy flooding changed the timing of dust emission by suppressing dust generation longer than typical into dry seasons and delaying peak emissions during the following dry season.

Franklin Lake playa contrasts with some globally significant dry-lake dust sources in basin size and in its incapacity to accumulate large amounts of flood sediment. Nevertheless, FLP provides an example of a dust-producing playa where a large proportion of the total dust load is composed of evaporite minerals. At FLP, sustained aridity impedes dust emission, probably by development of salt-crusted surfaces that resist wind erosion. Local and regional moisture, either through rapid effects of direct rainfall on the playa surface or longer-term (months) effects of decreasing depth to the ground-water table, seems to promote dust emission at almost any time of year by creating relatively soft surfaces vulnerable to wind erosion.

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