Effects of wind erosion, off-road vehicular activity, atmospheric conditions and the proximity of a metropolitan area on PM10 characteristics in a recreational site

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ABSTRACT

PM10 concentrations were measured at Nellis Dunes Recreation Area (NDRA), Nevada, USA. NDRA is a desert area located 6 km northeast of the metropolitan area of Las Vegas. Three sources contribute to the dust at the site: local wind erosion, off-road vehicular activity and dust production in the city of Las Vegas. PM10 concentrations were measured during one complete year and stored as 20-min averages. Grain-size distribution was also determined from sediment collected in sediment traps. PM10 concentrations at NDRA are greater, and dust is finer in April–September as compared to October–March. Concentrations are also higher during the day than at night. The diurnal pattern of PM10 concentration at NDRA is characterized by a maximum in the early afternoon and a minimum in the morning. In all months except June–August, a secondary peak in concentration occurs around midnight. The higher concentrations during the day hours are not explained by local wind erosion, by meteorological parameters such as wind speed, wind direction, atmospheric stability or ventilation, or by the supply of dust from the Las Vegas metropolis. The diurnal pattern of PM10 concentration in NDRA also differs from that observed at other rural sites in the Las Vegas Valley and in the city itself. The aberrations in the PM10 pattern at NDRA are caused by intense off-road vehicular driving in this area. Although dust from NDRA is blowing towards Las Vegas from late autumn to early spring and also during most of the nights, no quantitative data is currently available to determine the impact NDRA-emitted dust may have on the PM10 concentrations in the city.

1. Introduction

Measurements of fine particulate matter (PM10 and PM2.5, i.e. the mass of particles present in the air having a 50% cutoff for particles with an aerodynamic diameter of 10 μm and 2.5 μm respectively) have become routine in air quality studies, mainly because they are associated with numerous health effects (Dockery and Pope, 1994). Air quality is a special concern in the Las Vegas valley, southern Nevada, USA. Las Vegas is one of the fastest-growing metropolitan areas in the United States (Lazaro et al., 2004). Moreover, it is located in the desert. Apart from human-produced dust in the city, large amounts of particulate matter are also emitted from the desert surfaces surrounding the metropolis, either by natural processes (wind erosion) or human activities. In the city, the most dust is produced in the non-developed but disturbed vacant lots and during construction. Also, traffic-caused resuspension of dust accumulated on the streets is an important mechanism (Lazaro et al., 2004). Outside the city, two types of areas are known to produce dust. The first are the dry lake beds south and north of the city, which are devoid of almost any vegetation. These lake beds are surrounded by areas rich in sand, acting as an initiator for deflation (Shao, 2008). The second dust source near Las Vegas is Nellis Dunes Recreation Area (NDRA), a popular destination for off-road driving (ORV) that contains a dune area located just northeast of the city.

Because of the dustiness of the region and the effects suspended particles have on the population of the Las Vegas metropolis, several studies on dust have been carried out in the region over the past decade. They include monitoring PM10 concentrations at locations in and outside the city (Chow and Watson, 1997); determining the potential of soil and surface types to produce dust, using wind tunnels (Wacaser et al., 2006) and portable in-situ wind erosion laboratories (Goossens and Buck, 2009a); measuring in-town dust production created by traffic (Etyemezian et al., 2006);...
quantifying dust emissions on unpaved roads resulting from off-road driving activities (Goossens and Buck, 2009b); measuring dust emissions resulting from wind erosion (Goossens and Buck, 2010); mapping of surfaces in terms of capacity to produce dust (McLaurin et al., in press); investigating the environmental impacts of dust suppressants (Piechota et al., 2004); and a comprehensive air quality modeling study assessing cumulative air quality impacts in the Las Vegas valley (Lazaro et al., 2004). Most of these studies focus on PM10, although those of Goossens and Buck (2009b, 2010) also provide information on coarser grain-size fractions. Apart from these studies conducted in or close by the city, regional data on dust production and dust deposition were also collected at a number of sites in southeast California and southern Nevada (Reheis and Kihl, 1995; Reheis et al., 1995, 2002, 2009; Okin and Reheis, 2002; Reheis, 2003, 2006; Reynolds et al., 2007, 2009; Urban et al., 2009).

A study to analyze and inventory the production of dust in the Nellis Dunes Recreation Area was launched in 2007. NDRA is by far the most important hotspot for dust emissions on natural land immediately north of Las Vegas. The situation in this 37 km² large area is rather complex in that, apart from natural emissions by wind, huge amounts of dust are also produced by off-road vehicular activity. NDRA is the most popular area in southern Nevada for ORV driving and is visited by over 300,000 visitors per year (Goossens and Buck, 2009b). With or without wind, dust is produced all year round. The amount of dust produced and the seasonal wind direction at NDRA is of special concern because of the close proximity of the Las Vegas metropolitan area that contains over 1.5 million residents plus approximately 40 million tourists each year. NDRA-emitted dust is blowing towards the city during most of the autumn and winter seasons (October–February).

Studies carried out in NDRA thus far include: dust production caused by off-road vehicular activity (Goossens and Buck, 2009a); dust dynamics in and outside off-road trails (Goossens and Buck, 2009b); dust production generated by wind erosion (Goossens and Buck, 2010); and the characterization and mapping of desert surfaces in terms of dust production capacity (McLaurin et al., in press). This paper focuses on the airborne concentrations in the area, and on the PM10 fraction in particular. This fraction is of special concern because (1) it is considered the most harmful fraction with respect to health issues (Carvacho et al., 2006), (2) toxic elements usually are most abundant in the finest particle fractions (Hartyani et al., 2000), and (3) it is transported in long-term suspension, thus easily reaching the city of Las Vegas and directly affecting its population.

The aim of the study is to characterize the PM10 concentrations in NDRA, investigate their patterns diurnally and seasonally, and to evaluate to what extent emissions caused by ORV activity affect diurnal and seasonal patterns in PM10 concentrations.

2. The study site

NDRA is located 6 km outside the northeastern margin of the city of Las Vegas, Clark County, Nevada (Fig. 1). It encompasses an area of approximately 37 km².

Four major types of surfaces, each containing several subtypes, appear in NDRA: sand and sand-affected areas, silt/clay areas, rock-covered areas and zones of bedrock (Fig. 2). Drainages occur in all of these zones, but they are dry most of the year and are also producing dust.

With respect to wind erosion the most dust-productive region is the sand area in the center and southwest (McLaurin et al., in press). Much of this zone is covered by sand dunes, some of which are partly vegetated with isolated shrubs. These dunes are active all year and mainly consist of NW-SE oriented reversing dunes reflecting the bi-modal wind regime in the area: NE in the winter months, and S-SW in the summer months. Dust is produced all year round in these zones. The silt/clay, rock-covered and bedrock areas are very stable and if not disturbed, do not produce much dust through natural wind erosion.
The situation is markedly different with respect to emissions caused by off-road vehicular activity (McLaurin et al., in press). NDRA is a major hotspot for off-road driving in south Nevada. The area is visited by several hundreds of thousands of visitors each year. Forty years of unlimited off-road driving has resulted in over 537 km of off-road trails, mainly in the NW and center. Trails are also present in the NE and SE, but are less dense. Trails occur on all surface types, but for NDRA as a whole most ORV-produced dust is generated from the silt/clay and rock-covered areas. Many of the rock-covered areas contain either well-developed desert pavements with associated underlying silty A\textsubscript{v} horizons or poorly-developed and/or degraded pavements that may or may not have an associated A\textsubscript{v} horizon. ORV-produced dust is much less in the sand areas and is almost nothing in the bedrock areas.

On an annual basis the individual contributions to dust production from wind erosion and ORV use in NDRA are almost equal. However, dust production is not uniform across the NDRA. The most emissive areas are located in the SW and NW, whereas the center and entire eastern portion of the study area produce only small amounts of dust and closely reflect the situation on undisturbed desert land.

3. Instrumentation and methods

All PM\textsubscript{10} concentrations were measured with a DustTrak 8520 aerosol monitor (TSI Inc., St. Paul, Michigan, USA). The instrument was installed in the north-central portion of NDRA (Fig. 2), on a surface very resistant to wind erosion and removed from the areas with the greatest natural wind erosion and ORV emissions. Direct contributions of local sources to the dust load were thus eliminated and the dust collected can be considered sufficiently representative of the background dust at NDRA as a whole. Dust was collected at a height of 75 cm. Concentrations were measured every second and stored as 20-min averages. Data were collected over one complete year, from December 19, 2007 to December 17, 2008. Instrument calibration was performed every 14 days, but corrections were hardly necessary.

To get an idea of the variations in grain size of the dust, two vertical poles 2 m high and 2 cm in diameter were installed near the DustTrak. Dust was collected with BSNE collectors (Fryrear, 1986) at four levels: 25 cm, 50 cm, 75 cm and 100 cm. For this study we analyzed the samples collected at 75 cm (same height as the DustTrak). All samples were analyzed with a Malvern Mastersizer 2000 laser particle size analyzer (Malvern Instruments Ltd., Malvern, UK). Because the instrument measures many grain-size classes in the range 0.1 \textmu m to 10 \textmu m it was possible to examine the PM\textsubscript{10} fraction in detail. The minimum to collect enough dust for these analyses required sampling periods of 14 days. Therefore, 26 periods of 14 days were analyzed.

Wind speed and direction were measured throughout the experiment using electronic cup anemometers and a wind vane. A 20-m wind tower was erected close to the DustTrak site and three supplementary towers (one 10 m; two 20 m) were also erected in other parts of NDRA for comparison. Data from the nearby Nellis Air Force Base meteorological station, which borders on NDRA, were used to fill data gaps. Such gaps were filled only after careful calibration between the wind towers and the Nellis Air Force Base station.

![Fig. 3. Wind speed regime at NDRA. (a) average wind speed (at 20 m); (b) ratio of wind speed by day to wind speed at night.](image)

![Fig. 4. Bi-seasonal regime of wind direction at NDRA. (a) N-NE sector; (b) S-SW sector. Percentages are based on 24-h data.](image)
4. Results

4.1. Wind regime

Data on wind speed and wind direction during the measuring period are shown in Figs. 3 and 4. Wind speed was highest in April, decreased systematically until December, and then stayed more or less constant until March. This pattern applies to both the day-time (8:00 - 20:00) and nighttime (20:00 - 8:00) winds. Winds were stronger during the day hours, and the difference between day and night was more or less constant between January and August but decreased considerably from September to December. There were nearly no differences in monthly average wind speed between day and night in November and December. In March wind speeds by day were abnormally low (at least, in 2008).

There is a distinct bi-modal regime of wind direction: in the late spring through early autumn, winds blow mainly from the S and SW whereas in the late autumn through early spring they blow opposite, predominantly from the NE-E (Fig. 4). However, they can blow from any direction at any time.

Fig. 5. Frequency distributions for PM10 concentrations measured over 1 year. Numbers and percentages are shown in both linear (left) and logarithmic (right) scales. (a) 20-min periods; (b) 24-h periods; (c) day hours; (d) night hours.
We compared our 2008 data to wind data collected at the nearby Nellis Air Force Base over the past decade (1998–2008) and found that the 2008 data can be considered “normal”. The 2008 average wind speed is 3.1 m s\(^{-1}\) and average gust speed is 11.2 m s\(^{-1}\). PM10 concentration peaked at 1297 μg m\(^{-3}\) (Fig. 5b). Most frequently, PM10 concentrations were 3–4 μg m\(^{-3}\). Only 11 days in 2008 (3%) had average PM10 concentrations > 20 μg m\(^{-3}\).

PM10 concentrations vary significantly between day and night (Fig. 5c,d). Dust concentrations are greater during the day: averaging 8.50 μg m\(^{-3}\) as compared to 5.67 μg m\(^{-3}\) for the night. During the night, episodes of very low concentrations occur frequently (Fig. 5d), whereas during the day, the distribution is much less skewed, with a mode between 4 and 5 μg m\(^{-3}\) (Fig. 5c).

### 4.3. Annual patterns

Average daily PM10 dust concentrations for 2008 show several individual events (Fig. 6). The dustiest day was January 27, when PM10 concentration peaked at 1297 μg m\(^{-3}\) around noon. This value suggests that total dust concentration should have been close to 26 000 μg m\(^{-3}\), if we use the 2008 average at NDRA of a 5% PM10 content in total dust (TSP). This is very high but still realistic for intense dust storms (Hagen and Woodruff, 1973). Apart from rather short dust episodes, there are several events lasting longer than 24 h such as April 20–22, September 30 to October 3, and November 27–28 (Fig. 6).

Both the number of individual dust events and the background PM10 concentrations are higher in April through September as compared to October–March (Fig. 6). Most dusty periods occurred in mid-April to mid-May, mid-June to mid-July, and the end of September to the beginning of October. Low PM10 concentrations occurred from early February to mid-March, during the first part of November, and nearly the whole of December. Interestingly, there is substantial internal variability during periods of high PM10 emissions. During these times, many periods of low emissions can be found alternating with high dust events.

In order to more easily discern general trends, we grouped the data into monthly averages (Fig. 7). April through September show increased dust for the daily averages as well as for day and night periods separately. However, these monthly averages show that the annual cycle of PM10 concentration is more variable at night than during the day hours (Fig. 7b,c). April was exceptionally dusty, mainly because of a very high number of high-magnitude dust events and very high background concentrations between April 15 and 30 (Fig. 6).

The ratio of PM10 concentration at night to PM10 concentration by day is variable throughout the year (Fig. 8a). Several temporary

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**Fig. 6.** Daily evolution of PM 10 dust concentration at NDRA based on 24-h averages (19 December 2007 - 17 December 2008).

**Fig. 7.** Monthly evolution of dust concentration at NDRA. (a) 24-h periods; (b) day hours; (c) night hours.
high-magnitude events (HMEs) obscure the seasonal trends. To exclude these temporary events, we used \( N/D < 0.25 \) and \( N/D > 4 \) as criteria to define HMEs, where \( N \) = dust concentration at night and \( D \) = dust concentration by day. These criteria enable one to locate the 12-h periods during which HMEs (which are short, but intense events) occurred. When these HMEs are excluded, the monthly ratio of dust concentration at night to dust concentration by day is highest in October–May and lowest in June–September (Fig. 8b). Although the month of March has a lower ratio as compared to the other autumn-winter months, it does not substantially affect these trends. Therefore, PM10 concentrations at NDRA are lower at night than during the day, but the difference is more expressed in summer than in winter.

Similar trends have been reported for other deserts. For the Negev desert in Israel, Offer and Goossens (1990) and Goossens and Offer (1995) measured \( D/N \) ratios (the reciprocal of the ratio \( N/D \) studied here) during the years 1989–1992 and found patterns similar to those at NDRA. In those studies too, the seasonal trends became evident when excluding the HMEs.

To evaluate seasonal variability in grain size for the PM10 fraction, we collected dust from BSNE samplers at NDRA. The median grain diameter of the PM10 fraction was calculated for all 12 months (Fig. 9). The finest dust occurs in summer and early autumn.
whereas the coarsest dust occurs in winter. Therefore, on an annual basis, the periods of highest dust concentration are associated with fine dust and those of lowest concentration with coarse dust. Higher airborne concentrations (expressed in mass per volume) are not related to a larger mass of individual particles but to a larger number of particles per volume. In other words, during the late spring, summer, and early autumn seasons, the periods of highest dust concentration are associated with fine dust and those of lowest concentration with coarse dust.

4.4. Diurnal patterns

The diurnal variation of PM10 concentration at NDRA is shown in Fig. 10a for each month. The picture is complex because the baseline of the curve varies throughout the year: minimum concentrations are considerably higher in summer than in winter.

Adjusting the curves to the same baseline (Fig. 10b) shows that during the summer months, monthly average diurnal PM10 concentrations are considerably higher, and also more variable as compared to the winter months. Notice also that PM10 concentrations peak more sharply in the hottest months (June–September) than during the coldest months (November–February).

When the results are normalized (Fig. 10c) we see that all months have increasing dust concentrations in the morning and a subsequent drop in the afternoon. In the morning, both the rate and uniformity of the increase in monthly average PM10 concentrations are highly variable. In the afternoon the drop in PM10 concentration is much more uniform and the rate of decrease is constant year round. Presenting the curves separately for each month (Fig. 11) we see that, at night, several months show a secondary maximum. In summer (June–August) no secondary peak occurs at night. For the remaining months, there are two maxima, a major in the early afternoon and a minor (sometimes double) at night. The nocturnal maximum is most pronounced in the winter months (November–February) and then decreases until it has disappeared in June.

Monthly average diurnal PM10 concentrations can be grouped into two distinct periods: October–March and April–September (Fig. 12a). In the period October–March PM10 concentration peaks in the early afternoon and at night; in the period April–September there is only one peak, in the afternoon. Also, a small plateau is apparent in both curves in the morning, around 8:00 in the period April–September and somewhat later, around 9:00, in October–March. The 1-h difference and the sharper peak in April–September result in a substantial difference in shape of the
curves in the morning; in the afternoon both time periods behave identically. To try and gauge any seasonal patterns, the monthly average diurnal PM10 concentrations were grouped according to the 4 meteorological seasons (Fig. 12b). The seasons show great variability in morning PM10 concentrations, but similar afternoon behaviors.

On a monthly basis, we compared the morning hours when the increase in PM10 concentration started (Fig. 13a). In winter, the increase starts somewhere between 5:00 and 5:30 (November and December), changes to approximately 3:30 in January, and then increases to between 4:00 and 5:00 in February and March. From April onward the hour slides back to midnight (in June—August) and then moves forward again in autumn. Note that the data for April may not reflect the average long-term pattern because of the many HMEs that occurred in 2008.

No significant monthly variation is observed for the hour when dust concentration starts to decrease in the afternoon (Fig. 13b). Concentration thus reaches its maximum at more or less the same hour (between 14:00 and 16:00) all year round.

Lastly, PM10 concentration curves are shown for the two major wind directions in the Las Vegas region (Fig. 14). From April to September winds blow predominantly from the S-SW; from October to March they blow predominantly from the NE-E. Because of the difference in wind regime between these two periods, and also because the diurnal pattern of PM10 concentration is different, we split the data in Fig. 14 in two figures: one for October—March (Fig. 14a) and the other for April—September (Fig. 14b). The figures were constructed by selecting those days where the wind blew from the northeastern (or southwestern) sector during both the night hours and the day hours, i.e. there is very little risk that short-term variations in wind direction during a day have affected the result.

Looking at the period October—March (Fig. 14a) there are no substantial differences between the two wind directions, except that during NE-E winds an extra peak occurs between 8:00 and 9:00 in the morning. S-SW winds do not show this peak. The situation is similar during April—September (Fig. 14b). Here too the extra peak between 8:00 and 9:00 is very pronounced during NE-E winds whereas it is much less expressed during S-SW winds. Additionally, in the period April—September PM10 concentrations are much higher during the morning when wind blows from the NE-E.

5. Discussion

Apart from emissions caused by wind erosion or human activity, dust concentration is expected to depend on atmospheric processes affecting transportation, concentration and/or dilution of airborne particles. For the NDRA the proximity of the Las Vegas metropolis requires special attention because of the huge amounts of PM10 produced in the city. In this section we investigate the effect of these factors on the PM10 characteristics at NDRA.

Diurnally, wind speeds and PM10 concentrations behave similarly throughout the year with a maximum in the early afternoon and a minimum in the morning (Fig. 15). However, they do not evolve in parallel. On average, dust concentration at NDRA runs 2 h ahead compared to wind speed (Fig. 15a). This difference is greatest
from April to September (Fig. 15b). In October to March the peaks in the afternoon coincide much closer, but the difference of 2 h is still apparent in the morning (Fig. 15c). That dust concentration at NDRA is not predominantly related to local wind speed is further illustrated in Fig. 16. There is no correlation between the parameters, either during the day or night hours. Studies based on long-term series of observations (i.e. not focusing on stormy events) also show that high dust concentrations do not necessarily occur during periods of high wind speed, even when the topsoil is dry (Offer and Goossens, 1990; Goossens and Offer, 1995; Chow and Watson, 1997). In a recent study carried out near Delhi (India), Tandon et al. (2010) compared the diurnal cycles of dust concentration and wind speed and found no parallel evolutions for either coarse (>10 μm) or fine (<10 μm) particle fractions.

We compared dust concentrations at NDRA with wind direction (Fig. 17). We used a wind speed below 3 m s\(^{-1}\) as a criterion for non-erosive periods, which is well below the wind erosion thresholds of 6–7 m s\(^{-1}\) for non-stabilized sand surfaces and 9–10 m s\(^{-1}\) for non-stabilized silt surfaces. During non-erosive periods dust concentration is close to uniform for all wind directions; only the N-NE sector shows (slightly) lower values (Fig. 17). During very windy periods (wind speeds above erosion threshold, i.e. local wind erosion is likely) the pattern becomes very asymmetric, with much higher concentrations during S, SW or W winds. These are also the directions where the most emissive zones in NDRA are located relative to the spot where PM10 concentrations were measured. Does this mean that the PM10 concentrations in this study were mainly determined by wind erosion? To test this hypothesis we calculated the diurnal patterns of dust concentration for the stable and windy periods separately (Fig. 18). During stable periods (no wind erosion) the pattern is very similar to the average annual pattern (Fig. 15a). This result shows that wind erosion is not the dominant factor determining the afternoon PM10 peak at NDRA. On the contrary, during wind erosion, concentrations show a clear tendency to be highest at night (Fig. 18).

An important atmospheric parameter affecting fine particulate concentration is atmospheric stability, which by itself is related to radiation (and, hence, temperature) and wind shear (i.e. wind speed). The literature states that PM10 concentrations are highest in stable atmospheres (usually at night) because of the reduced...
height of the mixing layer and limited ventilation (Choularton et al., 1982; Chow and Watson, 1997; Zhao et al., 2009). Vertical wind and temperature data were collected from the North Las Vegas Airport (NLVA) Integrated Upper-Air Monitoring Station, which is located only 20 km west of NDRA. This station records hourly values of wind speed up to 3 km altitude and hourly values of temperature and humidity up to 10 km altitude. NLVA started collecting data from September 11, 2009 onward. Although this NDRA study was carried out in 2008, reliable stability patterns can be calculated because the pattern of temperature is fairly constant from one year to another. Comparing atmospheric stability to PM10 concentration we find that the highest PM10 concentrations occur when atmosphere is unstable and lowest concentrations when atmosphere is stable (Fig. 19). Also, note that there is a lag of approximately 1.5 h between the peak in PM10 concentration and the peak in atmospheric instability in the early and late afternoon. Therefore, diurnal evolution of PM10 at NDRA is not a result of changes in atmospheric stability.

To investigate the potential effect of PM10 production in Las Vegas, data from various stations located in the Las Vegas Valley were analyzed. Most stations are located within the conurbations of Las Vegas/North Las Vegas/Henderson, Boulder City and Mesquite, and are heavily affected by traffic and construction works. Therefore, these stations are not useful comparisons to explain PM10 patterns at NDRA. However, there are two rural stations that can be studied. Apex station is located 32 km northeast of the center of Las Vegas, 12 km north of NDRA (see Fig. 1). Jean station is located 50 km SW of the city center. A third station in the center (Sunrise Acres, in Las Vegas) was also selected for comparison. Hourly PM10 data were collected from these stations, for the period investigated in this study (19 Dec 2007 – 17 Dec 2008). The location of the stations is very fortunate for investigating the effect of Las Vegas on the PM10 patterns in NDRA. Because of the bi-modal wind regime in the region one station will always be located upwind, the second downwind and the third in the center of Las Vegas.

The monthly averages of the ratio of PM10 concentration at night to PM10 concentration by day are similar for the rural stations of Apex and Jean (Fig. 20a, b). In general, the ratio is highest in summer and lowest in winter (note that the pattern is more irregular in Apex compared to Jean). In Sunrise Acres (Fig. 20c) seasonal effects no longer occur. This could be expected since there is human activity in the city all year round.

Fig. 17. Hourly average PM10 concentration (µg m⁻¹) as a function of wind direction. (a) windy periods (wind erosion likely); (b) calm periods (no wind erosion). See text for criteria.

Fig. 18. PM10 concentration and probability of wind erosion in NDRA.

Fig. 19. PM10 concentration and atmospheric stability at NDRA. Stability was measured as T100 – T0, where T100 = temperature at 100 m altitude and T0 = temperature at ground level. Curves are based on hourly averages and were normalized to facilitate comparisons. The figure shows the annual average.
These patterns differ significantly from that found at NDRA (Fig. 20d). Monthly average PM10 concentrations are always higher during the day hours than at night (note the small difference in January). This differs from the two other rural stations, where at least several months during the year nocturnal concentrations are higher. In the city, concentrations are also highest at night (Fig. 20c). Secondly, the annual pattern is different. In NDRA the ratio of dust concentration at night to dust concentration by day is lowest in summer and highest in winter. In Jean and Apex the situation is reverse.

Comparing the annual average of diurnal PM10 concentrations for the two primary wind directions shows that NDRA differs from the other stations (Fig. 20e–h). Apex, Sunrise Acres, and SW winds at Jean show higher PM10 concentrations during the night hours than during the day. Chow and Watson (1997) attributed the high PM10 concentrations during the day at Jean during NE wind to

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**Fig. 20.** Comparison of PM10 patterns for Apex, Jean, Sunrise Acres and NDRA. (a–d) monthly averages of the ratio of PM10 concentration at night to PM10 concentration by day; (e–h) diurnal pattern of PM10 concentration (curves are annual averages for the two wind directions shown).
inflow of dust from Las Vegas, especially during the rush hours. Rush hour effects in the city are substantial. PM10 curves for Sunrise Acres show a local peak in concentration in the morning (Fig. 20g). For S-SW winds it appears 2 h earlier because these winds mainly occur in the spring and summer whereas the N-NE winds mainly occur in the autumn and winter. In summer, many people in Las Vegas start working very early in the morning to take advantage of the cooler temperatures. No extra peak in PM10 concentration is observed in the afternoon, most probably because the end of the working-day is much more flexible.

The PM10 curve for NE winds for Jean shows two peaks during the day hours. The first, around 9:00, may result from inflow of PM10 produced in Las Vegas during the morning rush hour (see Chow and Watson, 1997). The 3-h difference with Sunrise Acres, 6:00 in Sunrise Acres and 9:00 in Jean, can be explained by the distance between the stations (50 km, which fits well with the average wind speed of 4–5 m s⁻¹, see Fig. 3a). The second peak, around 16:00, is less well developed. A dry lake 5 km ENE of Jean is used as a place for off-road driving activities, though much less intense than the Nellis Dunes. These activities could contribute to the small peak in the afternoon during NE winds. There are no large urban or recreation areas south and southwest of Jean. For this sector, minimum PM10 concentrations occur during the day and maximum concentrations at night.

The Apex station also shows a (small) peak in PM10 concentrations for winds blowing from the city center (Fig. 20e). This peak occurs approximately at noon. However, it is questionable whether this peak is caused by urban rush hours because it occurs at least 6 h later than the one at Sunrise Acres. The distance between the stations is 32 km. In order for the Apex mid-day peak to be a result of rush hour traffic, the average wind speed must be as low as 1.5 m s⁻¹, which is much lower than the actual values (shown in Fig. 3a) even if the greater surface roughness of the city is considered. A similar, although smaller, peak in concentration occurs in the Nellis Dunes around 12:00 for S-SW winds (see Fig. 14, which is based on 20-min data instead of the 1-h data in Fig. 20). Therefore, for both Apex and NDRA the patterns of PM10 concentration cannot be explained by rush hour effects produced in the conurbation of Las Vegas.

This conclusion is further supported by two observations. First, the increase in PM10 concentration in the morning at NDRA begins while the winds are still blowing from the N-NE sector (the common situation at night, both in autumn–winter and in spring–summer); there is a difference of about 2 h between the increase in dust concentration and the change in wind direction (Fig. 21). Also, in April–September, concentrations in the afternoon start to decrease well before the wind starts blowing from the eastern sector. Second, at NDRA PM10 concentration is always highest during the day hours, even when winds blow from the NE sector. This sector is much less dust productive than the SW sector. Apart from a power plant in Moapa 50 km to the northeast, the only substantial dust sources northeast of NDRA are Milford Flats and Sevier dry lake, both at a distance of 350 km, and Dugway Proving Grounds, about 450 km from NDRA. A quarry, a landfill and a (small) dry lake 7, 12 and 20 km north of NDRA respectively do not affect the area during NE wind conditions (dust from these sources does not flow over NDRA during NE winds). It is very unlikely that the more distant sources determine the diurnal PM10 pattern at NDRA because the dust plumes they generate are already significantly diluted upon arrival at NDRA. These sources could affect weekly, monthly, seasonal or annual PM10 curves by creating spikes of high concentration when active, but not diurnal curves. Variations in PM10 on a time scale of only hours or even less do not scale with the distance of these sources to NDRA. A further argument that distant sources do not explain the diurnal pattern of PM10 concentration is that the S-SW curve for Jean is not affected by S-SW located dust sources. Ft. Irwin tank training base is an important dust source 110 km SW of Jean, and several dry lake beds occur as close as 15–30 km S-SW of the Jean station. None of these appear to affect the diurnal PM10 pattern at Jean, although they may explain spikes of high dust concentration in weekly, monthly or annual PM10 curves.

Therefore, a local dust-producing mechanism must exist to explain the patterns of PM10 concentration at NDRA. It should preferentially be active during the day, and be more productive in summer than in winter. Off-road vehicular activity is the only realistic explanation. We recall that the number of ORV visitors at NDRA currently (2010) is close to half a million annually. Previous research (McLaurin et al., in press) showed that many surfaces in NDRA (especially the silty and silty rocky substrata) produce huge amounts of dust during ORV activity. ORV driving in NDRA occurs during the day hours only because of the absence of lighting and the rough and dangerous terrain. In addition there is much more dust production (by ORV) during the summer months compared to the winter months because the period of daylight is longer and the number of driving hours is higher. During our fieldwork, we observed that the intense heat during the summer months does not restrict the population from driving in the area. Measurements (unpublished) also show that the annual production of ORV-generated PM10 exceeds the production of wind erosion generated PM10 at NDRA. For all these reasons it is plausible that the diurnal pattern of PM10 concentration at NDRA is determined by the intense ORV activity in the area. The role of other factors such as inflow of PM10 from Las Vegas, local dust production by wind erosion, the effect of atmospheric stability, or the potential inflow

![Fig. 21. Comparison of diurnal evolutions of PM10 concentration and wind direction. (a) April–September; (b) October–March.](image)
of PM10 from distant sources, is subordinate to that of ORV activity. The effect of atmospheric stability, which usually is very dominant (see Fig. 20e–g), does not change the diurnal PM10 pattern at NDRA because nearly all PM10 produced by ORV during the day has already left the area well before midnight. The diameter of NDRA is only about 7 km; at an average wind speed of 4–5 m s−1 (see Fig. 3a) it takes less than 30 min to evacuate locally produced PM10 particles.

6. Conclusions

Two mechanisms of dust production occur in NDRA. Wind erosion in the sand dunes and on loose, uncompacted silty substrata in the center and west produce dust during periods of strong wind. All year round, off-road vehicular activity adds additional dust to the atmosphere. On an annual basis, the amount of dust produced at NDRA by ORV activity slightly exceeds the amount produced by wind erosion.

At NDRA PM10 concentrations are highest during April–September and lowest from October–March. They are also higher during the day than at night. Short-term high-magnitude wind erosion events may occur all year but are most abundant in spring. During such events PM10 concentrations can be very high, up to 1300 μg m−3 and more.

At NDRA PM10 is finest at the end of the summer and coarsest in winter. Median grain diameter in summer is around 3 μm compared to 4 μm in winter.

The diurnal pattern of PM10 concentration at NDRA shows a maximum in the early afternoon and a minimum in the morning. In winter, a secondary maximum occurs around midnight and two nighttime peaks occur in October–December and March–April. Summer months show only one maximum, in the afternoon. Also, the duration of high PM10 concentration is shorter in the summer: from 11:00 to 18:00 as compared to 7:00 to 18:00 in winter.

No correlation was found between PM10 concentration and wind speed. High concentrations were observed at all wind speeds, and high wind speeds did not necessarily result in high PM10 concentrations. Therefore, the higher concentrations during the day are not related to local wind erosion. They are also not explained by the diurnal pattern of atmospheric stability. Highest concentrations are observed in the early afternoon, when atmosphere is unstable and mixing height and ventilation are large. Lowest concentrations are observed at night, when atmosphere is stable and mixing height and ventilation are small. Importation of dust from the nearby conurbation of Las Vegas also does not explain the diurnal pattern of PM10 concentration at NDRA. No rush hour effects are present, and the increase in PM10 concentration in the morning occurs well before the wind starts blowing from the city. Also, peaks in PM10 concentration occur when winds are blowing from the much cleaner northeastern sector.

Off-road vehicular activity in NDRA is the most plausible mechanism for generating the diurnal and other patterns of PM10 concentrations recognized in this study.

Although dust from NDRA is blowing towards Las Vegas from late autumn to early spring and also during most of the nights, no quantitative data is currently available on the impact NDRA-emitted dust may have on the PM10 concentrations in the city. More research is necessary to determine the degree of dilution as the dust blows towards the city, and how concentrations change with the increased surface roughness in town.

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