February 24, 2025

Memo: Toward a Data-Informed Metric for Assessing Progress Leading to PM_{10} Reductions Downwind of the ODSVRA

From: Scientific Advisory Group (SAG)

To: Gary Willey, SLO Air Pollution Control District

Cc: Sarah Miggins, California Department of Parks and Recreation
Jon O'Brien, California Department of Parks and Recreation
Ronnie Glick, California Department of Parks and Recreation
Karl Tupper, SLO Air Pollution Control District

At the October 15, 2024, meeting of the SLO APCD Hearing Board a request was made by Board members to develop a simple, evidence-based method to demonstrate that the dust-mitigation efforts within the Ocean Dunes State Vehicular Recreation Area (ODSVRA) are continuing to yield improved air quality in downwind communities. During the meeting, the SAG Chair noted that there were already several lines of evidence demonstrating a trend to reduced dust emissions, including:

1. Results of computer simulation modeling show that current dust emissions from the ODSVRA are less than for the pre-disturbance scenario[1], consistent with the requirements of the Stipulated Order of Abatement (SOA #17-01 with modifications);
2. Actual measurements of dust concentrations and meteorological conditions at various monitoring stations over the last 8 years[2], such as:
    i. reduction in the number of hours of $PM_{10} > 300$ µg m^{-3} at CDF and Mesa2;
    ii. reduction in annual violations of Rule 1001, which have decreased from more than 65 in 2017 to fewer than 12 in 2023;
    iii. reduction in the number of exceedances of the California Ambient Air Quality Standard (CAAQS) of 50 µg m^{-3} (averaged over 24 hours) despite enhanced windiness recently; and
    iv. continued decrease in the ratio of Total PM_{10} over Total Wind Power Density, which is a metric that summarizes annual dust concentrations as normalized by wind energy for the period April through September.

Nevertheless, Board members expressed interest in a simple, measurement-based metric that was convincing and easily comprehended. In this memo, the SAG proposes a possible option for consideration, but with the following provisos:

[1] See SAG presentation given at the October 15, 2024 Hearing Board meeting, available at https://storage.googleapis.com/slocleanair-org/images/cms/upload/files/Hearing%20Board_SAG%20Presentation_Oct%2015%2C%202024_FINAL2.pdf
[2] See graphs in APCD presentation given at the October 15, 2024 Hearing Board meeting, available at https://storage.googleapis.com/slocleanair-org/images/cms/upload/files/KT-HB-Oct2024-final.pdf

1. A single metric is unlikely to provide a complete picture of a complex dynamical system that evolves progressively over multiple years;
2. Assessments of progress toward management objectives are most appropriately based on the preponderance of scientific evidence available (i.e., multiple data sources and general trends and outcomes that are aligned);
3. Measurements from fixed instruments are inherently site-specific and are unable to reflect broad spatial patterns unless they are part of a comprehensive network. Thus, data trends from one measurement site may differ from those at other sites, given the nature of spatial variability;
4. The simplest data representations (e.g., number of hours/days above a certain threshold PM_{10} value) are subject to considerable temporal variability, because of changing meteorological conditions (windiness, moisture) and altered surface/land use patterns (vegetation cover, Off-Highway Vehicle (OHV) traffic). Simplistic metrics, although easy to comprehend, are not necessarily indicative of the overall effectiveness of dust mitigation efforts in the ODSVRA;
5. Adopting a threshold condition or critical value of a single, data-based metric as a sentinel to trigger management or regulatory action is unwise because it involves subjective decision-making as to an “acceptable” level of PM_{10} concentration. A condition of “no dust at any time” is not a viable option, whereas a decision on “how much dust can be tolerated” should be based on medical, epidemiological, and environmental evidence; and
6. Understanding dust emissions and subsequent transport and dispersion is an exceedingly complex undertaking, and some of the inherent complexity must be appreciated and accommodated when interpreting a simplified metric intended to demonstrate progress toward a fixed dust concentration objective.

With respect to the latter proviso, it needs to be acknowledged that the ODSVRA is inherently dusty due to natural conditions beyond human control. Exceedance of the CAAQS will occur during particularly windy periods. A management objective that strives to reduce dust emissions to levels below the CAAQS at all times of the year is not realistic given the expansive sand sheets and dunes characterizing the coastal landscape.

It is also important to recognize that there is a fundamental difference between an evidence-based metric intended to demonstrate progress toward a management objective (the subject of this memorandum and accompanying report) and a metric used to indicate regulatory compliance such as conditions prescribed in Rule 1001 and by CAAQS and federal air quality standards. **The Stipulated Order of Abatement defines regulatory compliance according to current dust emissions being less than or equal to pre-disturbance conditions**.

During the October 15, 2024, Hearing Board meeting, robust and reliable evidence from a state-of-the-art simulation model was presented that indicates compliance with the SOA has been achieved. Given that Hearing Board members seemed reticent to embrace the results of the SOA-stipulated and CARB-approved simulation modeling because of its perceived complexity, the SAG has investigated trends in instrumentally-sourced measurements that are guided, in part, by CAAQS and Rule 1001 requirements. In short, this report intends to add to the preponderance of evidence that demonstrates that the dust-mitigation efforts within the ODSVRA continue to yield improved air quality in downwind communities.

The accompanying report explains the various data analysis methods used to develop a data metric that Hearing Board members might consider as a reliable indicator of progress toward achieving the mandates of the SOA. It is but one of myriad possibilities—all with certain challenges and complexities—but it is one that the SAG is comfortable in recommending.

The proposed metric is a normalized (by wind speed) PM_{10} concentration value that uses hourly measurements of PM_{10} from the CDF monitoring station. The metric uses data only from the 9 am to 6 pm period, which is when PM_{10} concentrations typically reach their maximum, as driven by daily increases in onshore westerly wind speeds (as a function of the diurnal land-sea breeze cycle common to most of the south-central coast of California). By focusing on the peak concentration period in each day, all data 'noise' associated with reduced PM_{10} concentrations during the early evening and through to the early morning are removed from consideration because they unduly influence the summary statistics that characterize air quality conditions. In addition, a directional filter is applied to eliminate periods with winds from the north, east, and south because they do not traverse the ODSVRA before influencing measurements at CDF.

The metric includes only those days for which the 9 am to 6 pm (9-6) mean PM_{10} concentrations at CDF exceed a threshold value of 99.9 $\mu g\ m^{-3}$ (for reasons explained fully in the report below). For these high-concentration days, or 'events' with above-normal PM_{10} concentrations, the 9-6 mean PM_{10} values are normalized by the 9-6 mean wind speed from the S1 tower, situated within the ODSVRA (which is the most reliable indication of wind conditions within the dust source area). This is a necessary step given that wind speed is the primary driver of dust emissions from sandy surfaces and to account for the fact that average wind conditions change substantially from day-to-day, month-to-month, and year-to-year. Finally, the annual average of this ratio (9-6 mean PM_{10} divided by 9-6 mean wind speed) for all the event days in a year is calculated for each year of the data record from 2016 to 2023 (i.e., average of the ratio for all events per year).

A plot of these values (Figure A1: see Figure 23 in report for fuller explanation) indicates that there has been a gradual, but steady decline in the ratio from values of about 20 in 2016 and 2017 to less than 15 in 2020 and thereafter. The general decrease in the ratio value is suggested to be indicative of the dust-suppressing effects of management interventions within the ODSVRA instituted by State Parks, whereas the relatively stable value of the ratio since 2020 may indicate that an equilibrium has been achieved.

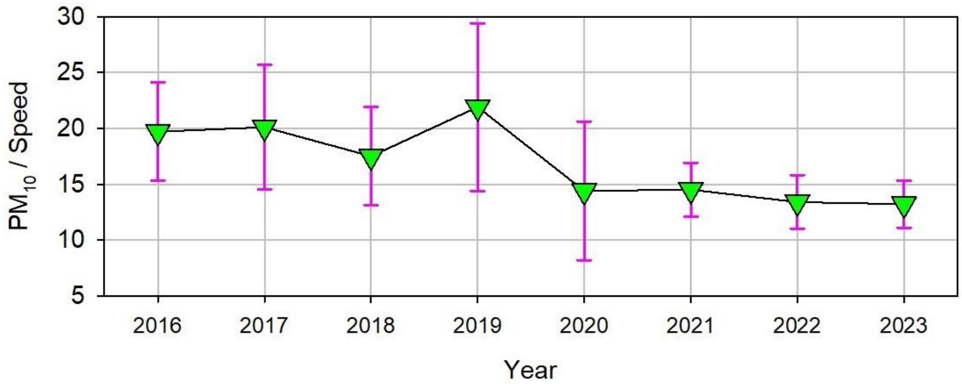

Figure A1: Trends in the annual average ratio of 9-6 mean PM_{10} concentrations at CDF for event days normalized by the associated 9-6 mean wind speed from the S1 tower. Error bars show the span of the standard deviation of the event ratio values for each year.

Despite the concerns expressed by Board members regarding the complex nature of the simulation modeling, the SAG is steadfast in its support of the simulation model as a reliable mechanism by which to assess whether compliance with the SOA has been attained. The US EPA and CARB endorse using air quality models to inform decisions on attainment or non-attainment of US Clean Air Act criteria pollutants including PM_{10} and $PM_{2.5}$, and to subsequently develop management strategies to achieve attainment of air quality standards. In addition, simulation modeling incorporates complicated system dynamics that are not captured fully by PM_{10} measurements at fixed locations.

Given the absence of PM_{10} measurements extending back to the pre-disturbance period, there is no means other than simulation modeling by which to estimate what dust emissions from the landscape currently utilized by the ODSVRA might have been like prior to the significant impact of humans. Thus, there is no measurement-sourced baseline against which to judge progress toward the management objective of reducing dust emissions from the ODSVRA to a pre-disturbance condition, and hence, there is no firm target to define expected PM_{10} concentrations from a natural, sandy dune landscape absent any Off-Highway Vehicle traffic.

The simulation model results indicate that current emissions are less than the pre-disturbance scenario. This knowledge can be used to provide guidance on how to interpret trends in the proposed data metric. Specifically, the model shows that compliance was achieved by 2023, and therefore a ratio value of 13 (+/- 2.1, which is the standard deviation) might be taken as a guiding threshold value.

However, future-year values should not be interpreted in isolation but, rather, in the context of long-term trends (i.e., several years running) with the understanding that there is natural variability in the system that partially masks the desired outcomes of management interventions in the ODSVRA. A specific value of the ratio in any given year should not be used to trigger immediate adaptive management action. For instance, a value greater than 15 (i.e., 13 + SD) should not mandate that more land should be taken out of OHV riding designation and re-vegetated. Conversely, a value below 11 (i.e., 13 – SD) should not suggest that land currently in non-riding status be returned to OHV access. Rather, the proposed data metric is simply one of many indicators that can be used to track whether long-term trends are consistent with a state of compliance and to evaluate the long-term impacts of dust-mitigation efforts in the ODSVRA. Decisions regarding compliance within the purview of the SOA should be evaluated according to periodically updated simulation modeling results that compare current emissions from the ODSVRA to pre-disturbance conditions.

Respectfully,

The Scientific Advisory Group

Bernard Bauer (Chair), Carla Scheidlinger (Vice-Chair), Jack Gillies, Jenny Hand, Leah Mathews, Ian Walker

SAG Report

Toward a Data-Informed Metric for Assessing Progress Leading to PM_{10} Reductions Downwind of the ODSVRA

Data Sources and Analyses

The SAG undertook an analysis of a data set provided by the APCD that spanned the eight full years from January 1, 2016, to December 31, 2023. Data prior to 2016 are not available for the Oso Flaco monitoring station, which was established in mid-2015. Conversely, data for 2024 have not yet been thoroughly quality-controlled, but could be added later. The global data set consists of time series of approximately 70,000 hours duration for PM_{10} concentrations collected by each of the instruments positioned at CDF, Mesa2, and Oso Flaco, all of which have been subject to quality assurance and control (QA/QC) following federal guidelines. In addition, corresponding QA/QC values of hourly wind speed and wind direction from the S1 tower (located within the ODSVRA) and the CDF station were examined.

Initial analysis focused on the raw hourly data (i.e., no averaging) to determine spatio-temporal correlations between stations. For example, Figure 1 shows the relationship between hourly wind direction at CDF as a function of wind direction at S1, which demonstrates that wind approach angles at these two locations are, on average, well aligned although there can be deviations from hour to hour, presumably when the regional wind is veering or backing in a new direction. There is also a certain amount of topographic steering that will yield directional differences, but for wind approach angles that are generally onshore (between 200^{o} to 300^{o}) there is close correspondence of the averages (as indicated by the regression equation parameters in the figure caption).

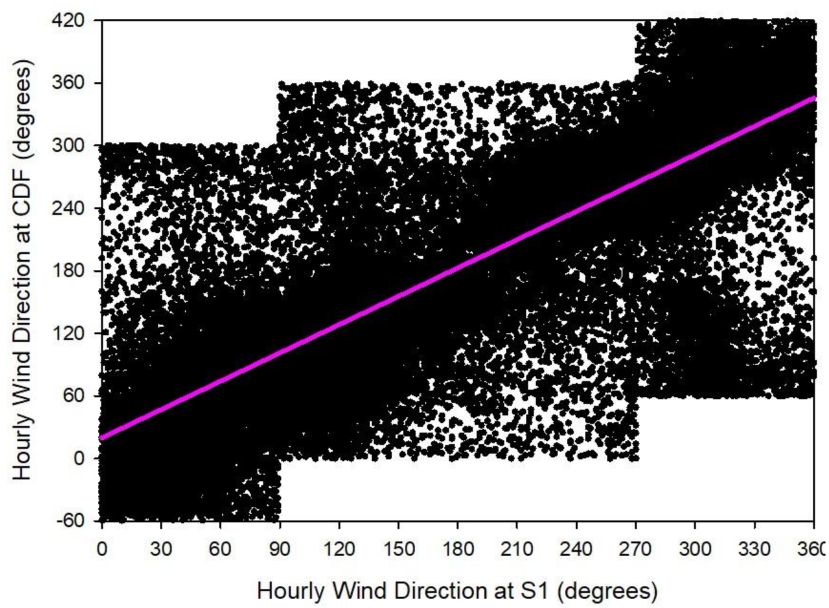

Figure 1: Correlation between hourly wind direction at S1 versus CDF.
$R^2 = 0.70$ (CDF = 19.9 + (0.905 × S1)).

Figure 2 shows the relationship between hourly wind speed at S1 versus CDF, which indicates a significant difference with the CDF station, which generally experiences less than one-half the typical wind speed observed at S1. This is due to the inland location of CDF and the frictional retarding influence of landscape elements (e.g., dunes, vegetation stands, buildings) on wind speed, which is most evident with onshore wind directions. Nevertheless, the regression statistics indicate that the wind speed at S1 is correlated with wind speed at CDF, and thus, it is legitimate to use either source of data when examining relationships between wind speed and PM_{10} concentrations depending on the objective. In general, wind direction and wind speed data from the S1 station were preferred because this station is closest to the ocean and therefore provides information that is representative of conditions in the ODSVRA. PM_{10} concentration data from CDF and Oso Flaco (rather than S1) are keyed upon because these two stations are used for air quality assessments and for operationalizing Rule 1001.

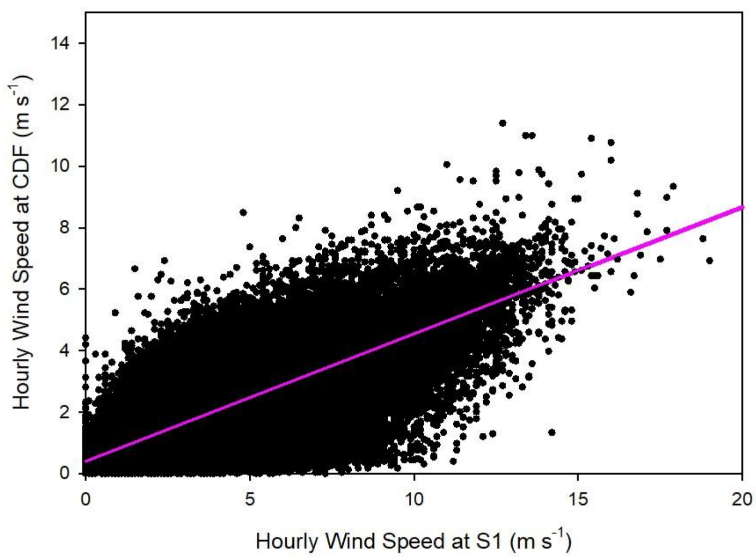

Figure 2: Correlation between hourly wind speed (m s^{-1}) at S1 versus CDF. $R^2 = 0.48$ (CDF = 0.404 + (0.415 × S1)).

Since the CAAQS and Federal Standards are based on 24-hour average PM_{10} concentrations, the hourly data were eventually averaged to produce daily values (midnight to midnight). These were used to examine other relationships (e.g., wind direction vs PM_{10} concentration), and in other analyses the hourly data were used to filter for certain conditions such as periods when PM_{10} concentrations were greater than 50 µg m^{-3} (the CAAQS threshold value) or periods when wind approach angle was from an onshore directional window. The data were not filtered to eliminate periods of rainfall or moist surface conditions, nor were days of large PM_{10} concentrations due to wildfires eliminated (which constitute a very small fraction of the overall data set: K. Tupper, personal communication). This is a refinement that can be undertaken in the future with additional resources and if deemed essential.

Results

General Trends in Hourly PM_{10} Data

Figure 3 shows the relationship between hourly PM_{10} concentrations at CDF and Oso Flaco as a function of hourly wind direction at S1, in radar plot format. Several trends emerge, including: (a) generally larger PM_{10} concentrations at CDF than at Oso Flaco (note difference in scale values of radar arms); (b) large clusters of data values in the central portion of each plot at relatively small values of PM_{10} concentration; (c) a small number of very large PM_{10} concentrations in many directional sectors, especially Oso Flaco; and (d) a very prominent bias in the CDF plot favoring large PM_{10} concentrations in association with winds from the north-west (centered around 300°), which is conspicuously absent in the Oso Flaco plot. This suggests that the PM_{10} concentrations at the Oso Flaco station are not well correlated with wind direction in the ODSVRA.

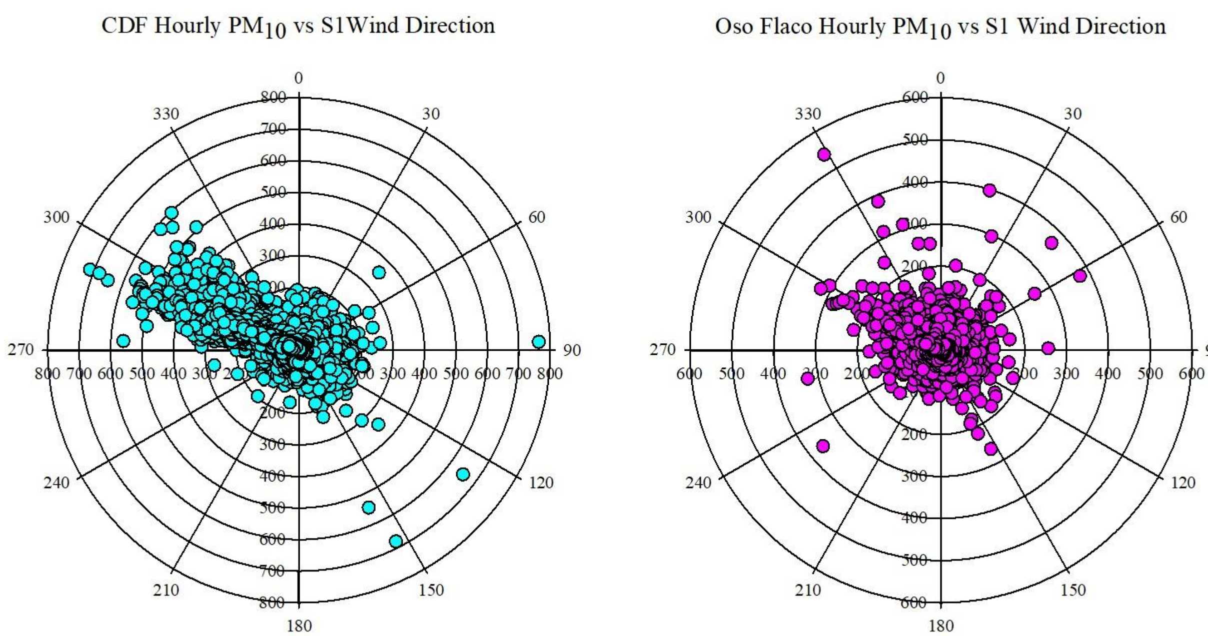

Figure 3: Radar plots of hourly PM_{10} concentrations (μg m^{-3}) at CDF (left) and Oso Flaco (right) as a function of hourly wind direction at S1.

Rule 1001 is predicated on the fundamental premise that PM_{10} concentrations at Oso Flaco (the control site) are indicative of 'natural conditions' not influenced by OHV riding, but are, in every other way, similarly responsive to meteorological drivers that impact the CDF station (the monitoring site). Under these assumptions, the PM_{10} concentrations at Oso Flaco and CDF should respond similarly to wind events with the exception of the degree to which quantities of dust are emitted from upwind surfaces (i.e., reduced dust emission at Oso Flaco). If this were strictly true, the radar plots in Figure 3 should have similar shapes, but they do not.

There is considerable scatter in the hourly values shown in Figure 3, and therefore two filters were applied to the data as follows: (i) consider only data within an onshore directional window between 180° and 360°; and (ii) exclude PM_{10} concentrations less than 50 µg m^{-3} (i.e., the CAAQS threshold value[3]) as an expedient to eliminate noise in the relationship based on small dust concentration conditions. Figure 4 shows the resulting plot of wind-direction filtered hourly PM_{10} concentrations at CDF versus those at Oso Flaco when both stations had hourly PM_{10} concentrations in excess of 50 µg m^{-3} simultaneously. The relationship is very poor, and the regression line is essentially flat with an R^2 value of only 0.018. The graph shows that when PM_{10} concentrations at Oso Flaco are in the range of 50-100 µg m^{-3} the concentrations at CDF can range anywhere from 0-550 µg m^{-3}. Conversely, when PM_{10} concentrations at CDF are in the range of 100-200 µg m^{-3} the concentrations at Oso Flaco can exceed 250 µg m^{-3}. A similar graph (not presented here) that filters only the CDF data for the same conditions and pairs the Oso Flaco concentrations for the same hour (regardless of whether above or below 50 µg m^{-3}) shows an equally poor correlation with many more data points close to the origin. These data trends suggest that the Oso Flaco hourly measurements are poor predictors of hourly conditions at CDF, and that Oso Flaco does not serve particularly well as a control site, presuming that the only difference between the stations is the degree to which dust is being emitted from the upwind surfaces (i.e., open sand in front of CDF and vegetated terrain in front of Oso Flaco).

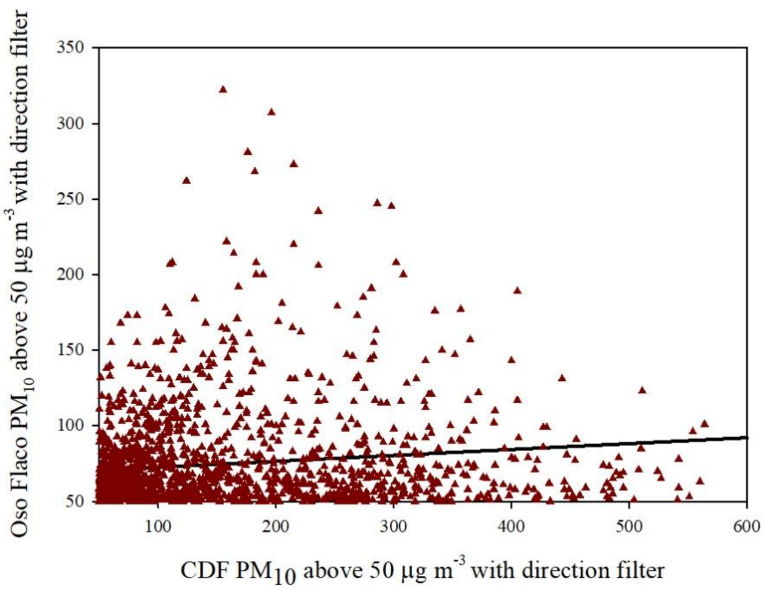

Figure 4: Correlation between hourly PM_{10} concentrations (µg m^{-3}) at CDF versus those at Oso Flaco. The data were filtered according to onshore wind direction only (180° - 360°) and a threshold concentration in excess of 50 µg m^{-3} at both stations simultaneously. $R^2 = 0.018$ (OsoFlaco = 68.6 + (0.039 × CDF)).

The CAAQS and Rule 1001 are based on 24-hour averages rather than hourly data. Figure 5 shows the relationship between daily (24-hour) mean PM_{10} concentrations at CDF above 50 µg m^{-3} versus the corresponding daily mean values at Oso Flaco. Although the correlation is slightly better than for the hourly data, the regression line remains flat and the R^2 is very small, indicating poor predictive ability. This also suggests that the Oso Flaco station serves poorly as

[3] The CAAQS threshold value is a 24-hr mean, but hourly PM_{10} values are often well above this threshold during strong wind events even if the CAAQS threshold is not exceeded.

a control site because of the absence of statistical correlation—i.e., the variations in concentration measurements at CDF are almost random when compared to those at Oso Flaco.

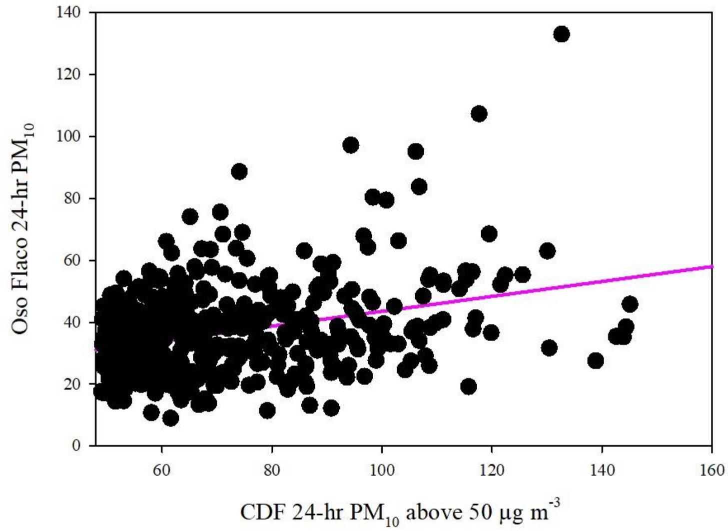

Figure 5: Correlation between daily (24-hour averaged) PM_{10} concentrations (µg m^{-3}) at CDF versus those at Oso Flaco. The data were filtered according to a threshold concentration in excess of 50 µg m^{-3} at the CDF station only.
$R^2 = 0.107$ (OsoFlaco = 19.5 + (0.24 × CDF)).

Annual Distribution of PM_{10}

April and May are, on average, the windiest months of the year along the Oceano coastline (Figure 6). Dust emissions from sand surfaces are strongly controlled by wind speed and moisture conditions, so average PM_{10} concentrations in the Oceano area should follow the trends in the meteorological drivers. Based on long-term (30-year average) public records[4], the most rainfall is generally received between the months of November (0.59″) through March (1.61″), after which it declines precipitously in April (0.47″) to minima in June (0.04″) and August (0.04″). Figures 7 and 8 show annual trends in monthly-averaged PM_{10} concentrations based on hourly data collected at CDF for the period 2016 through 2023, inclusive. Figure 7 shows the monthly averages for each of the individual years, whereas Figure 8 shows box plots for every month of the year in the form of a data distribution. Monthly-averaged PM_{10} concentrations tend to follow the monthly-averaged wind speeds with a peak in April-May and a secondary peak in October, separated by two periods of reduced concentrations in July-August and December-January. In addition, there is evidence to suggest that overall monthly-averaged PM_{10} concentrations have declined over this period, which is evident in Figure 8 where the annual trends for 2017 (generally falling at the top of the data distributions) are contrasted with those from 2023 (falling at the bottom of the data distributions). The monthly mean PM_{10} concentrations for April of 2016 and 2017 came close to (or exceeded) the CAAQS 24-hour standard of 50 µg m^{-3} when averaged over the entire month. In April 2017, there were 13 days

[4] https://www.weather-atlas.com/en/california-usa/oceano-climate

that exceeded the Rule 1001 criteria for violations (see next sub-section), five days of which had CDF concentrations in excess of 100 µg m^{-3} and a maximum of 145 µg m^{-3} (on April 23, 2017). In April 2023, there were only three Rule 1001 violations with the maximum having a peak of 83 µg m^{-3}.

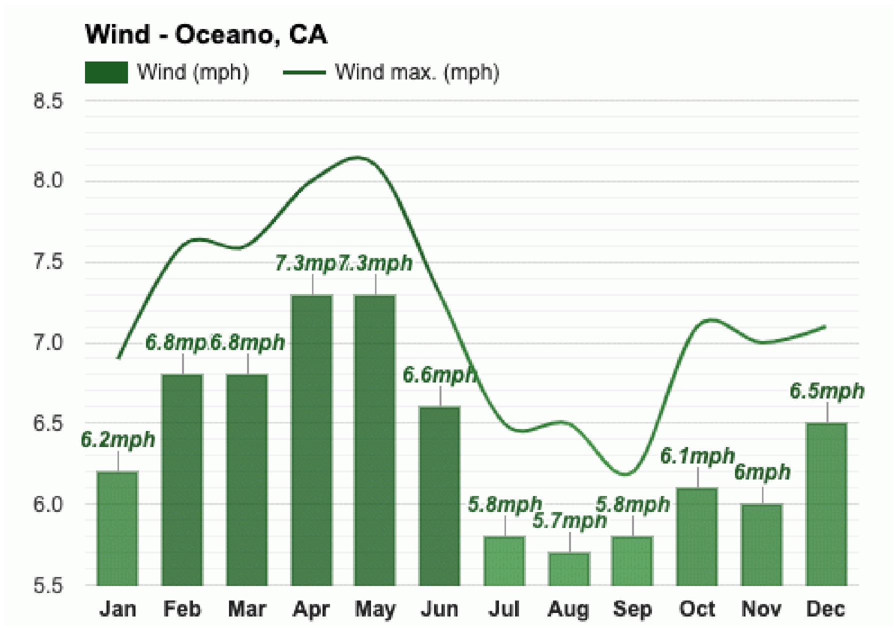

Figure 6: Monthly average wind conditions (mph) in the vicinity of Oceano, California. Image taken from https://www.weather-atlas.com/en/california-usa/oceano-climate

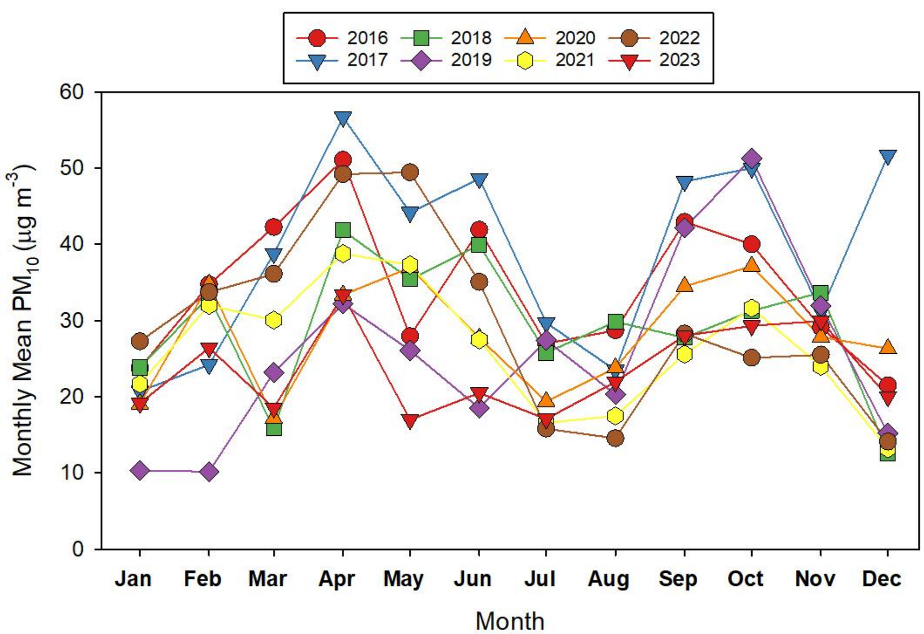

Figure 7: Annual distribution of monthly mean PM_{10} concentrations (µg m^{-3}) for the years 2016 through 2023, inclusive, from the CDF monitoring station.

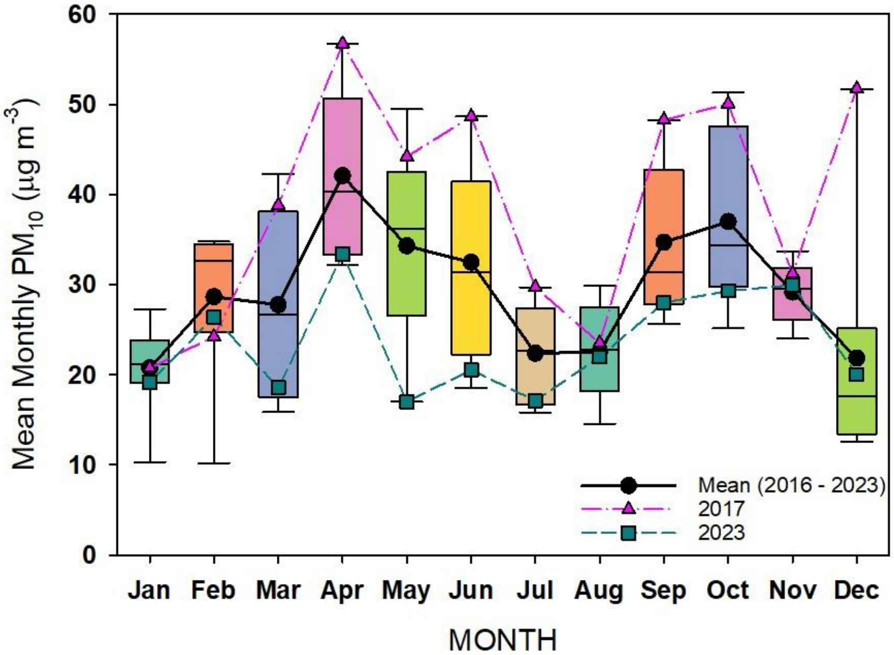

Figure 8: Annual distribution of mean monthly PM_{10} concentrations (µg m^{-3}) from the CDF monitoring station for the period 2016 – 2023, inclusive, represented as box plots. Colored vertical bars represent the upper and lower quartiles of the data distribution (i.e., 50% of the data points); upper and lower whiskers show the maximum and minimum values, respectively; and small horizontal bar in the colored box indicates the median (i.e., middle) value of the distribution. Also shown are the average monthly values (black, solid circles connected by solid black line), and the values for 2017 (triangles) and 2023 (squares).

Annual trends in monthly-averaged PM_{10} concentrations at Oso Flaco for the same period are shown in Figure 9 and 10. The monthly trends are similar to CDF, with peak PM_{10} concentrations in April and October, and reduced values in July and August. The year 2017 again seems to have greater-than-normal concentrations (relative to other years) and 2023 has lesser-than-normal values. There is a noticeable difference in the average concentrations at Oso Flaco in comparison to CDF. The monthly means at Oso Flaco range between about 12 µg m^{-3} and 26 µg m^{-3} (Figure 10, solid black line), whereas the monthly means at CDF range between 21 µg m^{-3} and 42 µg m^{-3} (Figure 8, solid black line), almost twice as large.

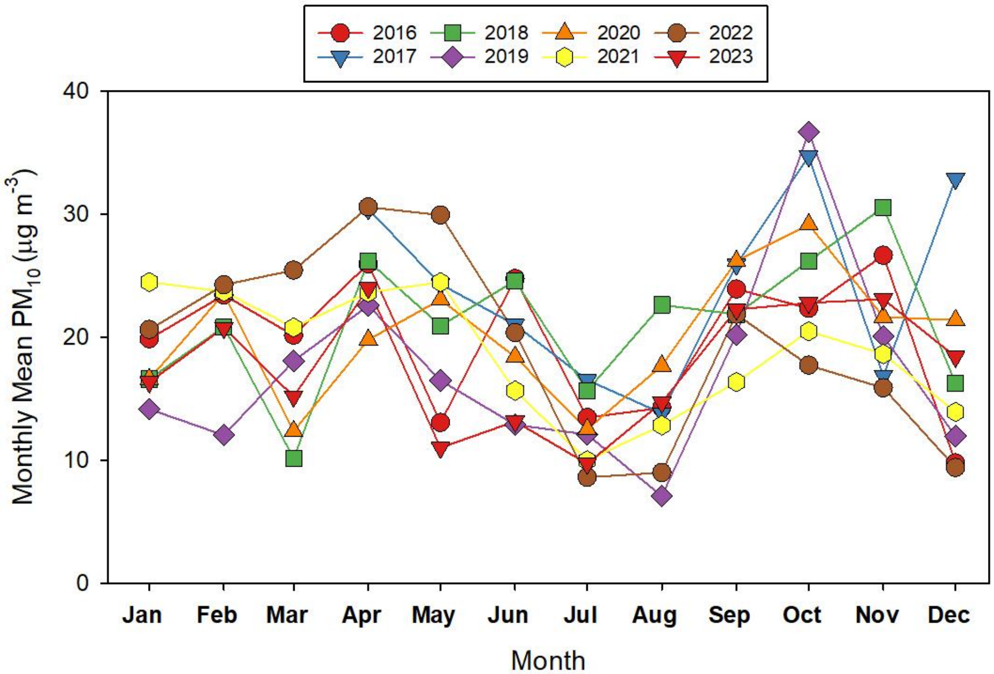

Figure 9: Annual distribution of monthly mean PM_{10} concentrations (µg m^{-3}) for the years 2016 through 2023, inclusive, from the Oso Flaco monitoring station.

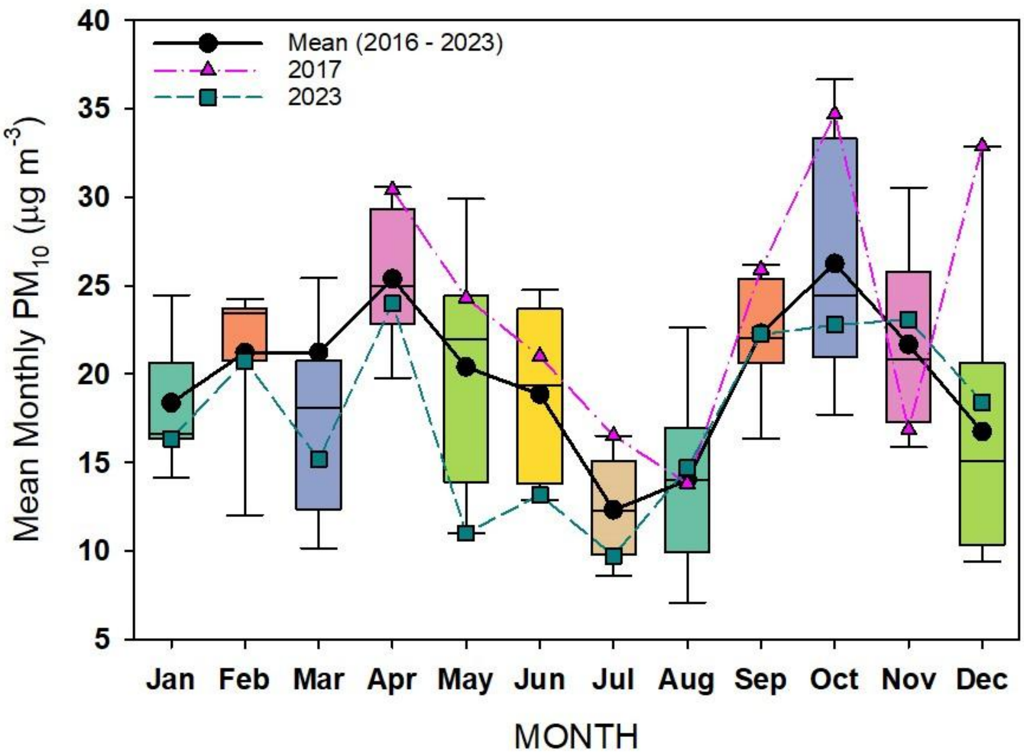

Figure 10: Annual distribution of mean monthly PM_{10} concentrations (µg m^{-3}) from the Oso Flaco monitoring station for the period 2016 – 2023, inclusive, represented as box plots. See Figure 8 for explanation of symbols.

Trends in Rule 1001 Violation Events

Violations of Rule 1001 are triggered when 24-hour average PM_{10} concentrations at CDF (monitoring site) are 20% above the 24-hour average PM_{10} concentration at Oso Flaco (control site). When the PM_{10} ratio (CDF/OsoFlaco) is in excess of 1.2, the 24-hour average PM_{10} concentrations at CDF are required to be less than 55 µg m^{-3}. These two conditions were applied as filters to the data set to identify when Rule 1001 exceedance events occurred during the period 2016 – 2023, inclusive. Figure 11 shows the annual distribution of Rule 1001 exceedance events for that period plotted with the 24-hour average PM_{10} concentrations at Oso Flaco, CDF, and Mesa 2. Despite an evident decline in the number of events from year-to-year (five-fold decrease from 2017 to 2023), the average PM_{10} concentrations during these violation (exceedance) events has remained fairly constant at Oso Flaco and Mesa2, and perhaps only a small decrease at CDF. However, the mean PM_{10} concentrations at CDF are greater than at Mesa2, and approximately twice as large as at the Oso Flaco station. Noteworthy is the fact that even at the Oso Flaco control site, the CAAQS of 50 µg m^{-3} is exceeded on occasion.

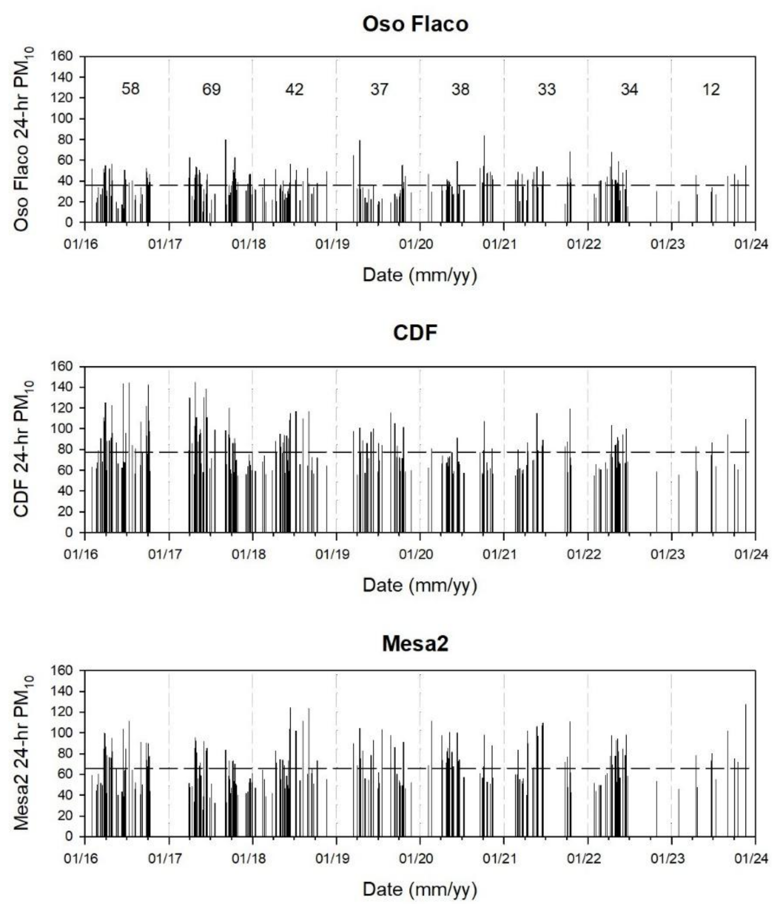

Figure 11: Annual distribution of Rule 1001 exceedance events and the 24-hour PM_{10} concentrations (µg m^{-3}) at Oso Flaco, CDF, and Mesa 2. Horizontal dashed lines show the mean concentrations for these events across the entire period 2016-2023. Numbers across the top panel are the number of events in each year.

Violations of Rule 1001 are triggered when the ratio of PM_{10} at CDF divided by Oso Flaco is greater than 1.2, and Figure 12 shows how this ratio has changed through time. Although there is considerable variation in the ratio, the largest values occurred in 2016, 2017, and 2019, and it appears that there is an overall downward trend. Not only are the number of violations decreasing, but the differential between PM_{10} concentrations at CDF and Oso Flaco is also declining.

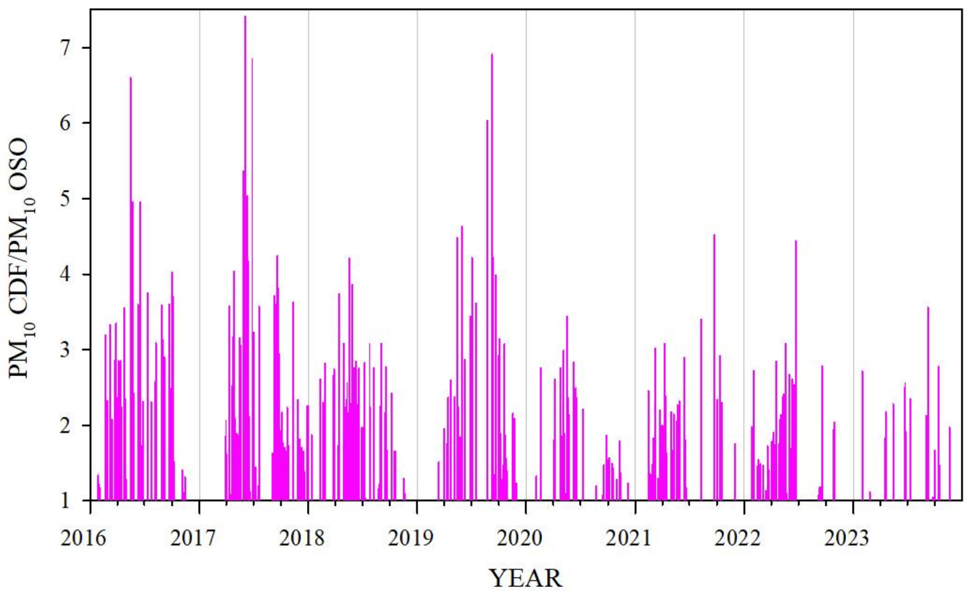

Figure 12: Annual distribution of Rule 1001 exceedance events and the ratio of 24-hour PM_{10} concentrations at CDF divided by Oso Flaco.

Although Rule 1001 is relatively straight-forward to apply as a regulatory instrument, it fails to take into account the potential dust emissions that may be influencing the monitoring station at CDF emanating directly from the ODSVRA. Specifically, it ignores wind parameters, especially directional approach angles that traverse the ODSVRA. Figure 13 shows the relationship between 24-hour average wind direction and 24-average wind speed at the S1 tower during all the Rule 1001 exceedance events. Two things are immediately apparent: (1) the majority of exceedance events are associated with wind directions from the north-west (although not exclusively so); and (2) winds from the north-west quadrant are typically associated with greater mean speeds than from other quadrants.

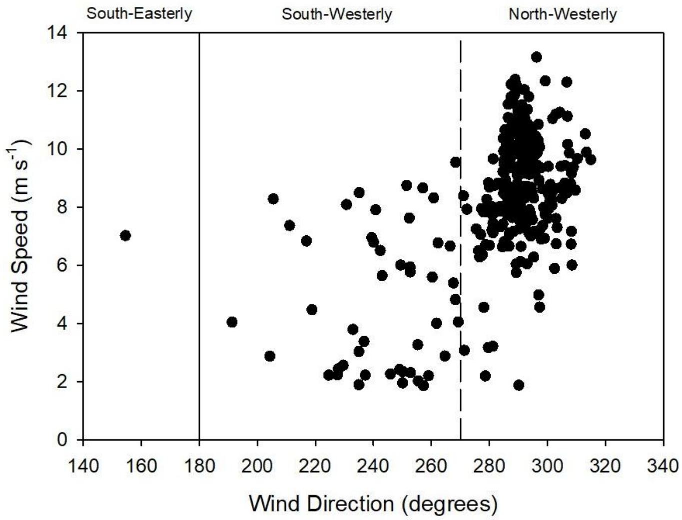

Figure 13: Wind conditions (24-hour averages) at the S1 station during days when Rule 1001 violations were identified in the period 2016-2023.

The question arises as to whether the Rule 1001 violations associated with the faster wind events from the north-westerly quadrant are generally associated with greater 24-hour average PM_{10} concentrations. Figure 14 indicates that this is largely the case at CDF but not at Oso Flaco. At Oso Flaco there is no clear relationship with concentration and wind speed nor with wind direction even though there are clearly more violations occurring with north-westerly winds. In contrast, 24-hour average PM_{10} concentrations at CDF crudely increase with mean wind speed and for wind directions centered around 290^o azimuth, noting however, that there is large variance in 24-hour average PM_{10} concentrations for any given event. Thus, there can be very small or large values of PM_{10} concentrations for any given wind approach angle, likely influenced by mean wind speed and perhaps other conditions such as atmospheric humidity and surface moisture (which have not been taken into account in this preliminary analysis).

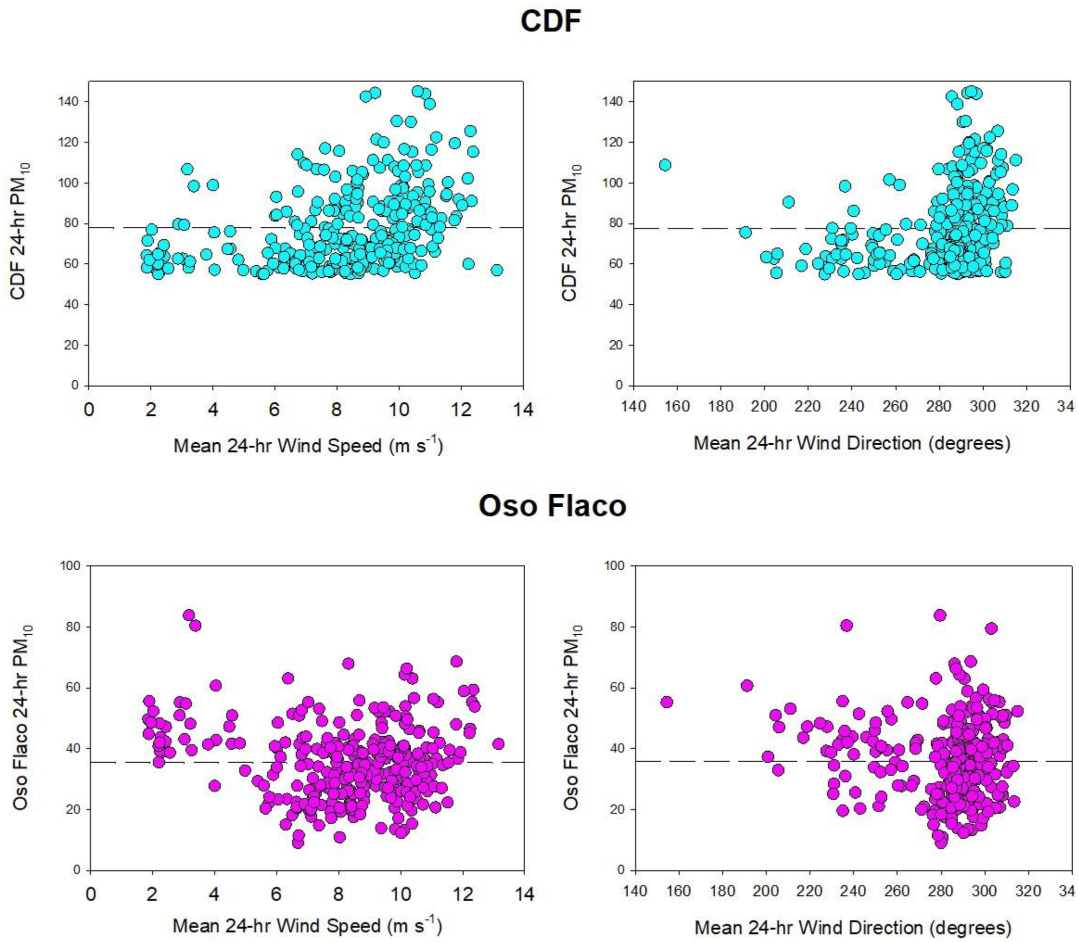

Figure 14: Mean (24-hour) PM_{10} concentrations (µg m^{-3}) at CDF (top panels) and Oso Flaco (bottom panels) as a function of mean (24-hour) S1 wind speed (m s^{-1}) (left panels) and wind direction (right panels) during Rule 1001 exceedance events. Dots refer to the mean concentrations for each separate violation whereas the dashed horizontal lines indicate global mean PM_{10} concentrations across all violations.

Rule 1001 exceedance events can occur at any time during the year but are typically clustered to a certain degree and may appear as multiple-day sequences. Figure 15 shows the distribution of multiple-day ‘cluster events’ for each year during the period 2016 – 2023, with each vertical bar representing the number of clustered events lasting between 2 and 8 days in sequence (from left to right in each year). For example, in 2017 there were eighteen 1-day events, five 2-day events, five 3-day events, one 4-day event, one 5-day event, one 6-day event, and one extraordinary 11-day event (n = 69 total days). In contrast, during 2023 there were six 1-day events and three 2-day events (n = 12 total days). Not only have the total number of Rule 1001 exceedance days decreased in total, but the multiple-day events with sequential violations have also decreased in overall number and duration to the extent that in 2023 there were no ‘cluster events’ lasting longer than two days. In terms of potential health impacts on residents, this is a positive outcome with fewer periods of lengthy exposure to critical dust levels, and longer recovery periods between events. The lower panel in Figure 15 indicates that this downward trend has occurred despite progressively enhanced windiness since 2020 as measured by the anemometer at the CDF station. In particular, 2022 and 2023 were the windiest years in the period under consideration, but they had the fewest violations of Rule 1001. Most of the multiple-day events longer than three days in duration have occurred in April, although there were single long-duration events in March, June, September, and October.

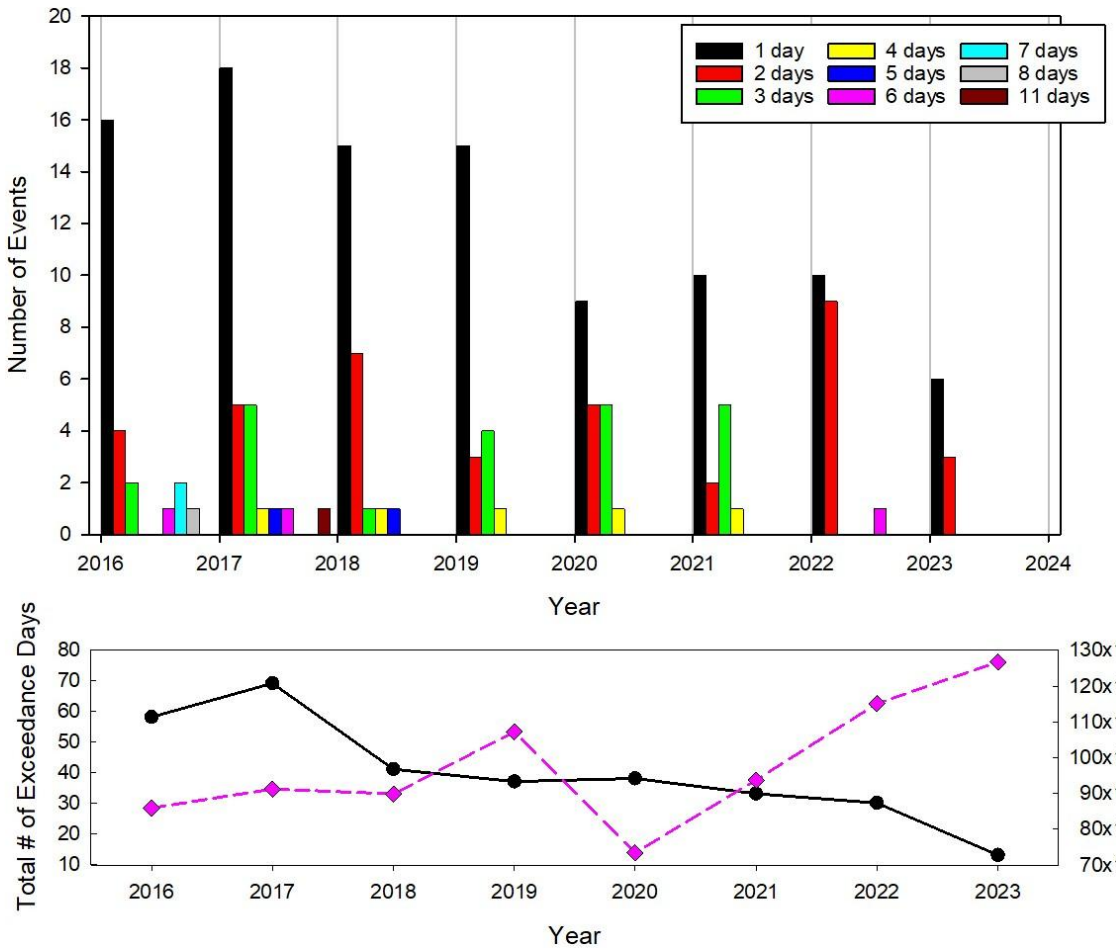

Figure 15: Frequency of multiple-day 'cluster events' for which Rule 1001 violations have occurred (upper panel). Lower panel shows trends in total number of exceedance days (solid black line) relative to Total Wind Power Density (W m^{-2}, dashed pink line) at CDF calculated as the sum of daily mean wind power density (defined as WPD = 0.5 $\rho_a u^3$, where ρ_a is air density (kg m^{-3}) and u (m s^{-1}) is wind speed at the measurement height above ground level (10 m AGL)). A wind speed threshold of 3.5 m s^{-1} was applied, following the recommendations of Gillies, Nikolich, and Furtak-Cole (2023, *Increments of Progress Towards Air Quality Objectives – ODSVRA Dust Controls, 2023 Update – Revised*), but no other filters (directional, seasonal moisture) were used.

Anatomy of Events – 24-hour cycles

As mentioned previously, the CAAQS and Federal Standards are based on 24-hour mean concentrations. Acceptable levels of exposure are based on medical and epidemiological evidence regarding risk to human health, but the prescription of a 24-hour averaging time (rather than hourly exposures) is largely a practical outcome of measurement/monitoring constraints. Until recently, most measurements of PM_{10} concentrations were made using filter samplers, and given the labor-intensive nature of filter analysis, a 24-hour sampling period seemed a reasonable compromise between data fidelity and expense. Advanced technologies have recently facilitated monitoring and reporting at hourly intervals, and it is of interest to understand hourly variations in dust concentrations across a day, especially during major events, which may lead to health concerns.

Figure 16 shows trends in hourly values of PM_{10} concentrations organized according to hour of the day (beginning at midnight) acquired from the monitoring stations at CDF, Mesa2, and Oso Flaco over the period 2016-2023. The three left-hand panels show the daily distributions of all the hourly values (over 2800 in each hourly interval; total of over 70,000 in each graph), whereas the three right-hand panels show the daily trends in the mean hourly PM_{10} concentrations with error bars represented by the standard deviations. It is apparent that, on average over the 8 years of data used in these graphs, the evening and early morning hours have relatively small PM_{10} concentrations whereas a distinct peak arises during mid-day. This is especially the case for the CDF and Mesa2 stations, where the initial ramp-up begins around 9 am, peaks between noon and 3 pm, and returns to smaller values by 6 pm. The dashed horizontal reference line, set arbitrarily at 50 µg m^{-3}, following the CAAQS threshold, indicates that the long-term hourly average PM_{10} concentrations at CDF exceed this value at 1 pm, 2 pm, and 3 pm whereas at Mesa2 this value is exceeded at 2 pm and 3 pm. For all other hours of the day, the PM_{10} concentrations are smaller, typically below 25 µg m^{-3} for about 15 hours through the evening.

The trends from the Oso Flaco monitoring station (lower panels in Figure 16) are somewhat different. Average hourly PM_{10} concentrations never exceed 25 µg m^{-3} and are typically in the range of 10 – 20 µg m^{-3}, much lower than at CDF and Mesa2. In addition, peak concentrations occur later in the day, between 3 pm and 7 pm. However, on any given day, hourly PM_{10} concentrations at Oso Flaco can exceed 200 µg m^{-3} (Figure 16, bottom left panel), as is also the case at CDF and Mesa2.

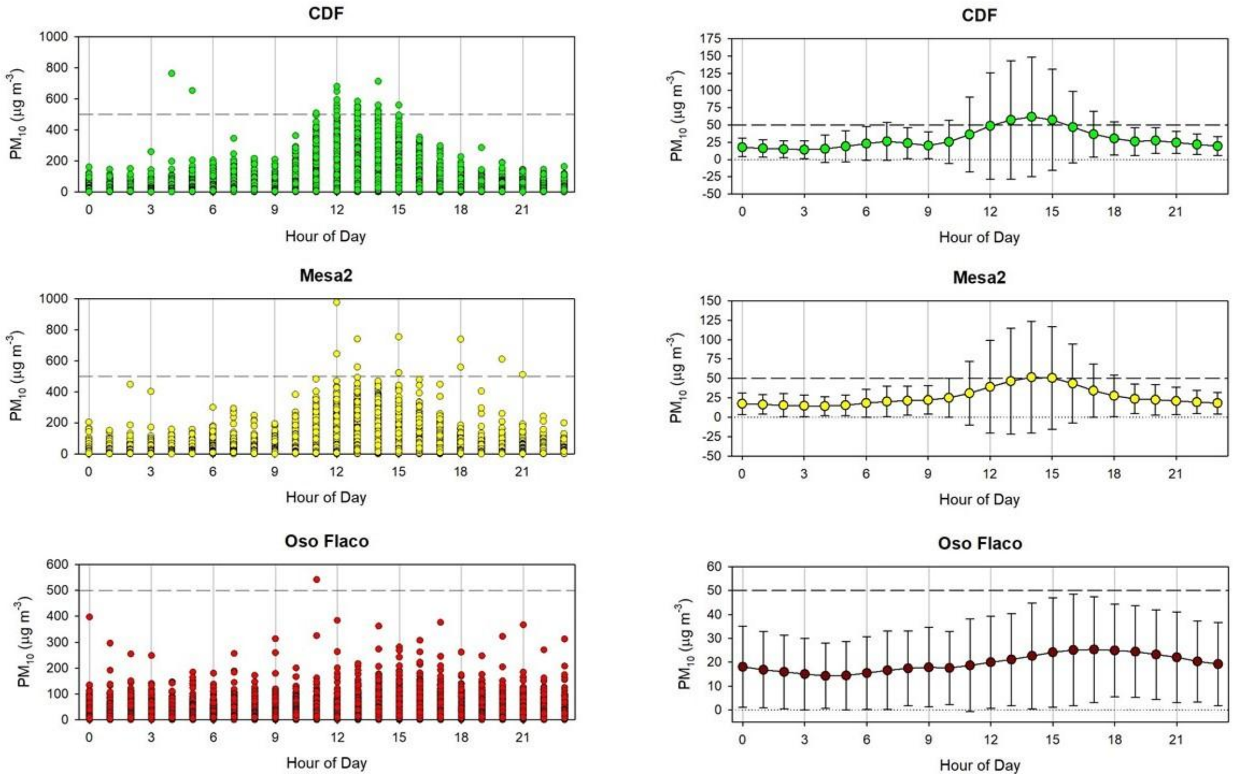

Figure 16: Hourly trends in PM_{10} concentrations (µg m^{-3}) for the combined period 2016-2023 for monitoring stations at CDF (top panels), Mesa 2 (middle panels), and Oso Flaco (bottom panels). The three panels on the left show the distributions of all hourly data recorded for every hour of the day for all 8 years of the record. The three panels on the right show the mean values (and standard deviation as whiskers) for every hour of the day. The horizontal lines are simple reference lines with the same value for all three stations to aid in visual interpretation of the data ranges.

The data in Figure 16 have not been filtered in any way, and they represent the entire distribution of available data for the period 2016-2023. Figures 3, 13, and 14 suggest that PM_{10} concentrations are dependent on wind conditions (speed and direction), especially for the CDF station, whereas Figure 15 indicates that the frequency of multiple-day events has been decreasing. Further, Figure 16 demonstrates that there is a daily rhythm to PM_{10} concentrations, most likely driven by wind conditions associated with the land-sea breeze cycle. This was explored further by examining the hourly trends in several of the multiple-day events.

Figure 17 shows the hourly evolution of PM_{10} concentrations and wind speed at the CDF station during a 7-day event occurring in late March of 2016 (left panels) and an extraordinary 11-day event on April 19-29, 2017 (right panels). There is a clear association of hourly PM_{10} concentrations (upper panels) with wind speed as measured at the CDF station (middle panel) and the S1 station (lower panel). A daily cycle is evident, with peaks in the mid afternoon and lulls in the evening and early morning. Peak concentrations during these multiple-day events sometimes exceed 500 µg m^{-3}.

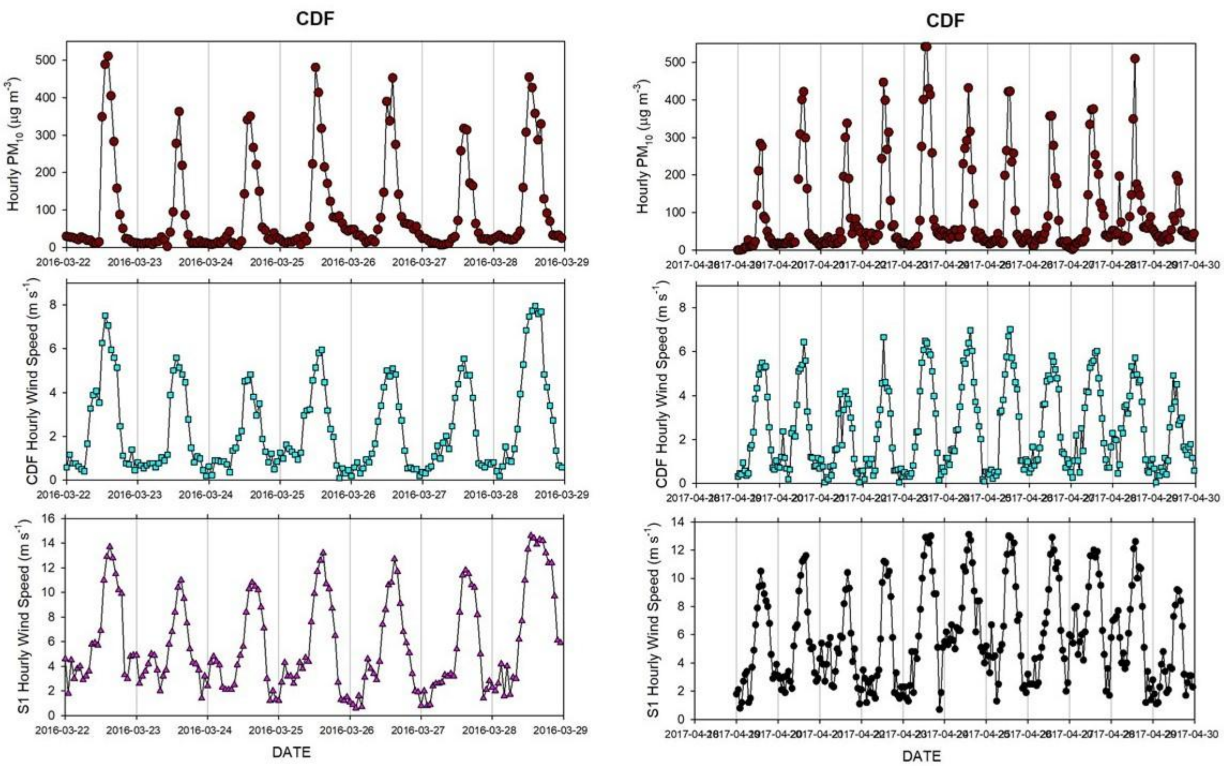

Figure 17: Hourly trends in PM_{10} concentrations (µg m^{-3}) (upper panels) at the CDF station for the multiple-day events occurring on (left) March 22-28, 2016 and (right) April 19-29, 2017. Accompanying wind speeds (m s^{-1}) from the CDF station (middle panels) and S1 station (lower panels) are also shown.

For a more robust analysis of the daily cycle of PM_{10} concentrations, all the multiple-day events exceeding six consecutive days in 2016 and 2017 were clustered and averaged according to hour of the day. The only other six-day event in the period 2016-2023 occurred on April 26-May 1, 2022, and it was excluded from this analysis because of the extensive management treatments in the ODSVRA between 2017 and 2022 (i.e., the 2022 event may differ in unknown ways from those in 2016 and 2017). Figure 18 shows the distribution of hourly PM_{10} concentrations for the six multiple-day events, totaling 45 days in total, for the stations at CDF (upper panel), Mesa 2 (middle panel), and Oso Flaco (lower panel). An arbitrary reference line of 150 µg m^{-3} is included in each graph (dashed line) to aid in visual comparison between the stations, and the 24-hour mean for each station is represented as a solid black line. The trends in these graphs are very similar to those shown for the global data set in Figure 16, with a daily increase in PM_{10} concentrations at CDF and Mesa2 beginning around 9 am, peaking between noon and 3 pm, and declining to evening lows around 6-7 pm. The peak at Oso Flaco is, again, delayed by 2-3 hours.

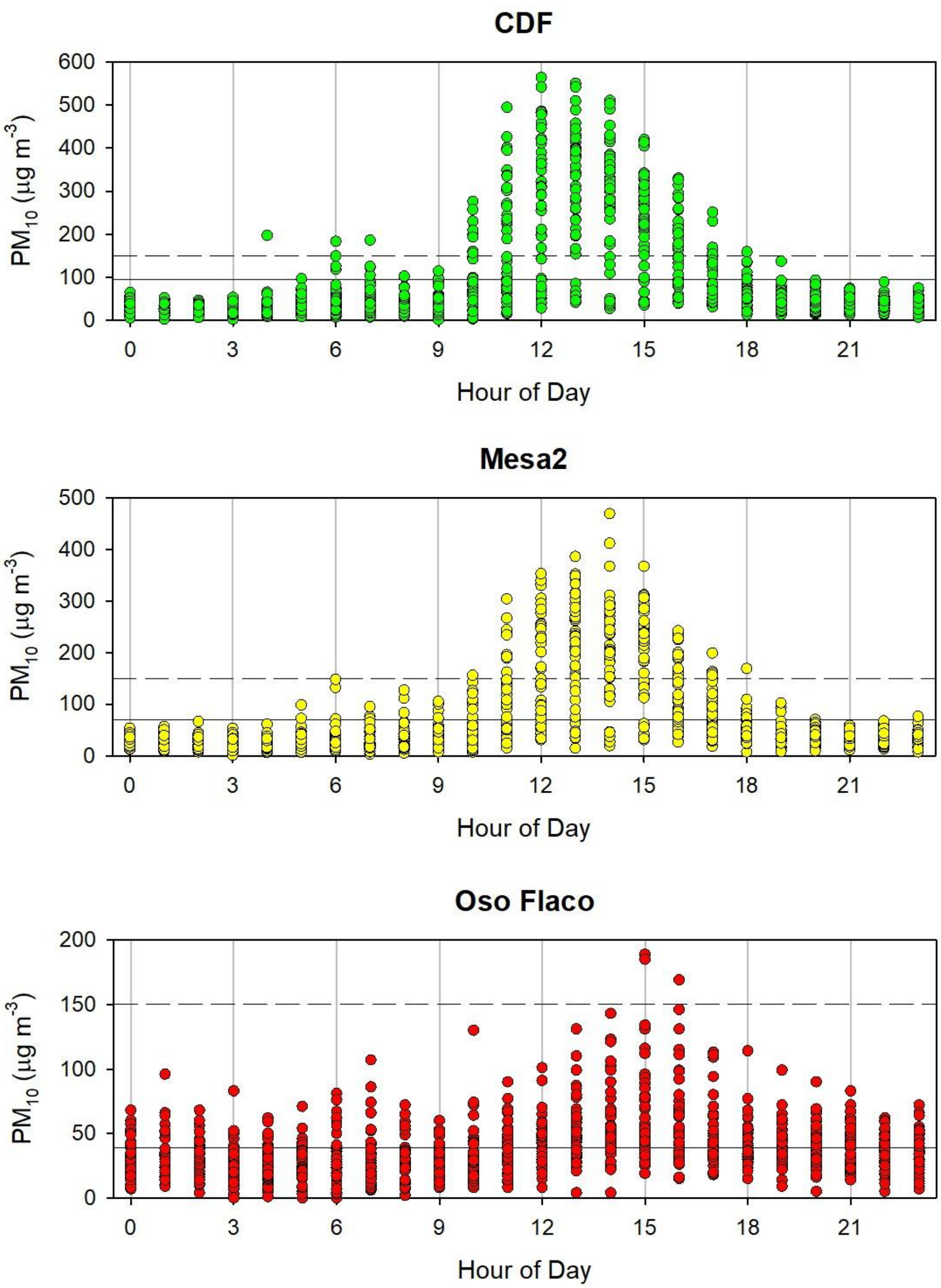

Figure 18: Hourly trends in PM_{10} concentrations (µg m^{-3}) for six multiple-day events (exceeding 6 days in sequence) during 2016 and 2017. Solid black line shows the average concentration for all days in the record, whereas the dashed line is an arbitrary reference line to assist in visual comparison of the graphs, which have different scaling on the vertical axes.

The hourly wind records from the CDF station that accompany the PM_{10} concentrations shown in Figure 18 are presented in Figure 19. Given the close association of PM_{10} concentrations with wind speed evident in Figure 16 for specific days, it is unsurprising that the 24-hour trends in wind speed represented in Figure 19 (upper panel) closely follow the concentration trends in Figure 18. Once again, there is an apparent increase in wind speed beginning mid-morning, leading to a peak between noon and 3 pm, and a general decline in wind speed into the early evening. The wind direction (lower panel) during this period of enhanced wind speed is onshore from the north-west (centered around 290 degrees), especially during peak hours. In the evening, the wind direction is generally offshore (north-easterly to easterly), with very few instances of southerly or south-easterly wind. This reflects the land-sea breeze phenomenon that is characteristic of the coast of central California, particularly in the spring and summer months. An analysis of the wind records from the S1 station for the same multiple-day events yields virtually identical results with the exception that the wind speeds are much stronger in the ODSVRA than at CDF.

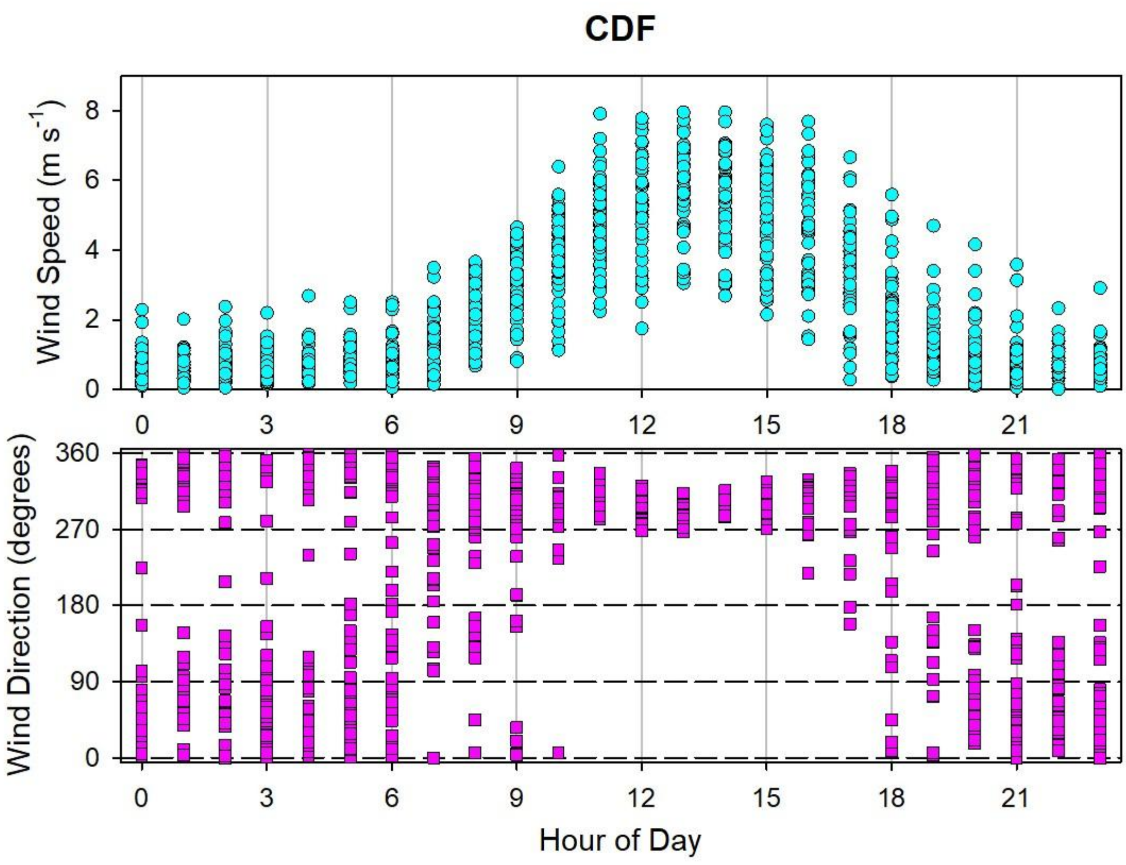

Figure 19: Hourly trends in CDF wind speed (m s^{-1}) (upper panel) and wind direction (lower panel) for six multiple-day events (exceeding 6 days in sequence) during 2016 and 2017, identical to the days included in Figure 18. Note that 270 degrees is westerly (onshore) wind whereas 180 degrees is southerly wind.

The daily cycle of wind and PM_{10} concentrations shown in Figures 16-19 suggest that, for purposes of further analysis, focus should be placed preferentially on data trends between the hours of 9 am and 6 pm. The evening hours typically have much lower PM_{10} concentrations and reduced wind speeds (often in the offshore direction), and they introduce significant noise into any understanding of how dust emissions may be changing through time as a consequence of significant wind events that traverse the ODSVRA. Moreover, low concentrations during the evening hours pose a reduced hazard for human health, both overall and in consideration that many people are indoors during the evening.

The global hourly data set was filtered initially to isolate entries between the hours of 9 am and 6 pm, only. Those hours were averaged to produce 9-6 mean values of PM_{10} concentrations and wind parameters for every day of the 2016-2023 record. Subsequently, an additional set of filters was applied to identify significant 'events' according to:

a) 9-6 mean PM_{10} concentrations at CDF > 99.9 µg m^{-3};
b) 9-6 mean wind direction between 225^o and 345^o, inclusive.

The directional filter was applied to capture only those wind events that had originated from the south-west through to north-north-west, thereby capturing the potential emissions from the ODSVRA that directly influence PM_{10} concentrations at the CDF monitoring stations. This is also consistent with trends shown in Figures 13, 14, 19 for wind directions during Rule 1001 violations.

The concentration filter was set somewhat arbitrarily at 99.9 µg m^{-3} in order to focus attention on the most significant events in the record. Nevertheless, this level is also indicative of potential exceedances of the 24-hour CAAQS of 50 µg m^{-3}. As shown in Figure 16 (upper right panel for CDF), evening concentrations are typically less than 25 µg m^{-3}. Therefore, if the hourly concentrations for the nine-hour period between 9 am and 6 pm average 100 µg m^{-3}, then the 15-hour period between 6 pm and 9 am cannot exceed 20 µg m^{-3}, on average, if the CAAQS is not to be violated. Thus, any days with 9-6 mean PM_{10} concentrations greater than 100 µg m^{-3} have an increased likelihood of exceeding the CAAQS.

To test this idea, the number of events (days) for which the 9-6 mean PM_{10} concentrations exceeded 99.9 µg m^{-3} was tallied for each year and compared to the number of Rule 1001 violation events. Figure 20 shows that the two independent methods of identifying significant events produce very similar, but not identical, results. The majority of events identified by either method are the same, especially the multiple-day events with very large concentrations. There are instances when a Rule 1001 violation is not identified by the 9-6 mean CDF threshold, and vice versa, which makes sense given that Rule 1001 events are based on a ratio between CDF and Oso Flaco concentrations, and it was demonstrated above that the Oso Flaco values are not closely aligned with CDF values. Nevertheless, the 9-6 mean CDF threshold method closely mimics the year-to-year trends in the overall data set, which is reassuring.

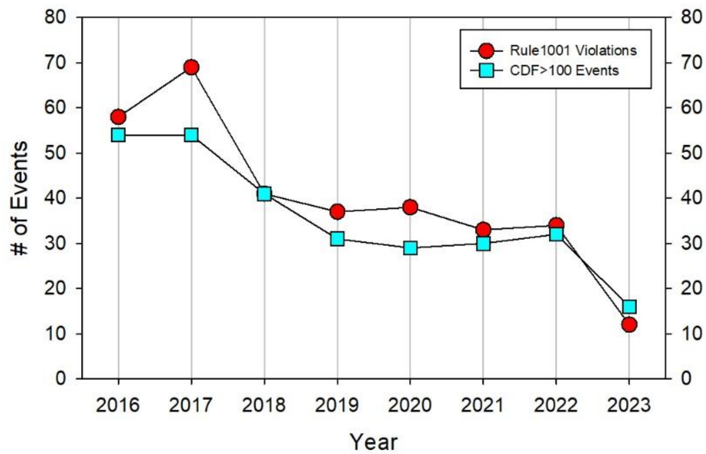

Figure 20: Comparison of the number of significant dust events annually calculated using Rule 1001 (red circles) relative to those events identified with a PM_{10} concentration filter of 99.9 µg m^{-3} applied to the 9-6 mean values in the record (blue squares). See text for explanation of calculation methods.

Figure 21 shows the annual distribution of event days for which the 9-6 mean CDF PM_{10} concentrations were 100 µg m^{-3} or above. Not only have the number of events per year decreased, but so have the overall concentration levels, which were at a peak in 2016 and 2017, followed by a steady decrease since. As was noted above, the majority of the events occur during the windier period between March and May, with secondary activity in the fall months. Nevertheless, isolated events can occur any time of the year.

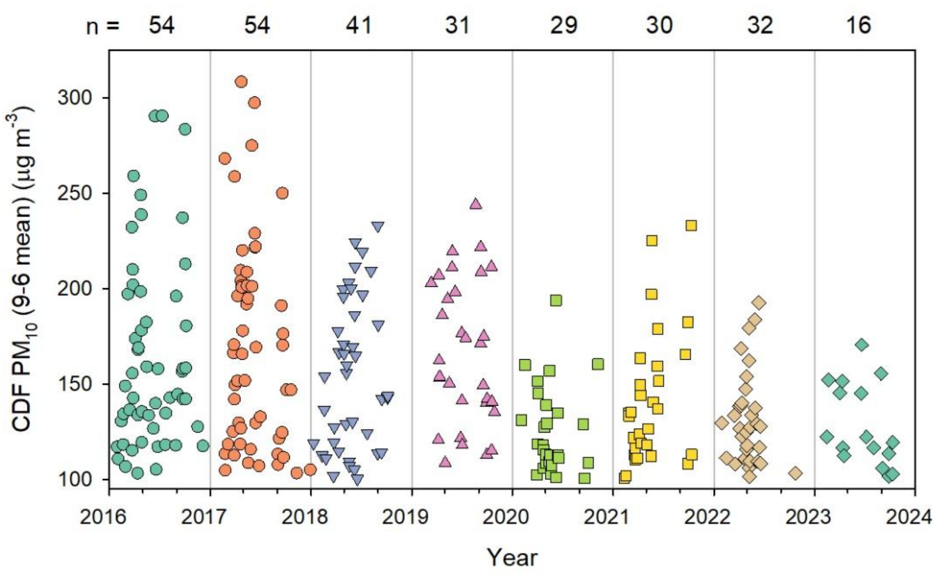

Figure 21: Annual distribution of PM_{10} (µg m^{-3}) during significant dust-generating events identified by a PM_{10} concentration filter of 99.9 µg m^{-3} applied to the 9-6 mean values for every day in the CDF record between 2016 and 2023.

Based on the data shown in Figure 21, an annual average was calculated for all events in a given year identified by the PM_{10} concentration filter of 99.9 µg m^{-3} applied to the 9-6 mean values for CDF. In addition, the accompanying average wind speed at S1 was calculated. The trends between 2016 and 2023 are shown in Figure 22. As noted with respect to Figure 21, the mean PM_{10} concentration values at CDF for the 9 am to 6 pm period events have declined from an annual mean of about 170 µg m^{-3} to values around 130 µg m^{-3}, recalling that these are for the most extreme events in the data record. Interestingly, this decline in average annual PM_{10} concentrations has occurred during a period when the average wind speed associated with these events has increased by approximately 1.5 m s^{-1}. This is significant given that these are average values across hundreds of hours of data collection throughout the year, and more importantly, because sediment transport is governed by the cube of wind speed (i.e., not a linear increase, but a geometric increase). Thus, predictions of dust emissions from sand surfaces during saltation events, based on wind speed trends alone, would have suggested that the CDF PM_{10} concentrations should have increased substantially from 2016 to 2023, but the measurements indicate quite the opposite.

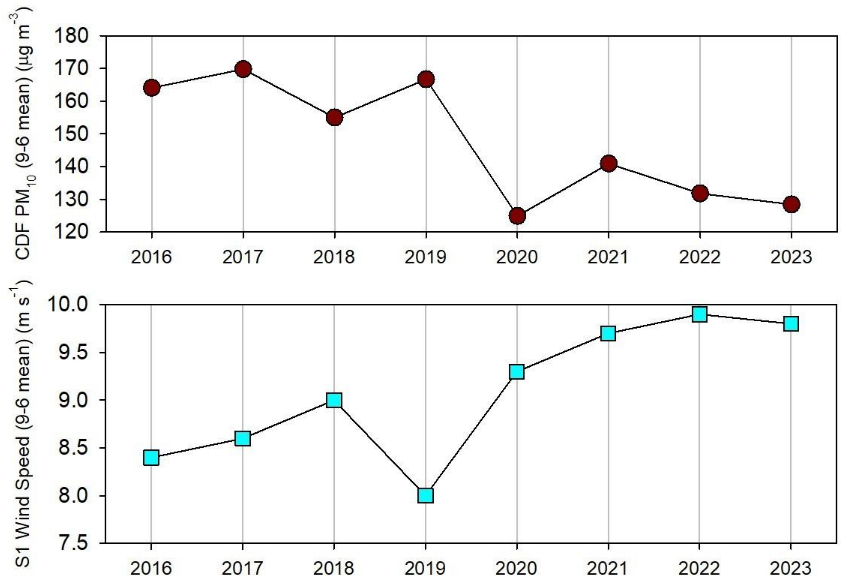

Figure 22: Trends in average annual PM_{10} concentrations (µg m^{-3}) at CDF for 9-6 mean events (upper panel) and associated mean wind speed from the S1 tower.

In order to properly consider the influence of wind speed on dust emissions from the ODSVRA, and hence, PM_{10} concentrations at CDF, it is necessary to normalize (i.e., divide) the PM_{10} concentrations by wind speed (or wind power). This provides a simple metric by which to compare normalized PM_{10} concentrations from year to year while factoring in the reality that every dust event is driven by a wind event with different hourly wind speeds. The details of the time-evolution of the events are lost in the averaging process, but the annual means provide a strong indication of how conditions are changing on the landscape as a function of surface characteristics (noting that this preliminary analysis has not considered surface moisture conditions or atmospheric moisture influences).

Figure 23 shows the trends in the annually averaged, normalized (by wind speed) PM_{10} concentrations at CDF for the 9-6 mean events with PM_{10} concentrations in excess of 99.9 µg m^{-3}. There has been a gradual, but steady decline in the ratio from values[5] of about 20 in 2016 and 2017 to less than 15 in 2020 and thereafter. The peak in 2019 is somewhat unusual given that the mean PM_{10} concentrations for the 2019 events was quite large (166.7 µg m^{-3}) despite the mean wind speed for these events (8.0 m s^{-1}) being smaller than other years (i.e., reduced forcing for dust emissions). Moreover, 2019 was a relatively wet year (20.1″ for January through December, inclusive, based on precipitation records from Station 795, Oceano, San Luis Obispo County Public Works), second only to 2023 (23.8″) and twice as much as 2020 (10″). If moisture was a dominant controlling factor, 2019 should have had very small PM_{10} concentrations whereas 2020 should have had the largest PM_{10} concentrations. This is but one example of the complexity embedded in the processes leading to dust emissions from the ODSVRA and consequent PM_{10} concentrations at downwind locations such as CDF.

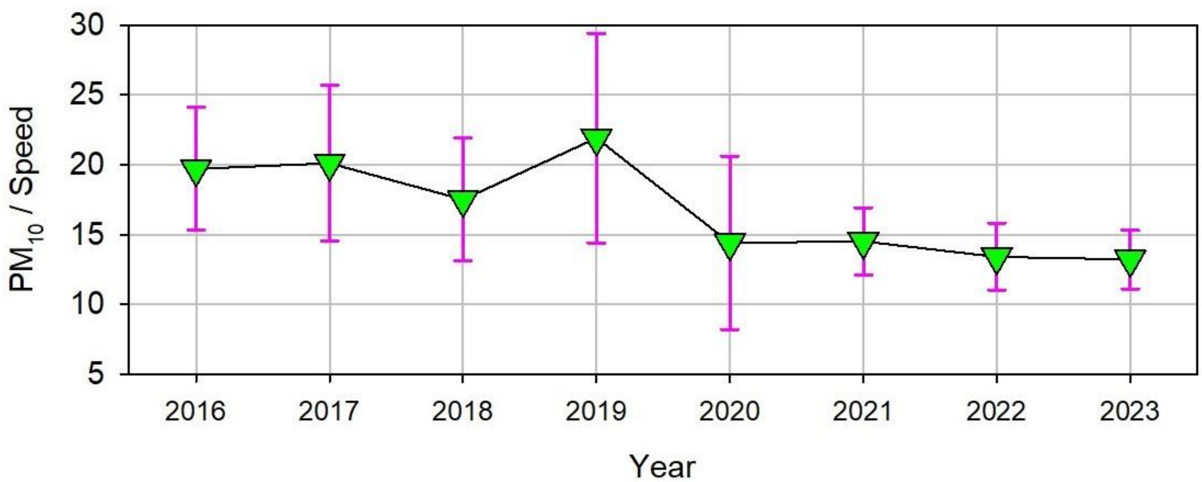

Figure 23: Trends in annual PM_{10} concentrations at CDF for 9-6 mean events normalized by associated mean wind speed from the S1 tower. Error bars show the span of the standard deviation of the yearly event values (see Figure 20 for number of events per year).

The normalized PM_{10} concentrations at CDF for 9-6 mean events shown in Figure 23 are considered a reliable indicator of progress toward achieving the management imperatives required by the Stipulated Order of Abatement (SOA #17-01). The values are based on measurements of PM_{10} made at the CDF monitoring station according to protocols and standards set by the federal government with quality assurance and quality control by the San Luis County Air Pollution Control District (APCD). Wind speeds at the S1 tower are independently collected following standardized protocols by State Parks in collaboration with the Desert Research Institute (DRI), which undertakes quality assurance and data processing, and shares the results with APCD. Thus, the data are very reliable, and no modeling is involved in generating the normalized values shown in Figure 23. The persistent downward trend in normalized PM_{10} concentrations since 2017 (the unusual results of 2019, excepted) are a strong indicator that the

[5] The units of the ratio are (µg m^{-3})/(m s^{-1}), which is an awkward combination that will be left off since the change in numerical value from year-to-year is what is most important.

management interventions instituted by State Parks within the ODSVRA are having a positive effect on mitigating the airborne dust challenges innate to this region.

The proposed data metric has several advantages even though it is not the only indicator of progress toward improved air quality in the Oceano area. Among these advantages is:

1. Based on actual PM_{10} measurements at CDF that are collected routinely by APCD using federally approved methods and analyzed using well-established quality assurance and quality control standards.
2. No modeling involved.
3. No predictive equations embedded—only raw hourly data that is filtered and averaged.
4. Not dependent (as is Rule 1001) on measurements from the Oso Flaco control site, which are not well correlated to measurements at CDF.
5. Uses a normalized parameter that factors in wind strength and accommodates changing wind conditions, thereby facilitating year-to-year comparisons directly.
6. Trends are consistent with many other indicators of improved air quality in the region.
7. Easy to calculate, and simple to understand.

The SAG hopes that the proposed metric satisfies the needs of Hearing Board members, and that they will find it a useful tool in future discussions regarding SOA compliance.