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Particulate Matter Concentration and Air Quality Affected by Windblown Dust in the Columbia Plateau

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ABSTRACT

The USEPA has proposed to regulate PM_{coarse} (particulate matter 2.5 to 10 μm in diameter). Exceedance of the proposed National Ambient Air Quality Standard (NAAQS) for PM_{coarse} is expected within the Columbia Plateau of the Pacific Northwest United States based on the high frequency of dust storms and the large contribution of crustal material to fugitive dust in the region. The objective of this study was to explore the implication of the proposed NAAQS for PM_{coarse} on air quality. Concurrent observations of both PM10 (particulate matter ≤10 μm in diameter) and PM_{fine} (particulate matter ≤2.5 μm in diameter) were made at Kennewick, WA from 1999 through 2005. Daily PM_{coarse} concentration was determined as the difference between PM10 and PM_{fine} concentrations. The number of exceedances of the proposed USEPA NAAQS for PM_{coarse} was determined for various levels of the standard (the proposed daily level is 70 μg m^{-3}). Over the 7 yr of this study, the PM10 standard was exceeded on 16 d with PM_{fine} constituting 4 to 7% of PM10. The proposed PM_{coarse} standard would have been exceeded on 35 d and represents a 120% increase in the number of exceedances over the current PM10 standard. Changing the level of the proposed PM_{coarse} standard to that of the current PM10 standard (150 μg m^{-3}) would result in a 20% decrease in the number of exceedances of the PM standard. The results of this study suggest that the proposed NAAQS for PM_{fine} and PM_{coarse} will be exceeded more frequently than the current PM_{fine} and PM10 standard in a region subject to seasonal dust storms.

MICRON-SIZED PARTICLES EMITTED INTO THE ATMOSPHERE as a result of natural events (e.g., wind) or anthropogenic activities (e.g., cultivation) can adversely affect the quality of the environment and human health. In 1971, the Clean Air Act required the US Environmental Protection Agency (USEPA) to establish both primary and secondary standards for six air pollutants that could potentially impair human health and welfare (US OFR, 1971). Primary standards were to protect the public health whereas the secondary standards were to protect the public welfare. One criteria pollutant, particulate matter (PM), was regulated as a result of the Clean Air Act; particulate matter included total suspended particles (TSP) up to a nominal diameter of about 45 μm. The primary standards set forth for TSP included a 24-hour average concentration not to exceed 260 μg m^{-3} more than one time per year and an annual geometric mean concentration not to exceed 75 μg m^{-3}. In 1987, the PM standard was revised to protect against inhaling airborne particles that could be deposited in the thoracic portions of the respiratory tract (US OFR, 1987). Particles regulated and used as the indicator of the PM standard were PM ≤ 10 μm in aerodynamic diameter (PM10). The level and form of the primary standards established for PM10 included a 24-hour average concentration of 150 μg m^{-3} with no more than one expected exceedance per year and an annual concentration not to exceed 50 μg m^{-3} averaged over 3 yr. Further epidemiological studies examining the effect of PM on respiratory illnesses suggested that the finer-size fraction of PM10 deposited in the lower portion of the respiratory tract could potentially have a greater influence on respiratory illness than coarser-size particles. Particles ≤2.5 μm in diameter (PM2.5 or PM_{fine}) were used as the indicator of the finer-size fraction. Thus, in 1997, the USEPA began to regulate both PM10 and PM_{fine} as criteria air pollutants (US OFR, 1997). Whereas no changes were made to the annual PM10 standard, the form of the 24-hour PM10 standard was revised based on the 99th percentile of 24-hour concentrations. In addition, new standards were set forth for PM_{fine} that included a 24-hour average concentration of 65 μg m^{-3} not to exceed the three year average of the 98th percentile of 24-hour concentrations and an annual concentration not to exceed 15 μg m^{-3} averaged over 3 yr.

Several locations within the Columbia Plateau region of the Pacific Northwestern USA failed to achieve the National Ambient Air Quality Standard (NAAQS) for PM10 in the late 1980s and early 1990s (Department of Ecology, 2003). Exceedance of the NAAQS for PM10 is largely associated with dust storms that are spawned by high winds as intense synoptic-scale low-pressure systems pass through the region. These storms usually occur in spring and autumn. Although annual precipitation can vary from about 150 to 700 mm across the region, the zone with <300 mm of annual precipitation (low precipitation zone) is particularly vulnerable to wind erosion (Schillinger and Young, 2004). Land in the low precipitation zone is primarily used for crop production with winter wheat as the principal crop. Winter wheat is grown every other year due to the poor distribution of and inadequate amount of annual precipitation. In non-crop years, the land is maintained in summer fallow whereby the soil is periodically cultivated and the soil surface remains partially or totally denuded for much of the 14-mo fallow period. Agricultural soils in the low precipitation zone are predominately silts and fine sands; these soils are particularly

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Abbreviations: PM10, particulate matter ≤10 μm in diameter; PM_{coarse}, particulate matter 2.5 to 10 μm in diameter; PM_{fine}, particulate matter ≤2.5 μm in diameter; PM, particulate matter; TSP, total suspended particles; TEOM, tapered element oscillating microbalances.

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vulnerable to wind erosion as a result of low organic matter content and poor aggregation. The NAAQS for PM_{fine} has also been exceeded within the Columbia Plateau, but these exceedances are largely due to wood or field-burning activities and not due to the emission of fugitive dust from agricultural lands. Although daily PM10 concentrations may exceed the NAAQS for PM10 during high wind events on the Columbia Plateau, exceedance of the standard does not violate the Clean Air Act due to exclusion of these high concentrations in accordance with the natural events policy (USEPA, 1996).

In accordance with the Clean Air Act, the NAAQS are periodically reviewed to determine whether the standards conform to the most recent scientific findings. The USEPA has recently proposed to regulate both PM_{coarse} and PM_{fine} (USEPA, 2004). The proposed NAAQS for PM_{coarse} targets particulate matter with a nominal diameter of 2.5 to 10 μm. The purpose for this designation is to separate the fine and coarse particles constituting PM10 since PM_{fine} is included in PM10. The USEPA has proposed that the level and form of the primary and secondary NAAQS for PM_{coarse} not exceed a 24-hour concentration of 70 $\mu g\ m^{-3}$ based on the 98th percentile of 24-hour concentrations over 3 yr (US OFR, 2006). The level of the proposed NAAQS for PM_{coarse} will be lower than that previously set for PM10, but the finer fraction of PM10 will be excluded from the measured concentration. Furthermore, whereas the USEPA proposes to retain the level of the annual PM_{fine} primary and secondary standard, they have proposed to revise the 24-hour primary and secondary standard for PM_{fine} not to exceed 35 $\mu g\ m^{-3}$ based on the 98th percentile of daily concentrations over 3 yr (US OFR, 2006).

The NAAQS were established to protect the health and welfare of society. Indeed, exceedance of the NAAQS can jeopardize human health, particularly affecting those who suffer from respiratory illnesses. High PM concentrations can also reduce visibility and degrade natural resources. Therefore, due to these adverse effects, exceedance of the NAAQS is in violation of federal law, the consequences of which may affect private businesses, industries, and local and state governments. For example, violation of the standards can exact civil penalties on land owners or industry as well as withhold federal funds from state governments.

The PM_{coarse} fraction is largely derived from crustal or geologic material (Chow et al., 1994). Exposure to PM_{coarse} may have potential adverse health effects, but these adverse effects have not been consistently reflected in studies that have examined short-term and long-term exposure (USEPA, 2005). As a result of the adverse effects of short-term exposure to PM_{coarse} on human health, the USEPA has proposed a 24-hour standard. However, due to little or no evidence that links increased mortality or morbidity to long-term exposure, the USEPA has not proposed an annual PM_{coarse} standard. The impact of the level of the proposed NAAQS for PM_{coarse} on the number of exceedances of the standard is not known for the Columbia Plateau. Exceedance of the proposed NAAQS for PM_{coarse} is expected based on the high frequency of dust storms and the large contribution of crustal material to fugitive dust in the region. Therefore, the aim of this paper was to explore the implication of the proposed NAAQS for PM_{coarse} on air quality within the Columbia Plateau.

MATERIALS AND METHODS

The Columbia Plateau lies within northern Idaho, northern Oregon, and eastern Washington. The Plateau is bound by the Okanagan Highlands to the north, the Cascade Mountains to the west, the Blue Mountains to the south, and the Bitterroot Mountains to the east. Winds are predominately from the southwest and are typically the strongest during spring and autumn. Five state and local air-monitoring stations within the Columbia Plateau currently measure particulate matter; these stations include Clarkston, Kennewick, Spokane, Sunnyside, and Yakima, WA. The Spokane and Yakima monitoring sites were originally designated as nonattainment for PM10, but have since been redesignated as attainment. The Kennewick site was designated as unclassified. Major industries are located within the communities of Clarkston and Spokane. Kennewick, located at the confluence of the Columbia and Snake Rivers, receives about 200 mm of annual precipitation; the community lies immediately downwind (north and east) of the Horse Heaven Hills (Fig. 1), an area of over 200 000 ha which are extremely susceptible to wind erosion (Chandler et al., 2004; Papendick, 2004).

Data collected from the Kennewick site were used to assess the impact of the level of the proposed NAAQS for PM_{coarse} on air quality. This site was chosen due to absence of major industry in the immediate area, proximity to source of wind-blown dust, and detailed daily records of PM10 and PM_{fine} concentrations. PM10 observations at Kennewick were initiated in 1987 whereas PM_{fine} observations were initiated in 1999. Thus, from 1999 through 2005, concurrent observations of both PM10 and PM_{fine} have been made at the Kennewick site. Daily PM10 and PM_{fine} concentrations were measured using federal reference method filter-based samplers. Filters for the samplers were equilibrated in a controlled environment for 24 h and weighed before and following deployment. The volume of air sampled during the deployment was calculated from the flow rate of the sampler and sampling time (24 h). Ambient PM_{fine} and PM10 concentrations were calculated by dividing the weight of collected particulate matter on the filter by the volume of air sampled. The samplers were periodically serviced and calibrated according to guidelines established for federal reference monitors (USEPA, 1998). In addition, PM10 and PM_{fine} were monitored using tapered element oscillating microbalances (TEOM). The TEOM measures real-time PM concentration; daily concentration from the TEOM was used in the event that the federal reference method filter-based sampler was being serviced or inoperative.

Daily PM_{coarse} concentration was determined as the difference between PM10 and PM_{fine} concentrations. The number of exceedances of the proposed USEPA NAAQS for PM_{coarse} was determined for various levels of the proposed standard (the proposed daily level of the standard is 70 $\mu g\ m^{-3}$ and the various levels defining an exceedance in this study varied from >0 to 150 $\mu g\ m^{-3}$). An exceedance was defined when the measured daily concentration exceeded the level of the standard.

RESULTS AND DISCUSSION

Daily PM10 concentrations that exceed the current USEPA NAAQS for PM10 of 150 $\mu g\ m^{-3}$ have been observed at Kennewick, WA (Fig. 2). In fact, 16 d exceeded the NAAQS between 1999 and 2005, whereas

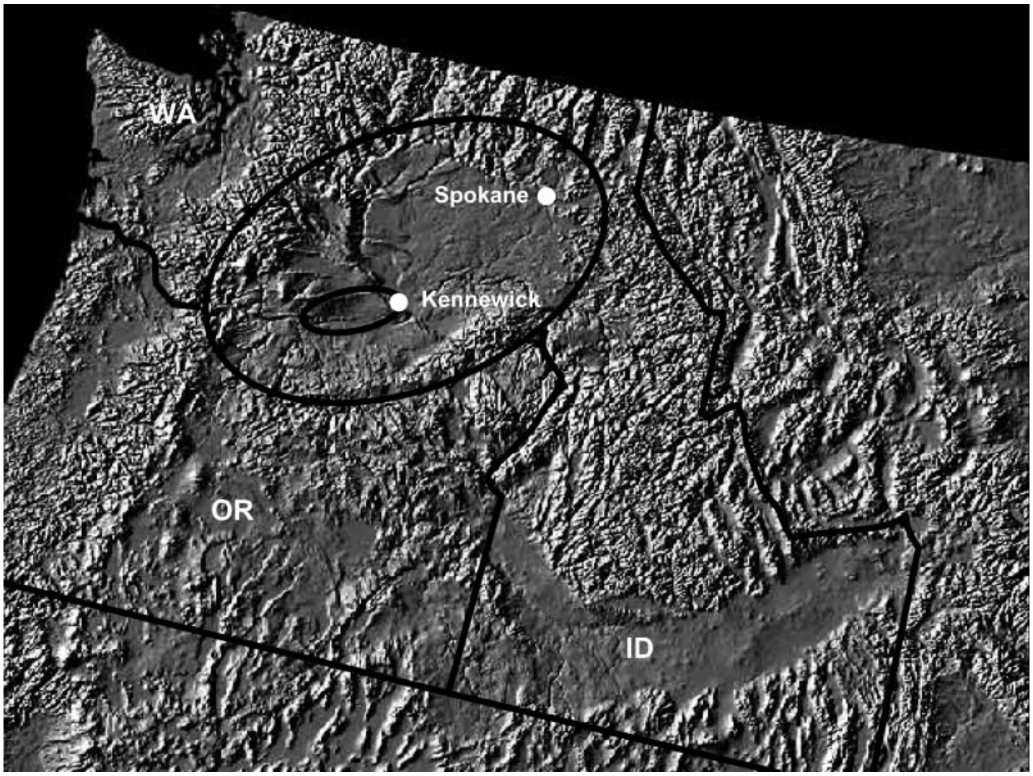

Fig. 1. Location of communities (dots) within the Columbia Plateau (oval) of the Pacific Northwest. The Horse Heaven Hills (smaller oval) lie immediately to the south and west of Kennewick, WA.

38 d exceeded the NAAQS between 1987 (the first year of observation) and 2005. Therefore, the current NAAQS for PM10 is exceeded on average 2 d per year at Kennewick. The highest daily PM10 concentration measured by the federal reference method at Kennewick, WA from 1987 through 2005 was 1689 $\mu g\ m^{-3}$ which occurred on 16 Oct. 1991. This concentration was caused by a dust storm that developed as a result of high winds across the region. Indeed, winds observed on 16 October at the USDI-BR AgriMet weather stations 50 km SSW (Hermiston, OR) and 15 km E of Kennewick (Legrow, WA) were from the SW, in excess of 6 $m\ s^{-1}$ for at least 5 consecutive hours, and attained a maximum hourly speed of 10 $m\ s^{-1}$. The fraction of PM_{fine} comprising this high concentration of PM10 could not be assessed since measurements of PM_{fine} concentration did not begin until 1999.

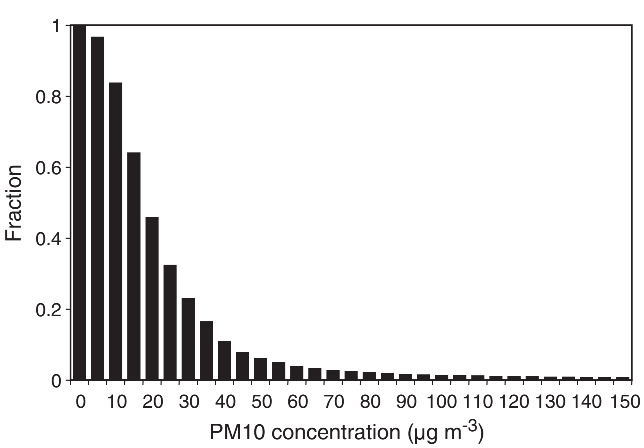

Fig. 2. Cumulative frequency distribution of PM10 concentrations at Kennewick, WA from 1999 to 2005. Daily PM concentrations, categorized by 5-$\mu g\ m^{-3}$ intervals, were measured by a federal reference method filter-based sampler or tapered element oscillating microbalance.

The cumulative frequency distribution of days with specified ranges in PM10 concentration at Kennewick from 1999 through 2005 is illustrated in Fig. 2. A small fraction or percentage of days had very low or high PM10 concentrations. For example, 3% of all days between 1999 and 2005 had concentrations either $<5\ \mu g\ m^{-3}$ or $>65\ \mu g\ m^{-3}$. Days with PM10 concentrations between 10 and 20 $\mu g\ m^{-3}$ were most commonly observed at Kennewick. In fact, PM10 concentrations within this range occurred on nearly 40% of all days (Fig. 2). An exponential decline was observed in the number of days with PM10 concentrations greater than 10 $\mu g\ m^{-3}$. This decline in the number of days with higher PM10 concentrations was apparent until concentrations exceeded about 75 $\mu g\ m^{-3}$; thereafter, the decline in frequency was nearly linear (Fig. 2). This apparent shift in the frequency distribution suggests that PM10 concentrations below and above 75 $\mu g\ m^{-3}$ are influenced by different sources or transport processes. Lower concentrations may be influenced more by local sources (i.e., industrial activities) while higher concentrations are likely influenced by infrequent large scale processes (i.e., synoptic low-pressure systems or seasonal farming operations). Days with concentrations $>150\ \mu g\ m^{-3}$ were seldom observed (0.7% of all days) from 1999 through 2005.

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Daily PM2.5 concentrations from 1999 through 2005 have not exceeded the current 24-hour USEPA NAAQS for PM2.5 of 65 μg m^{-3} at Kennewick, WA (Fig. 3). The highest concentration of 42 μg m^{-3} was observed on 10 Jan. 2004. The corresponding PM10 concentration was 44 μg m^{-3}. Winds were variable (at the USDI-BR AgriMet weather stations in Hermiston, OR and Legrow, WA, winds shifted from the east to north or south and hourly speeds ranged from 0 to 5 and 1 to 8 m s^{-1}, respectively) and blowing dust was not observed on 10 January. Thus, the high PM_{fine} concentration was likely due to wood burning or orchard heating. Daily PM_{fine} concentrations are much more skewed toward lower concentrations (Fig. 3) as compared with trends in PM10 concentrations. Days with PM_{fine} concentrations between 5 and 10 μg m^{-3} were most frequently observed (45.6% of all days) whereas days with concentrations greater than 30 μg m^{-3} were seldom observed (0.5% of all days) from 1999 through 2005.

The fraction of PM_{fine} comprising PM10 is small for synoptic dust storms that occur across the Columbia Plateau. This is exemplified for the 27 Apr. 2004 storm when the daily PM10 concentration measured by the federal reference method at Kennewick was 539 μg m^{-3}. The corresponding PM_{fine} concentration on this day was 22 μg m^{-3}. Thus, PM_{fine} comprised 4.1% of PM10. The PM_{coarse} (PM10 minus PM_{fine}) concentration was 517 μg m^{-3} or 95.9% of PM10. Based on concurrent PM_{fine} and PM10 data collected from 1999 through 2005, the PM_{fine}/PM10 ratio ranged from 0.03 to 0.07 when daily PM10 concentrations exceeded the USEPA NAAQS for PM10 of 150 μg m^{-3} (Fig. 4). The low PM_{fine}/PM10 ratio during dust storms at Kennewick supports past observations that PM_{coarse} is largely crustal material (eroded soil) and constitutes a large portion of PM10 (Chow et al., 1994). However, our ratios are higher than those observed by Claiborn et al. (2000) at Spokane, WA. They report ratios ranging from 0.07 to 0.36 across five dust storms during the 1990s. Although the elevated PM10 concentrations arising from dust storms are typically lower at Spokane than at Kennewick, we believe the higher PM_{fine}/PM10 ratio observed at Spokane is a result of PM_{fine} enrichment of the atmosphere associated with long range transport. Smaller particles are transported longer distances in the atmosphere because smaller particles tend to fall more slowly through the atmosphere (lower terminal velocity) as compared to larger particles. Spokane is located within the intermediate precipitation zone (300 to 400 mm annual precipitation) of the Columbia Plateau and farther downwind than Kennewick from the highly erodible agricultural fields that are traditionally maintained in summer fallow every other year. At Kennewick, a wide range in the PM_{fine}/PM10 ratio was evident for daily PM10 concentrations below 50 μg m^{-3} with the ratio varying from 0.04 to 1.00 (Fig. 4).

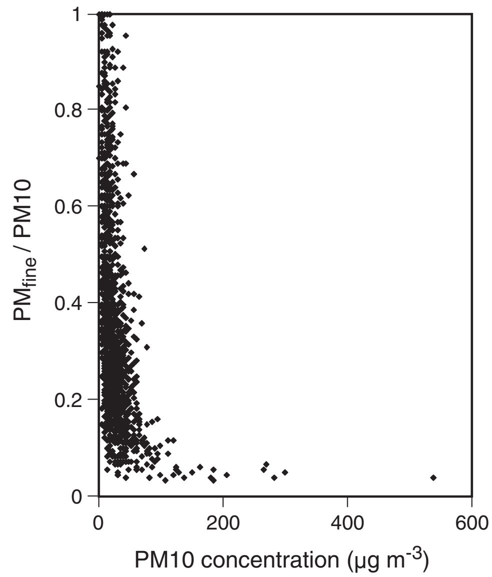

Fig. 4. PM_{fine}/PM10 ratio as a function of daily PM10 concentration from 1999 through 2005 at Kennewick, WA.

From 1999 through 2005, concurrent measurements of PM_{fine} and PM10 using either the federal reference method filter-based samplers or TEOMs were made on 68% of the days. Concurrent measurements of PM_{fine} and PM10 using federal reference method filter-based samplers were made on 20% of the days. Although the same type of sampler was used to measure both PM_{fine} and PM10 on any given day, inadequacies of the sampler design to capture only PM_{fine} or PM10 (Buser et al., 2003; Wang et al., 2005) will contribute to inaccuracies in measuring PM_{coarse}. However, similar trends in the frequency distribution of days with various levels of PM_{coarse} were found using data collected by both the federal reference method filter-based sampler and TEOM. Therefore, the frequency of daily PM_{coarse} concentrations is reported using data collected by both the federal reference method filter-based sampler and TEOM. The frequency distribution for PM_{coarse} (Fig. 5) is similar to that for PM10 (Fig. 2) and suggests that the concentration of PM10 is largely dependent on PM_{coarse}. About 15% of the days from 1999 through 2005 had PM_{coarse} concentrations below 5 μg m^{-3}, but an ex-

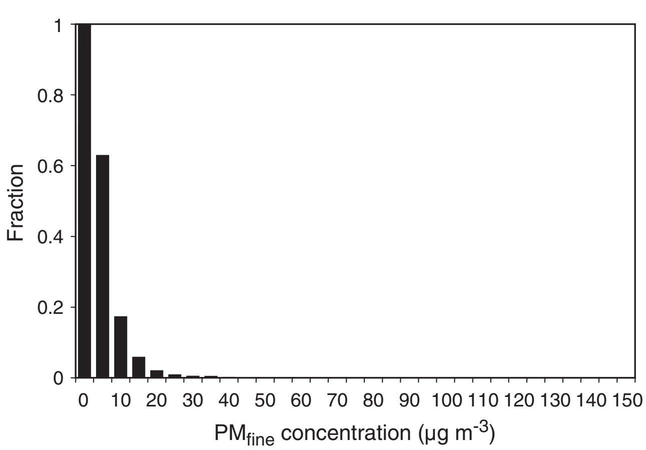

Fig. 3. Cumulative frequency distribution of PM_{fine} concentrations at Kennewick, WA from 1999 through 2005. Daily PM concentrations, categorized by 5-μg m^{-3} intervals, were measured by a federal reference method filter-based sampler or tapered element oscillating microbalance.

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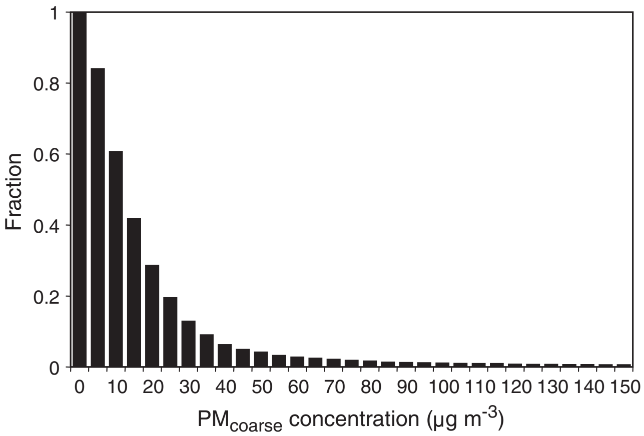

Fig. 5. Cumulative frequency distribution of PM_{coarse} concentrations at Kennewick, WA from 1999 through 2005. Daily PM concentrations, categorized by 5-µg m^{-3} intervals, were determined using federal reference method filter-based samplers or tapered element oscillating microbalances.

ponential decline was observed in the number of days with higher PM_{coarse} concentrations (Fig. 5). Days were most frequently observed with PM_{coarse} concentrations between 5 and 10 µg m^{-3} (23.3% of all days). The exponential decline in the number of days with higher PM_{coarse} concentrations was apparent until concentrations exceeded about 75 µg m^{-3} (Fig. 5) after which the decline was linear. Similar to PM10, this point of inflection in the frequency distribution may suggest that PM_{coarse} concentrations below and above 75 µg m^{-3} are influenced by different sources or transport processes.

The USEPA has proposed a NAAQS for PM_{fine} not to exceed a daily concentration of 35 µg m^{-3} and a NAAQS for PM_{coarse} not to exceed a daily concentration of 70 µg m^{-3}. The frequency distribution of PM_{fine} in Fig. 3 would suggest that the proposed NAAQS for PM_{fine} would be exceeded 7 d from 1999 through 2005. During these 7 d, 24-hour PM_{fine} concentrations ranged from 36 to 42 µg m^{-3}. These high PM_{fine} concentrations were likely associated with wood burning or other activities and not to windblown dust, as 5 of the 7 exceedances occurred in autumn and winter. In addition, PM10 concentrations did not exceed 70 µg m^{-3} and the PM_{fine}/PM10 ratio ranged from 0.51 to 1.00 across the 7 exceedances. These 7 exceedances would not be caused by windblown dust as dust storms were previously shown in this paper to be characterized by low PM_{fine}/PM10 ratios (0.03 to 0.07). Nevertheless, windblown dust could lead to exceedance of the PM_{fine} standard under conditions of extreme 24-hour PM10 concentrations. For example, the highest 24-hour PM10 concentration observed from 1999 through 2005 of 1438 µg m^{-3} was associated with a blowing dust event on 28 Oct. 2003. Although PM_{fine} concentration was not measured on that day, a 24-hour PM_{fine} concentration of 43 to 101 µg m^{-3} was likely based on a PM_{fine}/PM10 ratio of 0.03 to 0.07 during windblown dust events. According to the frequency distribution of PM_{coarse} in Fig. 5, the proposed NAAQS would be exceeded 35 d from 1999 through 2005. This represents a 120% increase in the number of exceedances over the current NAAQS for PM10. However, changing the level of the proposed NAAQS for PM_{coarse} to that of the current NAAQS for PM10 (150 µg m^{-3}) would result in a 20% decrease in the number of exceedances of the NAAQS for PM at Kennewick, WA. Thus, any reduction in the level of the proposed NAAQS for PM_{coarse} will greatly increase the number of exceedances of the NAAQS for PM. Such changes in the level of the standard will not only affect businesses, industry, and local and state governments, but also state and federal air quality agencies in regulating and documenting these exceedances.

CONCLUSIONS

The current USEPA NAAQS for PM10 is exceeded in the Columbia Plateau as a result of dust storms that occur with the passage of intense synoptic low-pressure systems. At Kennewick, WA, 4 to 7% of the PM10 measured during these storms was PM_{fine}. Thus, 93 to 96% of the PM10 was PM_{coarse}. The USEPA has proposed to lower the level of the 24-hour PM_{fine} standard and to regulate PM_{coarse} since PM_{coarse} and PM_{fine} constitute PM10. Based on the frequency distribution of PM_{fine} and PM_{coarse} observed from 1999 through 2005, the proposed PM_{fine} and PM_{coarse} standards would be exceeded respectively one and five times per year at Kennewick. Any change in the level of the proposed NAAQS for PM_{fine} or PM_{coarse} will greatly affect the number of exceedances of the NAAQS for PM at Kennewick, WA.

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