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Variations of nanoparticle concentrations at the Fresno Supersite

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Abstract

Particle size distributions from 3 nm to 2 μm were measured at the Fresno, CA, Supersite from August 25, 2002 through July 31, 2003. Nanoparticle (3–10 nm) concentrations and the ratio of nanoparticle to total particle concentration were inversely related to particle surface areas from 50 to 1000 $\mu m^2\ cm^{-3}$. Elevated nanoparticle concentrations were associated with motor vehicle emissions and with photochemical particle production. In contrast with Atlanta, GA, where concentrations of photochemically derived nanoparticles exceeded $10^5\ cm^{-3}$, 5-min average nanoparticle concentrations in Fresno never exceeded 24,400 cm^{-3}. While photochemical particle production occurs in Fresno, evidence of new particle production (i.e., an increase in number concentration with decreasing size below 10 nm) was not observed. This suggests that photochemical particle production may have occurred at a higher altitude followed by mixing to the surface, or that the fresh particle production rate was smaller with respect to the loss rate by coagulation than it was in Atlanta. Lower production rates in Fresno are more consistent with lower concentrations of sulfur precurors and low relative humidity in Fresno than they are in Atlanta.
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1. Introduction

Aerosols are a major focus of research and remediation efforts aimed at improving air quality in the United States (U.S. EPA, 1997, 1999). While Federal air pollution standards are formulated in terms of atmospheric particulate matter (PM) mass concentration, previous studies suggest that adverse health effects may be related to the ultrafine particle (<100 nm diameter) and/or nanoparticle (~3–10 nm) concentrations, which represent small fractions of PM mass (Oberdörster, 1996; Peters et al., 1997). Light scattering by aerosols and their ability to act as cloud condensation nuclei are important components of the earth's radiation balance and may contribute to global

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climate change (Twomey et al., 1984; Charlson et al., 1992; Watson and Chow, 2002).

Concerns over air quality, health effects, and climate change, coupled with the development of instrumentation (e.g., the TSI, Inc., ultrafine condensation particle counter [CPC] and nano differential mobility analyzer [DMA]) able to count and size particles as small as 3 nm in diameter have led to extensive research on aerosol particle formation and evolution (Clarke et al., 1998; Birmili et al., 2000; Kulmala et al., 2004; O'Dowd et al., 1998; Weber et al., 1995, 1997; Donaldson et al., 1998, 2001; Ziemann et al., 2001).

Clarke (1992) measured nanoparticle (3–15 nm) concentrations in the marine free troposphere, where nanoparticle concentrations up to 80,000 cm^{-3} were inversely related to aerosol surface area in the range of 0.01 to 1 μm^2 cm^{-3}. Volatility at 300 °C suggested that particles in this size range were composed of sulfuric acid (H_2SO_4). Covert et al. (1992) observed a nucleation event in the remote marine boundary layer that appeared to be related to an increase in sulfur dioxide (SO_2) concentration and a decrease in aerosol surface area from 25 to 5 μm^2 cm^{-3}. O'Dowd et al. (1998) observed increases in nanoparticle numbers (3–10 nm) at a remote coastal site in Ireland. Nanoparticle concentrations of 40,000 cm^{-3} over a background of 500 cm^{-3} were attributed to photochemical conversion of gaseous biogenic precursors.

Birmili et al. (2000) observed new particle production at a mountain site in Germany. Total particle concentrations increased to 25,000 cm^{-3} (half of which were smaller than 11 nm) at midday in conjunction with solar radiation and increases in H_2SO_4 and hydroxyl radical (OH) concentrations. Lowenthal et al. (2002) reported peak hourly average nanoparticle (3–10 nm) concentrations of ~9000 cm^{-3} that followed the diurnal variation in solar irradiance at a mountaintop site in the Colorado Rocky Mountains. The diurnal trend in nanoparticle concentration appeared unrelated to aerosol surface area, which remained relatively constant (30–40 μm^2 cm^{-3}). Weber et al. (1995) measured concentrations of particles with diameters from 2.7 to 4 nm using ultrafine CPC pulse-height analysis at the Mauna Loa Observatory (MLO). Particle production was related to H_2SO_4 concentration and occurred over a range of surface area as high as 30 μm^2 cm^{-3}. Weber et al. (1997) observed new particle production at Idaho Hill in the eastern Colorado Rocky Mountains. Nucleation coincided with H_2SO_4 and OH production and lagged behind ultraviolet (UV) solar intensity by about an hour. Concentrations higher than 100 cm^{-3} of particles with diameters from 3 to 4 nm occurred over a range of aerosol surface areas between 30 and 80 μm^2 cm^{-3}.

Nanoparticles are also produced by nucleation in combustion emissions plumes (Kittleson, 1998). Tobias et al. (2001) suggested that high concentrations of nanoparticles in diesel exhaust are formed through binary nucleation of H_2SO_4 and water followed by condensation of organics on these particles. Harrison et al. (1999) reported peak concentrations of nanoparticles (3–7 nm) of several tens of thousands cm^{-3} at midday in Birmingham, England, and suggested that these resulted from photochemical gas-to-particle conversion. It was also found that 24 h mean PM_{10} (mass concentration for particles with diameters less than 10 μm) and total number concentrations were significantly correlated. Woo et al. (2001) reported high (>100,000 cm^{-3}) nanoparticle (3–10 nm) concentrations peaking around midday in Atlanta. On a yearly basis, the diurnal variation of nanoparticles was inversely related to that of particles larger than 10 nm. A nanoparticle "event" with a nanoparticle concentration of ~120,000 cm^{-3} on April 1, 1999, occurred with a pre-existing aerosol surface area of 423 μm^2 cm^{-3}. That these events represented fresh nucleation was evidenced by large increases in particle numbers with particle size decreasing from 10 to 3 nm (McMurry et al., 2000).

Watson et al. (2002) examined variations of particle size (>10 nm diameter) and number distributions at the Fresno Supersite during the winter of 2000–2001. Particle concentrations peaked in the morning rush hour, coinciding with increases in nitrogen oxides (NO_x) and black carbon (BC), went through a minimum in the early afternoon, increased through the evening rush hour, and remained high throughout the night, as did NO_x and BC. While nanoparticles (<10 nm) were not measured, the ratio of particles with diameters from 10 to 28 nm to the total particle concentration peaked during the morning rush hour and also in the early afternoon, coinciding with the minimum in total particle concentration. This suggested that particles may have been formed by pho-

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tochemically induced nucleation faster than they were being lost to coagulation.

In this paper, particle measurements (3 nm–2 μm) from August 25, 2002 through July 31, 2003 at the Fresno Supersite are examined, focusing on variations of nanoparticle (hereafter referring to particles with diameters of 3 to 10 nm) concentrations and contrasting them with measurements at other locations.

2. Methods

The Fresno air monitoring station at 3425 First Street (36° 46′ 54″ N, 119° 46′ 24″, 97 m ASL) has been in operation since 1990. The "Supersite" measurement program is described by Watson et al. (2000, 2002). Measurement instruments are located on the second floor of a two-story building with the PM_{10} inlet ~10 m above the ground. Particle size measurements are described by Watson et al. (2002). A TSI SMPS 3936L10 (scanning mobility particle sizer equipped with a TSI model 3080 "long" DMA and a TSI model 3010 CPC) measures the particle size distribution from 9 to 392 nm in diameter in 52 channels. The SMPS sizes particles based on their electrical mobility. Accumulation mode particles are measured with a Particle Measuring System (PMS) OPC 1003 optical particle counter (OPC), which sizes particles from 0.1 to 2 μm in diameter in seven channels. The instrument is factory calibrated with polystyrene latex (PSL) beads with a refractive index of 1.59, i0.0. This is close to the refractive index (1.579, i0.05) inferred from the chemical composition of aerosol samples collected at the site (Watson et al., 2002). A TSI "nano" SMPS 3936N25 (NSMPS) equipped with a TSI model 3085 nano-DMA and a 3025A-S ultrafine CPC was deployed near the end of August 2002. The nano-SMPS sizes particles with diameters from 2.94 to 86.6 nm in 47 channels. All particle measurements were taken over sequential 5-min periods beginning on the hour. The SMPS size distributions were corrected for multiple charges and for the decrease in small particle counting efficiency by the CPCs. Meteorological measurements (wind speed and direction, temperature, relative humidity [RH], pressure, and solar irradiance) were acquired for the same 5-min intervals. Five-minute average NO/NO_x and ozone (O_3) concentrations were determined with TEI 42 and API 400 analyzers, respectively. Particulate sulfate ($SO_4^=$) and nitrate (NO_3^-) were measured over 10-min periods with the *R* and P 8400S and 8400N analyzers, respectively. ($SO_4^=$ data are available from August, 2002 through May, 2003). BC was measured with a Magee Scientific AE31 7-color aethalometer at 5-min intervals. Hourly averages of these properties were calculated on the basis of a minimum data availability of 75%.

3. Results and discussion

3.1. Average size distributions

The average SMPS and OPC size distributions from August 25, 2002 through July 31, 2003 are plotted in Fig. 1. The discontinuities between the NSMPS and SMPS were most pronounced from August, 2002 through April, 2003. The increase in particle number with decreasing size in the first four channels of the standard SMPS appears to be artifactual and is thought to be related to "time smearing" in the TSI Model 3010 CPC. This effect is not observed in the NSMPS because the TSI Model 3025 CPC employs a sheath flow while the Model 3010 CPC does not. Continuous size distributions can be constructed by integrating channels 1–28 of the NSMPS (2.94–22.1 nm) and channels 14–53 of the SMPS (22.1–392 nm).

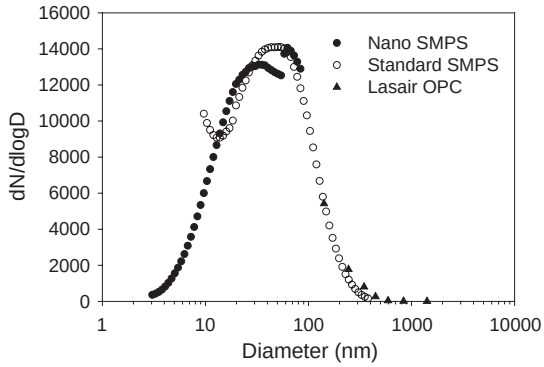

Fig. 1. Average hourly "nano" scanning mobility particle sizer (NSMPS), SMPS, and OPC optical particle counter (OPC) size distributions at the Fresno Supersite (August 25, 2002, through July 31, 2003).

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Watson et al. (2002) noted that there is an offset between the upper end of the SMPS (~100–392 nm) and lower end of the OPC (~100–400 nm) distributions. Ammonium nitrate (NH_4NO_3) is a major component of the Fresno aerosol during winter (Watson et al., 2000; Watson and Chow, 2002; Chow et al., in press). Because the sampling shelter temperature was up to 17 °C higher than the SMPS temperature during winter, Watson et al. (2002) suggested that the apparent loss of SMPS particles from the overlap region was caused by evaporation of NH_4NO_3 particles. This explanation was supported by the underestimation of particle light scattering (b_{sp}) estimated from particle size distributions compared to b_{sp} from a nephelometer in winter but not in summer, when NH_4NO_3 is virtually absent (Chow et al., 1992).

Fig. 2 presents average monthly SMPS and OPC size distributions for January and July 2003. Only the first three OPC channels overlap with the SMPS. Assuming that the SMPS is accurate, the offset between the SMPS and OPC could be due to oversizing

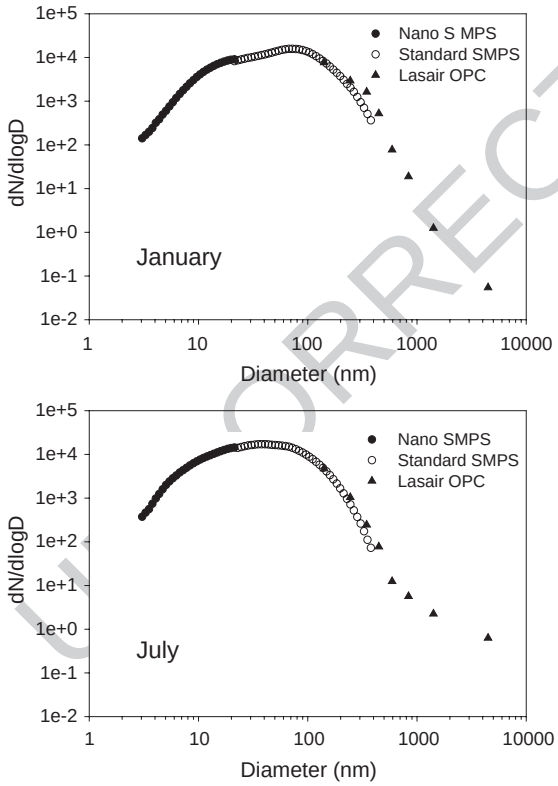

Fig. 2. Average hourly size distributions for January and July, 2003.

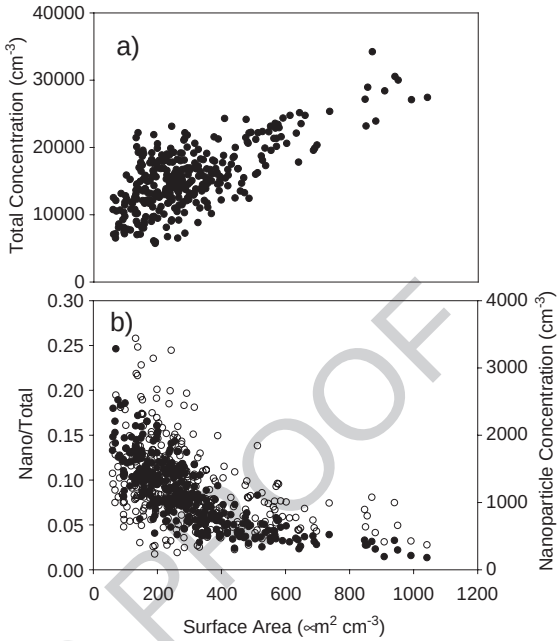

Fig. 3. (a) Relationship between 24-h average total particle (>3 nm) concentration and particle surface area; (b) relationships between 24-h average nanoparticle to total particle concentration ratio (nano/total) and surface area (closed circles), as well as nanoparticle concentration and surface area (open circles) (August 25, 2002, through July 31, 2003).

by the OPC because the refractive index of the PSL is different from that of the ambient aerosol. The midpoint of the third OPC channel is 346 nm. If this point is shifted to the left on the January plot in Fig. 2, it would overlap the SMPS curve at a diameter of about 250 nm. To produce this offset, the refractive index of the ambient aerosol would have to be nearly 2, which is inconsistent with the chemical composition of the winter aerosol. Fig. 2 shows that the vertical offset between the midpoint of the third OPC (346 nm) and third-to-last SMPS channel (328 nm) is much greater in January than in July. This is consistent with the evaporative loss of NH_4NO_3 particles in January but not in July.

3.2. Nanoparticle trends

Previous studies have examined the relationship between fresh particle nucleation and pre-existing particle surface area. Woo et al. (2001) reported a weak correlation between total (>3 nm) number concentration and surface area. Fig. 3a presents the rela-

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tionship between 24-h average total (>3 nm–2 μm) particle concentration and surface area in Fresno. In this case, the correlation coefficient (r=0.71) was moderately high, especially when the surface area exceeded 400 μm^2 cm^{-3}. Fig. 3b indicates that the ratio of 24-h average nanoparticle to total particle concentration decreased with increasing particle surface area over a wide range from about 50 to 600 μm^2 cm^{-3}. Fig. 3b also shows that nanoparticle concentration and surface area were inversely correlated for concentrations from less than 1000 to over 3000 cm^{-3}.

Long-term variations in nanoparticle and total particle (>3 nm–2 μm) concentrations are presented as a time series of monthly averages in Fig. 4. The highest nanoparticle concentrations occurred in June, 2003, followed by September, 2002. While total particle concentrations also increased in summer (June, 2003), the highest total concentrations occurred in winter (December, 2002). The monthly-average nanoparticle/total particle ratio was correlated with nanoparticle concentration (r=0.82) and inversely correlated with particle surface area (r=−0.92). Monthly-average nanoparticle concentration was also inversely correlated with surface area (r=−0.61). Monthly average surface area was directly correlated with total particle concentration (r=0.65). As expected, nanoparticle and total particle concentrations were not correlated (r=0.17). The inverse correlation of nanoparticle concentration and nanoparticle/total particle ratio with surface area is consistent with trends observed by Clarke (1992) and Covert et al. (1992), although the range of particle surface areas in Fresno was much greater. Watson et al. (2002) described the diurnal variations of SMPS particle concentration (9–392 nm), NO_x, and BC concentrations at the Fresno Supersite during winter (2000–2001). The morning rush hour peak in SMPS, NO_x, and BC concentrations dissipated by midday as vehicle emissions subsided and the mixed layer deepened. A steady increase in SMPS, NO_x, and BC concentrations from the evening rush hour through the early morning hours the next day was attributed to an increase and buildup of vehicle and wood burning emissions under the evening surface inversion (Watson and Chow, 2002).

Diurnal variations for summer (as represented by July, 2003) and winter (as represented by January, 2003), weekdays (Monday–Friday) and weekends (Saturday and Sunday) are examined in Fig. 5, which displays hourly nanoparticle and total particle concentrations, the nano/total ratio, NO_x concentration, and particle surface area. BC is not shown because its correlation (r) with NO_x for winter and summer was 0.72 and 0.77 for weekdays, and 0.63 and 0.81 for weekends, respectively.

The winter diurnal variation of total particle concentration is similar to that seen by Watson et al. (2002), i.e., morning and evening rush hour peaks

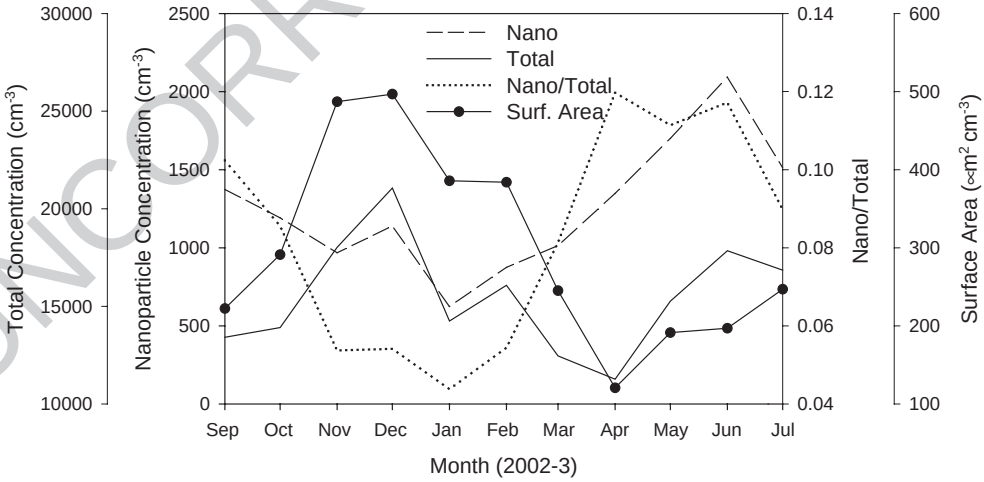

Fig. 4. Time series of monthly average nanoparticle (3–10 nm) and total particle (3 nm–2 μm) concentration, surface area, and ratio of nanoparticle to total particle concentrations (nano/total).

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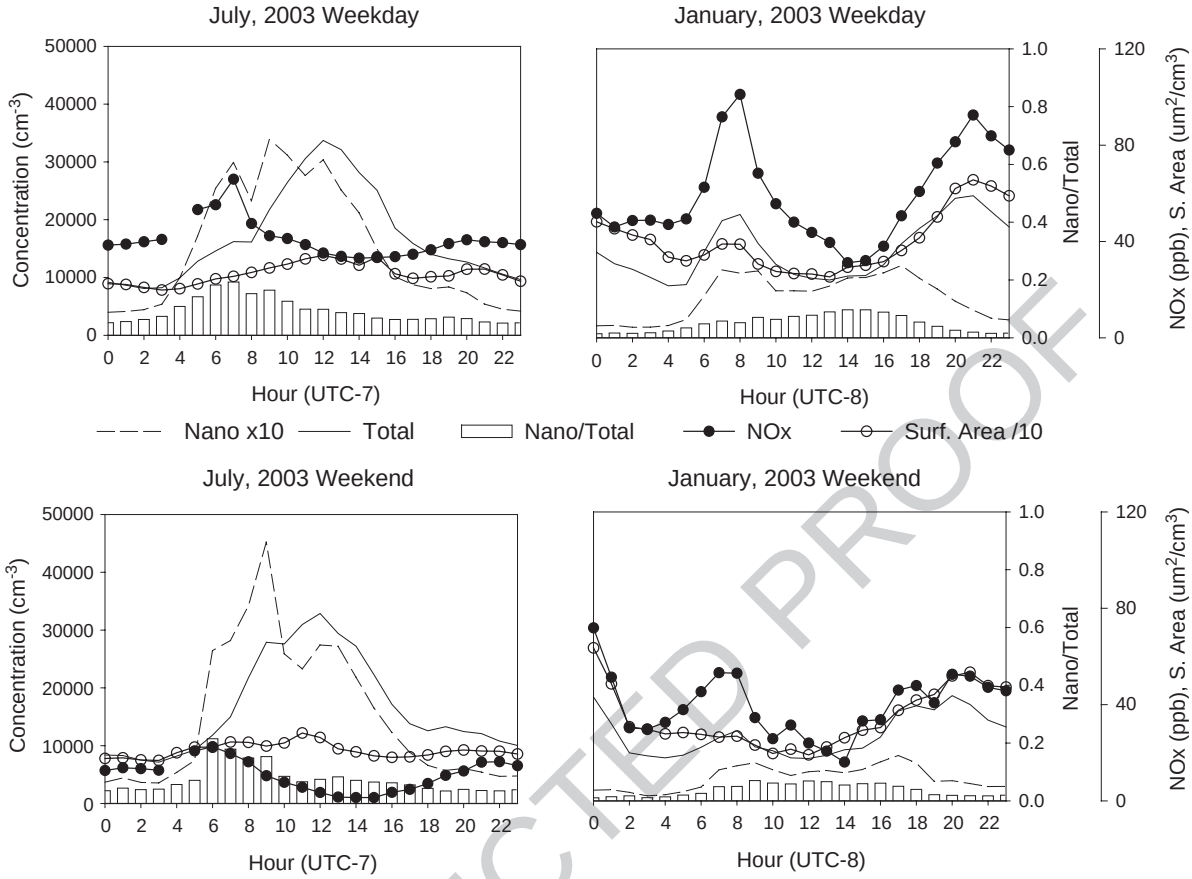

Fig. 5. July, 2003 and January, 2003 weekday and weekend diurnal trends in nanoparticle (3–10 nm) and total particle (3 nm–2 μm) concentration, nano/total ratio, surface area, and NO_x concentration. Pacific Standard Time (PST) is UTC minus 8 h.

coinciding with increases in NO_x. Total particle concentrations were lower on weekends, especially during the morning rush hour. Fig. 5 shows that nanoparticle concentration displayed distinct peaks in the morning (0700–0900 Pacific Standard Time [PST], UTC minus 8 h) and evening (1600–1700 PST) rush hours on winter weekdays and weekends, coinciding with an increase in total particle, NO_x, and surface area concentration. Nanoparticle concentration decreased after 1700 PST, while total particle number concentration, NO_x, and surface area continued to increase through the night, peaking during the period 1900–2100 PST. This continued increase could be due to residential wood burning emissions in conjunction with the development of a nighttime surface inversion. However, nanoparticles appear to be efficiently removed at night by the increase in surface area.

While the weekend morning rush hour peak during winter was much less intense, the evening peak was similar to that seen on weekdays. This suggests that the post-rush hour evening increases in particle number concentration, surface area, and NO_x came from sources other than vehicles, i.e., residential wood combustion. During winter, the peak in the nano/total ratio occurred in the early afternoon, although the absolute nanoparticle concentration fell to a relative minimum at this time. If the decrease in NO_x, total particle concentration, and surface area represent a decrease in primary emissions source strength, then the increase in the nano/total ratio could represent a relative increase in photochemical particle production rate with respect to primary production or reduced removal of nanoparticles by the decrease in particle surface area.

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As shown in Fig. 5, the diurnal variations during summer were different from those in winter. Peak nanoparticle, total particle concentrations, and the ratio of nano/total were higher in summer than in winter. The main peak in total particle concentration occurred at midday on weekdays and weekends in summer, which suggests photochemical particle production. Two other peaks in nanoparticle concentration were found at 0700 and 0900 PST on summer weekdays and weekends. The early morning (0700 PST) peak coincides with a peak in NO_x concentration, suggesting a vehicle emission source. However, the broad nano/total ratio peak between 0600 and 0900 PST was about twice as high as those seen on winter mornings. The average weekday morning rush hour nanoparticle concentration (~2800 cm^{-3}) was also higher in summer than winter. The higher morning rush hour nanoparticle concentration during summer may be sustained by higher ambient temperatures, which inhibit removal to existing particle surface area relative to wintertime, or by increased nanoparticle emissions related to warmer engine operating conditions in summer. Primary motor vehicle emissions are an important source of nanoparticles in Fresno. A maximum hourly average nanoparticle concentration of 14,490 cm^{-3} occurred on June 25, 2003, at 0800 PST.

The 0900 PST nanoparticle peak during summer on weekdays and weekends cannot be explained by primary vehicle emissions because NO_x concentrations had subsided by that hour. Because both nanoparticle and total particle concentrations increased between 0700 and 0900 PST while NO_x emissions decreased, it may be surmised that the increase in particle concentration resulted from different emission sources or from photochemical production. The average solar irradiance during the 0900 PST hour during summer was 757 Wm^{-2}, compared to an hourly average maximum of 935 Wm^{-2} during the 1100 PST hour. While total particle concentration continued to increase until 1200–1300 PST, the nanoparticle concentration decreased at 1100 PST before peaking again at 1200–1300 PST. There appears to be a balance between photochemical production of nanoparticles and their removal through condensational growth and coagulation with larger particles that may be mediated by dilution caused by deepening of the mixed layer through the late morning hours. In contrast with winter, nanoparticle and total particle concentrations decreased through the afternoon and displayed a slight increase during the evening rush hour (1700–1900 PST) coinciding with an increase in NO_x concentration. Perhaps this reflects the absence of residential wood combustion during summer. NO_x and particle surface area concentrations increased gradually through the evening hours, although to a lesser extent than observed in winter.

3.3. Evidence for fresh photochemical particle production in Fresno

Fresh photochemical particle production should be apparent from high concentrations of nanoparticles and increasing concentration with decreasing diameter from 10 to 3 nm during the hours of peak solar irradiance, as observed in Atlanta by McMurry et al. (2000) and Woo et al. (2001), who reported episodic nanoparticle concentrations exceeding 10^5 cm^{-3}. In Fresno, the highest 5-min average nanoparticle concentration was 24,400 cm^{-3} on March 11, 2003, at 1350 PST, about 1 h after the peak solar irradiance on that day. This concentration is two orders of magnitude lower than those observed during nucleation events in Atlanta. The size distribution for this 5-min average is presented in Fig. 6, which indicates a smooth decrease of concentration in sizes below 10 nm. This suggests that some degree of aging, with loss of nanoparticles to coagulation or condensational

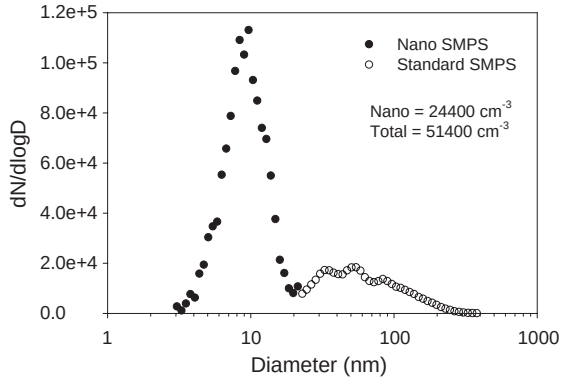

Fig. 6. Five-minute average particle size distribution for March 11, 2003, 1350 PST (UTC minus 8 h), with the highest 5-min nanoparticle concentration of 24,400 cm^{-3}.

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growth, must have occurred before these particles were sampled. Because the NO_x concentration of about 15 ppb during this period had been reduced from its morning rush hour peak value of about 100 ppb, this event did not represent fresh combustion emissions.

McMurry et al. (2000) reported 85 hourly average size distributions with increased new nanoparticle number concentrations and decreasing diameter from 10 to 3 nm over a 13-month period in Atlanta. To look for this trend in the Fresno data, hourly particle concentrations in three size ranges from the NSMPS were averaged: (1) U1 (2.9–3.65 nm), (2) U2 (5.23–6.49 nm), and (3) U3 (8.06–10 nm). Evidence of a clear trend of increasing numbers with decreasing diameter below 10 nm would entail U1 > U2 > U3. However, there was not 1 h out of 8087 h with valid data where this was the case.

The same trend was examined in the 5-min average data between the hours of 1100 and 1800 PST, when photochemical production is expected. While 21 cases fit the criterion noted above, there was only one case, on August 31, 2002 (1300 PST), with a nanoparticle concentration (16,970 cm^{-3}) that was greater than 2300 cm^{-3}. This was one of only four cases with a nanoparticle concentration greater than 1300 cm^{-3} where $U1 > 1.3 \times U2$ and $U2 > 1.3 \times U3$. Even in this case, the slope of the decrease in $dN/d\log D$ as a function of diameter from 3 to 10 nm was considerably less than that shown in Fig. 3 of McMurry et al. (2000).

The apparent absence of fresh (i.e., immediate) particle production in Fresno is not simply a function of high existing particle surface area on the same order as that found in Atlanta. There, nanoparticle events occurred with increases in SO_2 concentration and fresh particle production was attributed to binary nucleation of H_2SO_4 and water (Woo et al., 2001). SO_2 concentrations in Fresno are usually below the detection limit of the low-sensitivity continuous monitor deployed there. Particle $SO_4^=$ concentrations are much higher in Atlanta than in Fresno (Weber et al., 2003; Chow et al., 1993). In California's central valley, $SO_4^=$ distributions are regional and concentrations are generally low (Chow et al., 1993). Further, RH in Fresno is much lower than in Atlanta. During summer (June–August), hourly RH in Fresno averaged 40%. Perhaps nanoparticle concentration peaks around midday in Fresno result from nucleation of $SO_4^=$ aloft followed by relatively rapid mixing to the surface with a time lag sufficient to generate a distribution such as the one shown in Fig. 6, in contrast to those presented in Fig. 3 of McMurry et al. (2000).

Nonetheless, after initial nucleation, photochemical nanoparticle "events" in Fresno evolved predictably. Fig. 7 displays the diurnal variation of nanoparticle and total particle concentration, their ratio, particle surface area, and $SO_4^=$ concentration on March 29, 2003, when a maximum in nanoparticle concentration of 6490 cm^{-3} occurred at noon. The corresponding nano/total ratio for this period, 0.46, was among the highest hourly-average ratio of the study and occurred

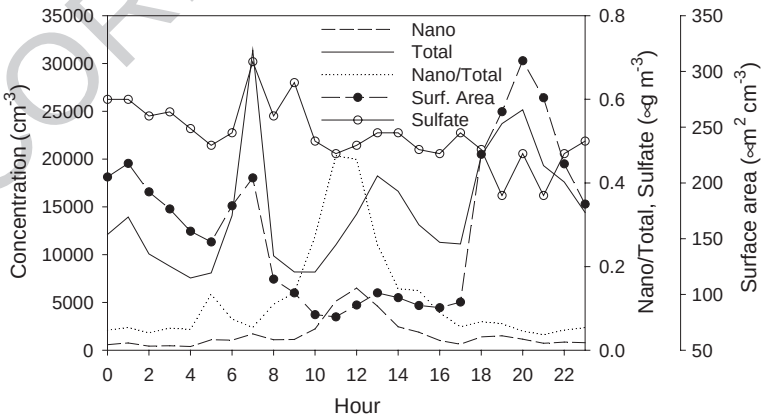

Fig. 7. Diurnal variation of nanoparticle (3–10 nm) and total particle (>3 nm) concentration, nano/total ratio, surface area, and $SO_4^=$ concentration on March 29, 2003.

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at the daily minimum in particle surface area. This nanoparticle concentration peak was preceded by a decrease in total particle concentration and surface area. Between 1200 and 1300 PST, nanoparticle concentration decreased and total particle concentration increased, reflecting the growth of nanoparticles into the larger size range.

Fig. 8 illustrates the diurnal variation of the size distribution on March 29, 2003. As shown in Fig. 7, the morning rush hour (0700 PST) produced a discrete burst of particles with a median diameter of 24 nm. This event was short-lived, with total particle concentration reaching the pre-rush hour level within an hour and surface area dropping below that level. The particle distribution corresponding to the nanoparticle peak at noon had a median diameter of 10 nm. By 1400 PST, the median diameter had increased to 18 nm. Total particle concentration and surface area both peaked at 2000 PST. The median diameter increased from 25 nm at 1700 PST to 38 nm at 2000 PST. The increase in particle concentration and surface area over this period was probably due to increases in emissions rather than to the development of a surface inversion because temperature decreased from 24.5 °C to only 19.1 °C between the hours of 1700 and 2000 PST.

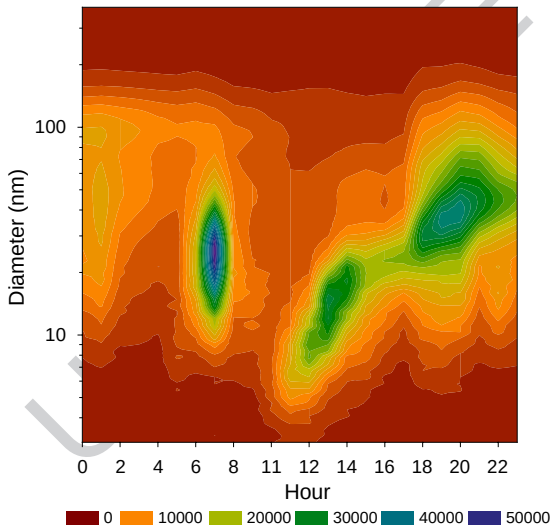

Fig. 8. Diurnal variation of the particle size distribution on March 29, 2003 with diameter on the vertical axis and particle concentration ($dN/d\log D$) represented by color contours.

4. Conclusions

A nano-SMPS (NSMPS) was deployed at the Fresno Supersite in August 2002. The NSMPS, a standard SMPS, and an OPC were used to measure the particle size distribution from 3 nm to 2 μm from August 25, 2002 through July 31, 2003. These data were examined with a focus on variations of nanoparticle size and number concentration. Nanoparticle concentrations and the ratio of nanoparticle to total particle concentration were inversely related to particle surface area from 50 to 1000 $\mu m^2\ cm^{-3}$. The highest nanoparticle concentrations were seen during the warmer months, i.e., spring, summer, and early fall. Nanoparticles were also present in high concentrations, up to 14,390 cm^{-3} on an hourly basis, with increasing motor vehicle emissions during the morning rush hours.

In contrast to Atlanta (Woo et al., 2001), where fresh photochemical production resulted in nanoparticle concentrations exceeding $10^5\ cm^{-3}$, 5-min average nanoparticle concentrations associated with peaks in solar irradiance never exceeded 24,400 cm^{-3} in Fresno. Further, an increase in number concentration with decreasing size below 10 nm was almost never observed in Fresno. This phenomenon constituted evidence for new particle production in Atlanta. This suggests that photochemical particle production may have occurred at a higher altitude followed by mixing to the surface or that the fresh particle production rate was smaller, with respect to the loss rate by coagulation with existing particles, than it was in Atlanta. This is consistent with much lower sulfur concentrations and RH in Fresno than Atlanta.

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