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Particle concentrations in data centers

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ABSTRACT

Cooling buildings with large airflow rates of outside air when temperatures are favorable is an established energy-saving measure. In data centers, this strategy is not widely used, owing to concerns that it would cause increased indoor levels of particles of outdoor origin, which could damage electronic equipment. However, environmental conditions typical of data centers and the associated potential for equipment failure are not well characterized. This study presents the first published measurements of particle concentrations in operating data centers. Indoor and outdoor particle measurements were taken at eight different sites in northern California for particulate matter 0.3–5.0 μm in diameter. One of the data centers has an energy-efficient design that employs outside air for cooling, while the rest use conventional cooling methods. Ratios of measured particle concentrations in the conventional data centers to the corresponding outside concentrations were significantly lower than those typically found in office or residential buildings. Estimates using a material-balance model match well with empirical results, indicating that the dominant particle sources and losses have been identified. Measurements taken at the more energy-efficient site show nearly an order of magnitude increase in particle concentration when ventilation rates were high. The model indicates that this increase may be even higher when including particles smaller than the monitoring-equipment size limitation. Even with the increases, the measured particle concentrations are still below concentration limits recommended in industry standards.

1. Introduction

Data centers house the vast amounts of equipment that provide the computational power, data storage, and global networking integral to modern information-technology systems. The high concentration of densely packed computers in data centers leads to floor-area-weighted power densities 15–100 times higher than those of typical commercial buildings (Greenberg et al., 2006). Data-center energy use has doubled in the last 5 years. In the US alone, it currently accounts for about 45 TWh y^{-1} of electricity consumption, >1% of total demand (Koomey, 2007). A substantial portion of the energy use in data centers, perhaps as much as half, is dedicated to cooling the computer equipment (Tschudi et al., 2004). The data-center cooling load can be reduced by a substantial fraction when large amounts of outside air are used to cool internal loads during favorable weather conditions (Sloan, 2007). However, many owners and operators are reluctant to use this cooling technique owing to concerns about the risk of equipment failure posed by introducing outdoor particulate matter into data-center buildings.

Fine particulate matter can deposit on electronic circuit boards in the space between isolated conductors. When the humidity of the surrounding air rises above the deliquescence point, particles composed of water-soluble

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ionic salts can absorb moisture and dissociate to become electrically conductive (Weschler, 1991). Empirical results show that exposure to high sulfate concentrations at high humidity can cause electronic equipment failure (Litvak et al., 2000). However, the risk of failure under the environmental conditions typical of data centers is not well understood. Owing to the competitive nature and high economic value of businesses in this sector, failure data are not publicly shared. Furthermore, the effect of introducing greater flow rates of outside air (or any other design change) on equipment failure cannot be predicted with confidence, because little is known about the concentrations of particles in data centers, the sources of those particles, or their fate once introduced into the data-center environment. This paper addresses these unknowns by measuring and modeling particle concentrations at operating data centers. The results provide a partial basis for assessing the equipment failure risk posed by particles for current data-center designs.

In the present study, time- and size-resolved particle concentration data were gathered over weeklong periods at eight different northern California data centers. Building parameters for three of these data centers were documented and a material-balance model was employed to predict concentrations under various conditions so as to better understand the relative influence of potential sources and fates of airborne particles. Predicted indoor concentrations were compared against the measured results. The loss mechanisms of filtration, deposition, and ventilation removal were compared to assess particle fate. The model was also applied to estimate indoor concentration levels for sulfate particles, which are of particular concern because of their ambient abundance and hygroscopicity.

2. Methods

2.1. Study sites

Size-resolved particle concentrations were measured as a function of time at data centers in eight different northern California cities. With respect to ventilation and cooling, all the data centers are conventional except for the one at the Sunnyvale site, which was specifically designed to be energy-efficient and therefore has distinctive characteristics. This article presents detailed results from three of the monitored data centers—at Rocklin, Walnut Creek, and Sunnyvale. The Rocklin and Walnut Creek sites are both large buildings with multiple rooms designated for computer severs. Each of these rooms has characteristics common in data centers: rows of server racks, a raised-floor plenum, and computer-room air-conditioning (CRAC) units. The CRAC units are data-center-specific air-handling units (AHUs) that are situated on the data-center floor. By contrast, the data center in Sunnyvale is located in a single room within an office building, and is a showcase for energy-efficient data-center design and equipment. The room utilizes overhead air distribution and therefore contains no underfloor air plenum. The AHUs at this site are located in a separate, adjacent room. In Sunnyvale, the amount of outside air entering the data center is controlled by an energy management and control system (EMCS). The EMCS implements the energy-efficient measure of cooling the computer equipment with large flow rates of outside air whenever climate conditions are favorable.

Fig. 1 schematically displays the airflow configuration at each site. At Rocklin, outside air enters a rooftop AHU, passes through a 40% filter,[1] and then enters the data center through a ceiling duct before mixing with the surrounding indoor air. Room air in the Rocklin data center enters the top of a CRAC unit, passes through another 40% filter, and is then cooled and discharged to the underfloor plenum. Perforations in the floor tiles in front of the server racks allow the cooled air to exit from the plenum into the data-center room. Fans within the computer servers draw the conditioned air upward and through the servers to remove heat generated by the equipment. After exiting the backside of the server housing, the warmed air then rises and is transported to the intake of a CRAC unit. The majority of air circulation at the Rocklin site is internal to the data-center zone. The Rocklin site has a single rooftop AHU to supply outside air to the room. This AHU supplies some outside air to positively pressurize the room and thereby limit infiltration. No air is mechanically removed from the room; rather, the mechanical supply air is balanced by air exfiltration across leaks in the data-center envelope.

Similar to Rocklin, the Walnut Creek site supplies only a small flow of outside air, as compared to the flow rate of air passing through the CRAC units. Supply air at Walnut Creek, however, is a combination of outside air and makeup air from other building zones. The rooftop AHU that supplies outside air to the data center also supplies air to office zones within the building. After entering the rooftop AHU, the outside air mixes with return air from the office zones. The ratio of outside air and office return air is automatically adjusted within the AHU, depending on the outside-air temperature. This blend of outside and return air first passes through a 40% filter and then through an 85% filter before entering the data center and mixing with the surrounding indoor air.

Traditional CRAC units and the underfloor plenum are absent from the Sunnyvale site. Rather, air moves into and out of the room through ceiling-mounted air supply registers. These registers are connected via ducts to AHUs, which are located in a separate utility room adjacent to the data center. Ducts also connect the AHUs to the outside environment. Air from outside passes across adjustable dampers before being blended with return air from the data center. Once mixed, the air passes through a bank of 40% filters and is then thermally conditioned. The conditioned air is ducted into the data center and supplied through ceiling registers located between the server racks. As the cold supply air migrates toward the floor, fans draw air through the servers. After exiting the server rack, the warmed air is removed via ceiling return registers and

[1] All filter efficiency specifications reported in this paper are based on the ASHRAE dust-spot test method (ASHRAE, 1992).

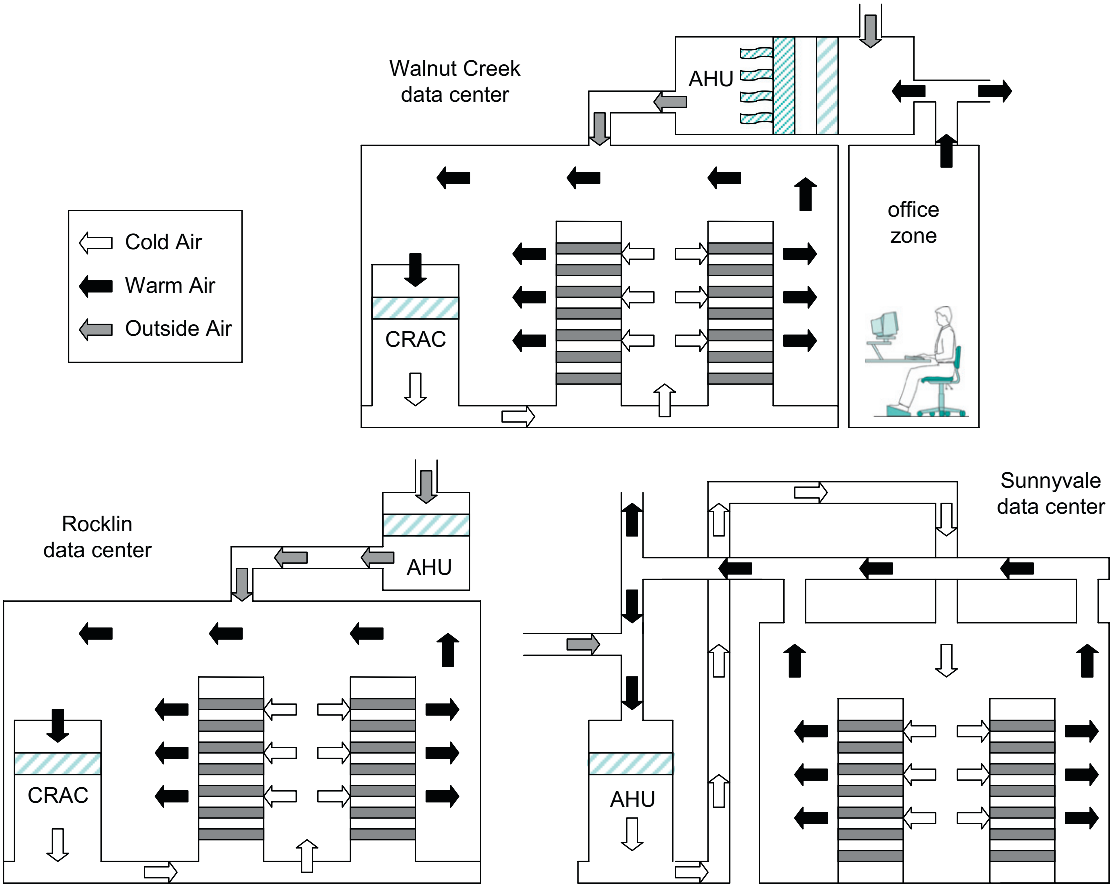

Fig. 1. Schematics of airflow at the data centers. The Rocklin and Walnut Creek sites use an underfloor air distribution system. Air handling units (AHUs) are placed on the data-center floor and air is thermally conditioned within the room. To maintain positive pressurization, a small amount of outside air is supplied from a separate rooftop AHU. The Sunnyvale site uses an airflow design common in office buildings. Air is supplied and removed through ceiling ducts and the AHUs are located outside of the data-center zone.

ducted back to the AHUs. Before reaching the AHU, the air passes through another set of dampers. Some of the return air is exhausted while the rest is returned to the AHUs to be mixed with outside air before being conditioned and then returned to the data center. During the monitoring period, the EMCS at the Sunnyvale site was set to provide 85% outside air whenever the outdoor temperature was below 15 °C. When the outdoor temperature increased above this set point, the amount of outside air was minimized to about 1% of the total flow. In each case, recirculation provided the remaining flow.

2.2. Experimental protocol

Particle concentrations were measured both inside and outside of each site over periods of approximately 1 week. Size-resolved data were gathered using Met-One 237B optical particle counters (OPC), capable of detecting and sizing particles within the range 0.3–5.0 μm optical diameter with a maximum uncertainty of ±20% in particle counts for each size bin. Particle counts are separated into different size bins based on light scattering: 0.3–0.5 μm, 0.5–0.7 μm, 0.7–1.0 μm, 1.0–2.0 μm, and 2.0–5.0 μm. Mass concentrations were calculated from particle number counts by assuming a particle density of 1.5 g cm^{-3} (Pitz et al., 2003). Outdoor concentrations were measured by placing an OPC within the outside-air intake that services the data center. Indoor concentrations were measured using a second OPC that was placed in front of a server aisle to measure the particle concentration in the air as it was about to pass through the server rack.

Measurements were taken for 5-min intervals once every 25 min. Each OPC would draw air at a rate of 2.8 L min^{-1} for 5 min and then pause for 20 min before beginning the next particle-counting cycle. At the Sunnyvale site, the count for the 0.3–0.5 μm size range in the outdoor OPC reached the instrument limit for some sampling cycles, indicating that the reported outdoor concentration would underdetermine the actual value. Consequently, data from this size range at the Sunnyvale site were not used in the analysis reported here.

The OPCs were factory calibrated prior to monitoring. Calibration was checked after monitoring by exposing both OPCs to the same conditions to ensure that each instrument produced consistent particle counts. During this calibration check, particle counts within each size category varied by <10% between the OPCs, and hence no corrections were applied to the analysis of data from the site measurements. Given the low concentrations measured at some of the data centers, the OPCs were also exposed to particle-free air, confirming that the monitors exhibited no lower-limit threshold.

2.3. Modeling indoor particle concentrations

Indoor particle concentrations were predicted from time-dependent outdoor concentrations measured at each site. In the model, each data-center zone was represented as a single, well-mixed chamber, using the parameters reported in Table 1. Assuming that the variation in particle concentration during each 5-min monitoring period is relatively small, the time-averaged, size-specific, mass-balance model is well represented by this equation:

$$\frac{C_{i,\text{in}}}{C_{i,\text{out}}} = \frac{\lambda_{\text{out}}(1-\eta_{i,\text{out}})}{\lambda_{\text{out}} + \beta_i + \lambda_{\text{rec}}\eta_{i,\text{rec}}} \quad (1)$$

Eq. (1) estimates indoor particle concentration as a size-specific proportion of the outdoor particle concentration. In the model, $C_{i,\text{in}}$ and $C_{i,\text{out}}$ are the indoor and outdoor concentration, respectively, for particles within size bin i. The parameter λ_{out} represents the outdoor air-exchange rate and λ_{rec} represents the recycled air-exchange rate, each defined as the respective airflow rate divided by the interior volume of the data center. The parameters $\eta_{i,\text{out}}$ and $\eta_{i,\text{rec}}$ are the respective size-dependent filter efficiencies for outside and recycled airflows. The coefficient, β_i, is the size-dependent deposition loss rate for particle-size section i. The terms in Eq. (1) represent time averages and assume uncorrelated ventilation rates and particle concentrations. This allows the dynamic time-averaged material balance to be represented by Eq. (1) without the need to assume steady-state conditions (Nazaroff and Klepeis, 2004). The model neglects resuspension, particle coagulation, or phase-change processes, based on the assumption that they have a relatively small influence as compared to the processes modeled. The data centers are positively pressurized and particle infiltration is designed to be negligible. The model assumes no unintended infiltration into these zones. Filter bypass, which reduces overall filter efficiency (Waring and Siegel, 2008) and merits investigation in data centers, is outside the scope of this analysis and not address in this model.

Recycled airflow rates at the Walnut Creek and Rocklin sites are obtained from CRAC unit design specifications and are assumed to be constant throughout the monitoring period. An AccuBalance balometer was used to determine the supply airflow entering the data-center zone at the Rocklin and Walnut Creek sites, since design specifications for the outdoor air supply were not available. Balometers, commonly used within the HVAC industry for measuring air flows at registers, have been shown commonly to have errors of approximately 20% (Walker et al., 2001), a level of accuracy that is adequate for the modeling analysis performed in this study.

Ventilation airflow at the Sunnyvale site depends on whether the HVAC system is in "low" (1% outside air) or "high" (85%) outdoor-air mode. Hourly data on the percentage of outside and recycled air entering the data center were gathered from the EMCS and then applied to the model calculations. As illustrated in Fig. 2, particle removal from the 40% and 85% filters used in the model are based on previous empirical measurements of new filters for particle diameters of 0.35, 0.9, 1.8, and 2.4 μm (Hanley et al., 1994). Each of the particle-size bins monitored by the optical particle counter was represented by its geometric median particle diameter for model calculations. Linear interpolation provided filter efficiency estimates for particle sizes between the measured data points. For particles >2.4 μm, the filter efficiency was estimated from a best fit of the data of Hanley et al. to theoretical predictions of fibrous-bed filter efficiency (Riley et al., 2002). Since data are unavailable on the ratio of outside air and makeup air from other building zones that together comprise the supply air at the Walnut Creek site, additional particle measurements were taken at this site after the supply air had passed through the 40% and 85% filters. These post-filter particle measurements were used to represent the supply air entering the Walnut Creek data center. Size-dependent values for the indoor loss-rate

Table 1
Characteristics of three data center sites

Parameters	Sunnyvale	Walnut Creek	Rocklin
Floor area (m^2)	616	360	1208
Ceiling height (m)	2.7	2.7	3.0
Volume (m^3)	1690	931	3681
Ventilation flows ($m^3\,min^{-1}$)			
Outdoor supply	23[a]	10	9
Recirculation	1332	2107	5607
Monitoring period			
Start date	18 August 2006	14 October 2006	15 September 2006
End date	25 August 2006	20 October 2006	20 September 2006

[a] When in low outside air mode.

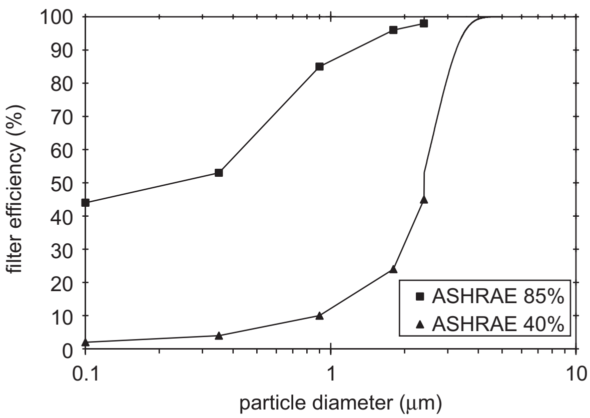

Fig. 2. Filter efficiency as a function of particle size, from measured data (represented by squares and triangles) (Hanley et al., 1994). Linear interpolation provides estimates between measured data points. Fibrous-bed filter theory was used to extrapolate efficiency for particles larger than the measured particle sizes (Riley et al., 2002).

coefficient (β_i) are based on six separate experimental studies that measured particle deposition rates across a range of particle sizes, ventilation conditions, and interior surface-to-volume ratios. The deposition loss coefficient, β_i, is equivalent to $\sum(v_{d,i,j}S_j/V)$, where $v_{d,i,j}$ is the size-dependent deposition rate for size section i onto surface j, S_j is the area of surface j, and V is the interior volume of the data-center zone. Fig. 3 presents a least-squares cubic polynomial fit to the logarithmically transformed results from these six studies, as developed by Riley et al. (2002).

Particulate matter composed of water-soluble ionic salts present a special concern for data centers, owing to the ability of some of these salts to deliquesce and thereby conductively bridge isolated elements on circuit boards (Shields and Weschler, 1998). To investigate this concern, indoor sulfate concentrations were also specifically modeled. Sulfate has been previously used to demonstrate current leakage attributable to particle deposition under conditions of high particle concentration and high humidity (Litvak et al., 2000). Sulfate, nitrate, and sea salt particles are the most common water-soluble ionic salts in ambient air and together represent a significant portion of urban particulate matter (McMurry et al., 2004). While each of the three particle types has the potential to cause equipment damage, sulfate was chosen for this study because its atmospheric abundance, size and thermal stability suggest that these particles may be of relatively greater concern than the other salts. Atmospheric sulfate is commonly found in the accumulation-mode size range (Milford and Davidson, 1987), which is expected to exhibit a relatively high indoor proportion of outdoor particles (IPOP) (Riley et al., 2002). By comparison, the IPOP of sea salt can be expected to be much lower, as sea salt particles are primarily found in the coarse mode (Seinfeld and Pandis, 1998), and so are efficiently removed by typical building filters and by settling onto room surfaces (Weschler, 1991). Sulfate is also likely to have a greater IPOP than nitrate (Sarnat et al., 2002). Nitrate particles, being volatile, can evaporate to their gaseous constituents when exposed to a warmer indoor environment (Lunden et al., 2003). The effects of nitrate particles on equipment risk in data centers appear to be worth investigating; however, to do so is beyond the scope of the present study.

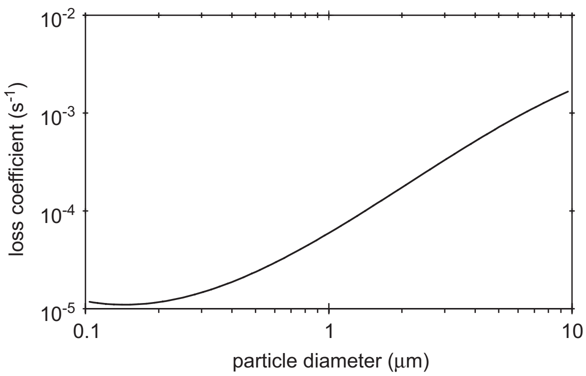

Fig. 3. Loss-rate coefficient for deposition to indoor surfaces as a function of particle size. Line represents a least-squares cubic polynomial fit to logarithmically transformed data based on results compiled from six separate experimental studies (Riley et al., 2002).

Outdoor sulfate particle concentrations were estimated from data collected by the South Coast Air Quality Management District (SCAQMD) in central Los Angeles during a study conducted from January 1995 to February 1996 as part of the PM_{10} Technical Enhancement Program (PTEP) (SCAQMD, 1996). SCAQMD used chemical mass-balance modeling to estimate that ammonium sulfate represented approximately 11% of the average ambient PM_{10} concentration of 48 $\mu g\,m^{-3}$. For the present paper, this mass concentration, 5.3 $\mu g\,m^{-3}$, was apportioned to a sulfate particle-size distribution using data compiled by Whitby (1978) from five studies of 15 urban sites: the mass-weighted sulfate particle-size distribution is summarized as a single lognormal distribution with a geometric mean (GM) of 0.48 μm and a geometric standard deviation (GSD) of 2.0. The size distribution allowed the representative outdoor sulfate mass concentration to be segregated by particle diameter and applied to estimate indoor sulfate concentrations using Eq. (1).

3. Results and discussion

3.1. Measured and modeled particle concentrations

Table 2 presents time-averaged, size-resolved, measured indoor particle concentrations for all eight data centers monitored. Average indoor concentrations for particles of diameter 0.3–5 μm average $<1\,\mu g\,m^{-3}$ in all conventional data centers and are substantially higher at the data center with an energy-efficient design (Sunnyvale). A closer evaluation of the results from Rocklin, Walnut Creek, and Sunnyvale follows. Fig. 4 presents the cumulative distributions of outdoor measured, indoor measured, and indoor modeled particle concentrations for these three sites during their respective monitoring periods. The average measured indoor concentrations at the Rocklin and Walnut Creek sites were 0.3 and 0.2 $\mu g\,m^{-3}$, respectively, with indoor concentrations being approximately 1% of the corresponding outdoor values. The median concentrations and IPOP from both of these sites are considerably lower than PM_{10} and $PM_{2.5}$ measurements previously reported for residential buildings

Table 2
Average measured indoor particle concentrations at eight northern California data centers ($\mu g\,m^{-3}$)

Data-center location	Particle size range (μm)					
	0.3–0.5	0.5–0.7	0.7–1.0	1.0–2.0	2.0–5.0	Total
Sunnyvale	n/a	1.07	0.84	1.44	1.28	4.64
Walnut Creek	0.06	0.02	0.03	0.07	0.05	0.22
Rocklin	0.13	0.02	0.03	0.07	0.08	0.33
Redwood City	0.20	0.07	0.05	0.12	0.40	0.84
Dublin	0.14	0.03	0.03	0.07	0.03	0.30
Oakland	0.08	0.02	0.01	0.02	0.03	0.15
San Francisco	0.33	0.12	0.07	0.13	0.30	0.95
Berkeley	0.08	0.04	0.03	0.05	0.11	0.31

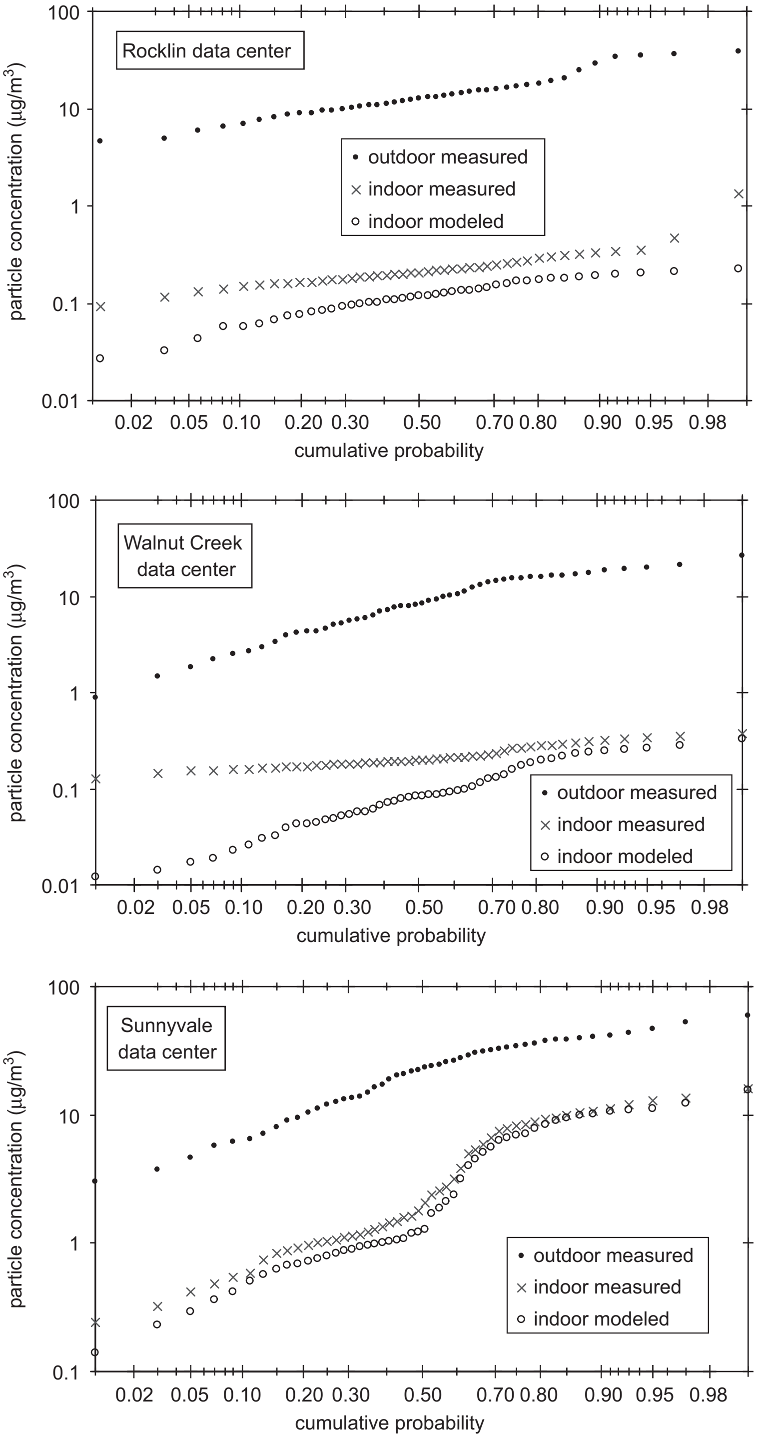

Fig. 4. Cumulative probability distributions of 5-min average measured and modeled mass particle concentration at three data-center sites. Sunnyvale concentrations only include particles 0.5–5.0 μm in diameter, while Rocklin and Walnut Creek include particles 0.3–5.0 μm in diameter. For clarity, only representative data points are displayed.

(Ott et al., 2000; Long et al., 2001). The indoor concentration was significantly higher at the Sunnyvale site where the average measured indoor concentration was 4.6 $\mu g\,m^{-3}$ and the IPOP was about 20%. This concentration remains lower than the indoor concentration limit for data centers suggested by ASHRAE for fine PM (15 $\mu g\,m^{-3}$). Particle guidelines for data centers vary widely among industry documents and some server manufacturers recommend maximum concentrations that are orders of magnitude higher (ASHRAE, 2005). The measured particle concentration at Sunnyvale is similar to previous measurements made in an office building across the same particle-size range (Fisk et al., 2000). However, outdoor concentrations at the office building in the Fisk et al. study were much lower than the levels measured in Sunnyvale. High variability in indoor concentration is observed at the Sunnyvale site and is clearly associated with the proportion of outside air being toggled between 1% and 85% of

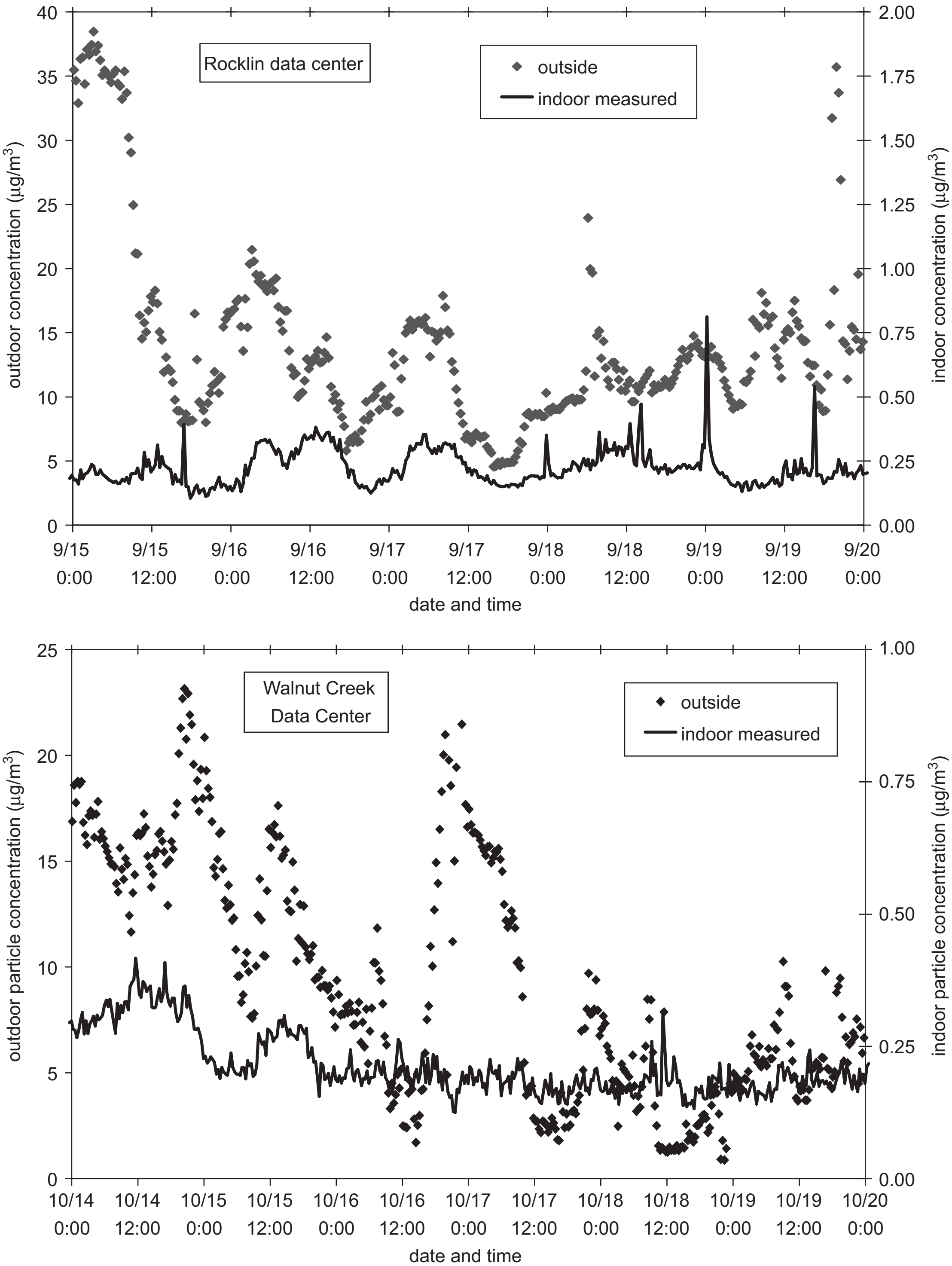

Fig. 5. Measured time-dependent particle mass concentrations at the Rocklin site (above), during 15–20 September 2006, and at the Walnut Creek site (below), during 14–20 October 2006. Concentrations represent particles 0.3–5.0 µm in diameter.

the supply airflow. The indoor concentration between these two HVAC modes differs by an order of magnitude.

Low and steady indoor particle concentrations were measured at the Walnut Creek and Rocklin sites (Fig. 5). The indoor concentration was $<1\,\mu g\,m^{-3}$ at almost all times, seemingly independent of fluctuations in the outdoor concentration. A few minor increases of short duration in indoor concentration are observed that do not correspond with any changes in outdoor concentration; these might be caused by occupants working or walking in the vicinity of the OPC. Fig. 6 shows that modeled indoor particle concentrations at the Rocklin site agree well with measurements in the smaller particle-size bins, but that the larger particle-size bins appear to be underrepresented by the model. Particles in the larger size bins also appear to be underrepresented by the model at the Walnut Creek site (Fig. 7). At both the Rocklin and Walnut Creek sites, the modeled indoor concentrations follow the fluctuations in the outdoor concentrations, while the measured indoor particle concentrations remained steady throughout the monitoring period for all size ranges except 0.3–0.5 μm. The influence of outdoor concentration fluctuations on indoor particle measurements appears to decrease with increasing particle size. The underrepresented and steady indoor particle concentrations measured in the larger size bins, relative to the model, suggest the presence of a weak, yet stable source of mechanically generated indoor particles. Conceivably, this particle source might be worn or misaligned fan belts in the CRAC units, which has been previously suggested as a possible source of particles in data centers (ASHRAE, 2005).

As expected, indoor particle concentrations are strongly related to the rates at which outdoor air enters the building. Time-averaged indoor concentrations are approximately an order of magnitude lower at the two sites that use minimal outside air than at the Sunnyvale site, where a high percentage of outside air was used during a portion of the monitoring period (Fig. 8). The indoor concentration responds rapidly to changes in the HVAC system between "low" and "high" outside-air mode. When in the "low" mode, results were similar to those at the other two study sites. During this mode of operation, the measured indoor concentrations were approximately 1–2 $\mu g\,m^{-3}$ for nearly all times, regardless of outdoor concentrations. During the "low" outside-air period, the IPOP was about 3%, which is comparable in magnitude to values at the other two sites (~1%).

A sudden increase in particle concentration is apparent in Fig. 8 whenever the HVAC system switches to the "high" outside-air mode. The increase in indoor particle concentration begins toward the end of the day, around midnight, and then typically ends late in the morning.

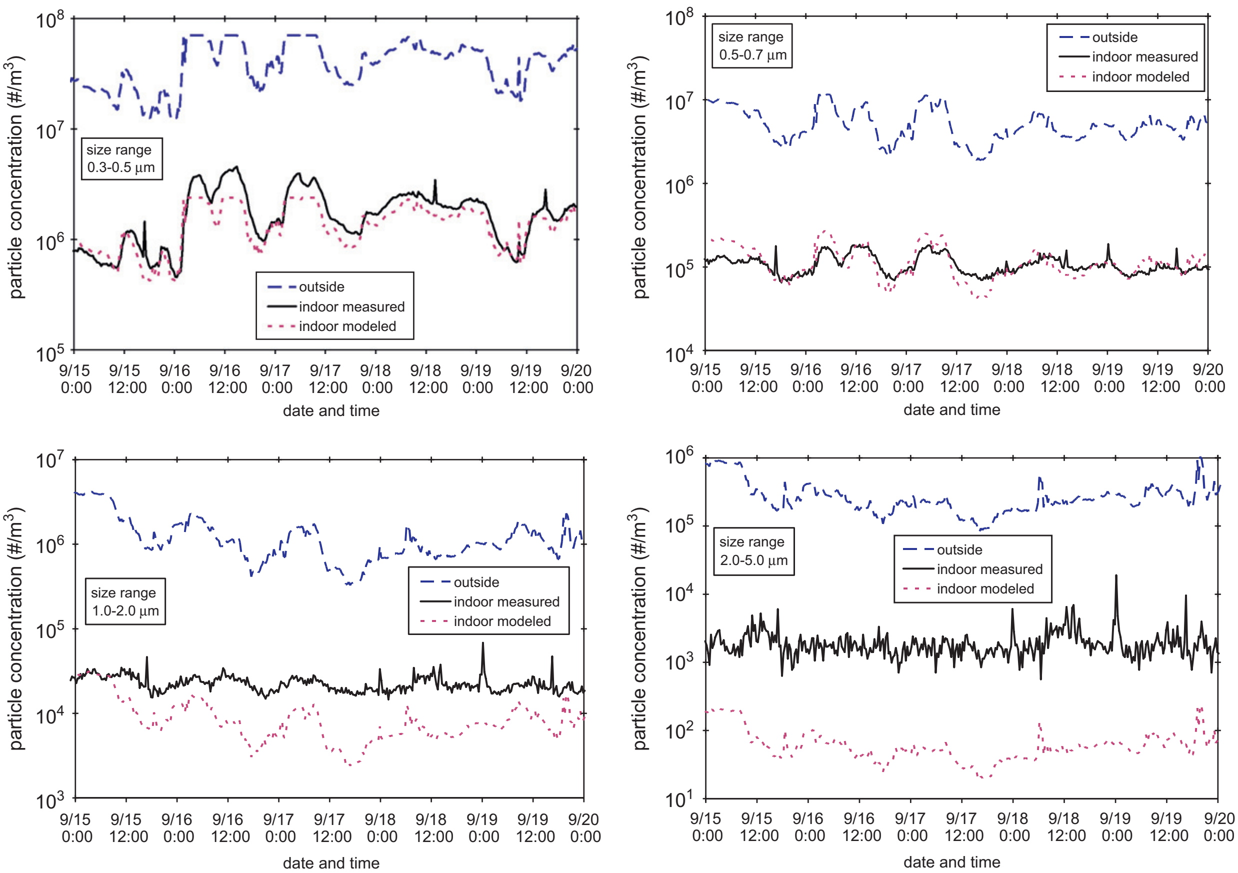

Fig. 6. Size-specific, time-dependent measured and modeled particle concentrations at the Rocklin data center during 15–20 September 2006.

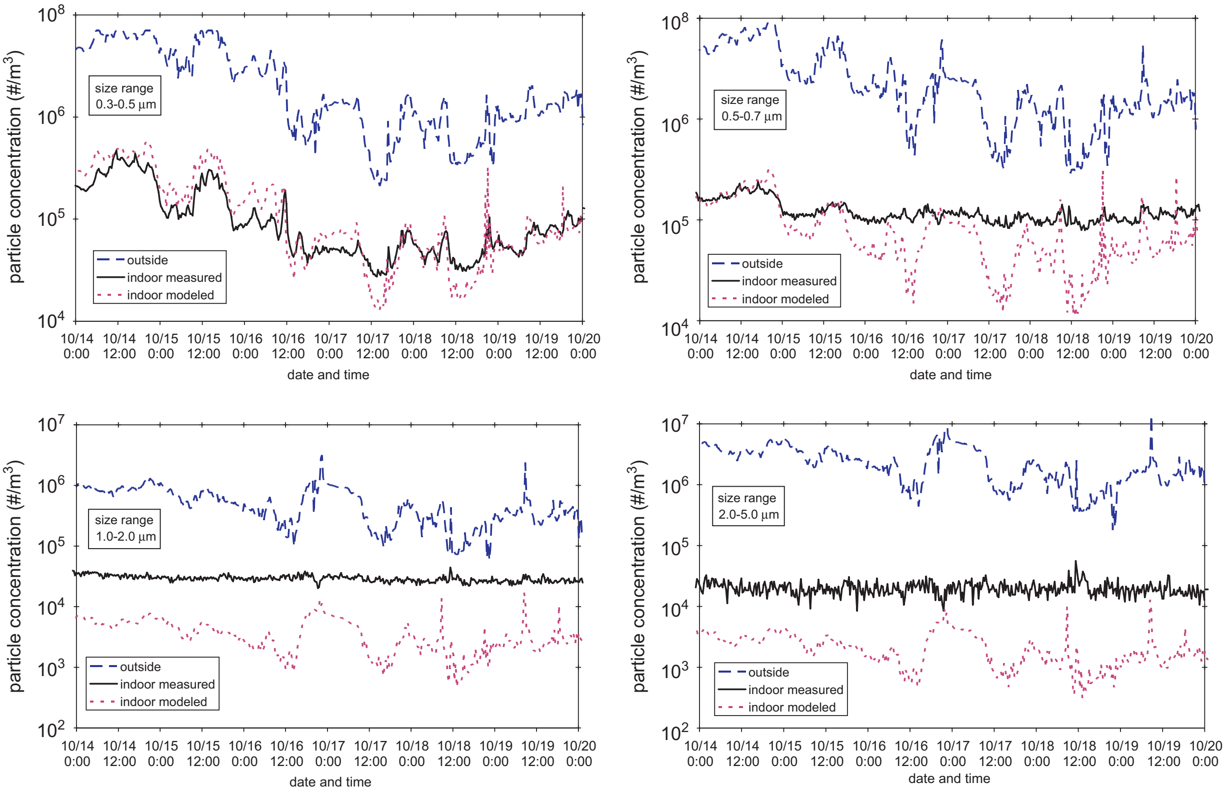

Fig. 7. Size-specific, time-dependent measured and modeled particle concentrations at the Walnut Creek data center during 14–20 October 2006.

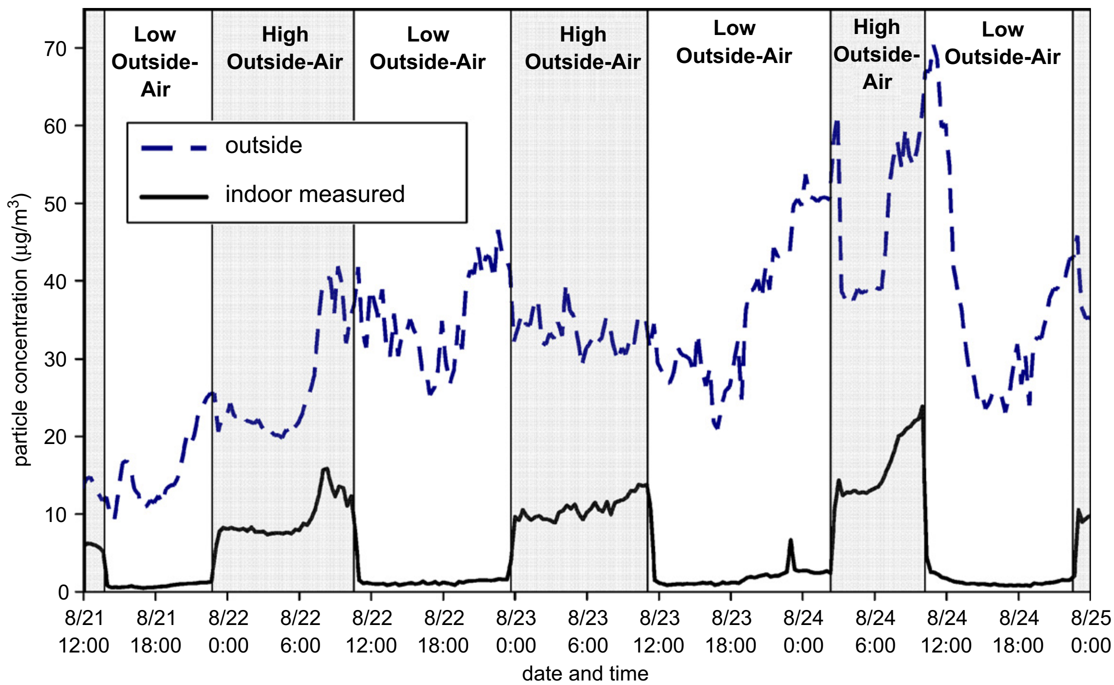

Fig. 8. Measured time-dependent particle mass concentrations at the Sunnyvale data center during 21–25 August 2006. Particle concentration represents 0.5–5 μm particulate matter.

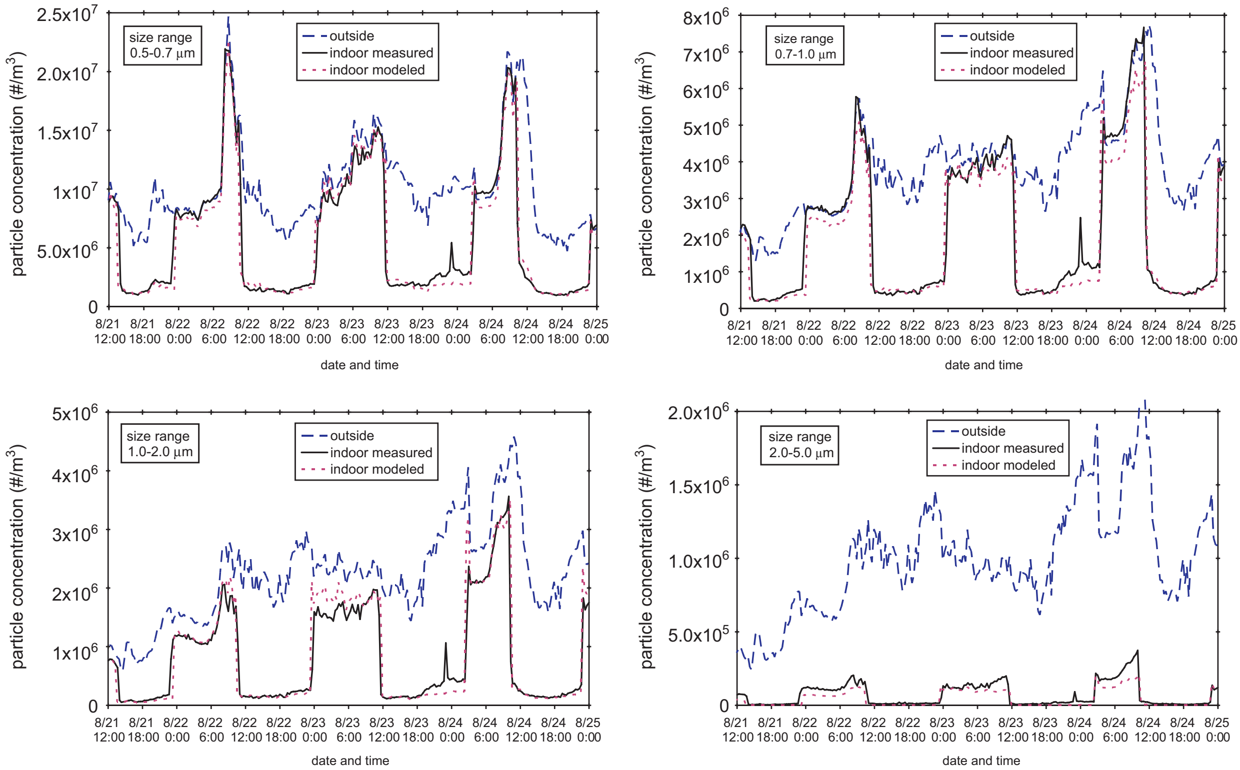

Fig. 9. Size-specific, time-dependent measured and modeled concentrations at the Sunnyvale data center during 21–25 August 2006.

During the "high" outside-air mode, the indoor concentration increases by nearly an order of magnitude (as compared with the "low" outside-air mode) and varies more directly in response to changing outdoor concentrations. The indoor concentration shifts from approximately 3% to 36% of the outdoor concentration. The higher indoor concentration is sustained until the HVAC returns to the "low" outside-air mode.

Fig. 9 shows modeling results for each of the particle-size categories measured at the Sunnyvale site (0.5–5 μm). The modeled indoor particle concentrations agree well with measurements during both "low" and "high" outside-air modes, except for the particle-size range 2.0–5.0 μm, which was slightly underrepresented by the model for "high" mode operation.

3.2. Particle sources and sinks

Outdoor air appears to be the main source of airborne particle mass in all three data centers. Additional potential indoor sources of particles in data centers include occupant activities, fan-belt wear, and resuspension from occupant activities (Shields and Weschler, 1998; Brusse and Sampson, 2004; Roth, 2005). While indoor particle generation may contribute to the particle concentrations in data centers, modeled indoor mass concentrations assuming no indoor-generated particles match well the indoor measurements. When comparing the measured and modeled indoor concentrations relative to the measured outdoor concentrations, the mean absolute deviation in IPOP is 1%, 1%, and 3% for the Walnut Creek, Rocklin, and Sunnyvale sites, respectively. This agreement indicates that any indoor source of particles during the monitoring periods was small in relation to the supply of particles from outdoor air. Indoor measurements show a fairly consistent indoor particle concentration level with few aberrant increases or decreases in concentration level, indicating that any sporadic indoor particle source, such as that from occasional occupant activities, has little impact on time-averaged indoor concentration levels. Data centers typically have air filters for both outdoor and recirculated air. Because of the importance of outdoor air as a source of indoor particles, the results of this study suggest that data-center particle mitigation efforts might benefit from focusing filtration more heavily on the entering outdoor air.

The difference between measured and modeled particle concentrations at the Rocklin and Walnut Creek sites, summarized for number concentration in Table 3, is a mass concentration of approximately 0.1 $\mu g\,m^{-3}$. While this concentration is small relative to ambient concentrations, the discrepancy is clearly detectable against the low indoor concentrations measured at these conventional data centers that supply minimal outside air. The time-series and size-dependent discrepancies between model and measurement presented in Figs. 6 and 7 suggest that there is a stable, yet weak mechanical source of indoor

Table 3
Average indoor modeled and measured particle concentrations at three data center sites ($\# \, m^{-3}$)

Particle-size range (μm)	Walnut Creek		Rocklin		Sunnyvale	
	Measured	Modeled	Measured	Modeled	Measured	Modeled
0.3–0.5	1.2×10^6	1.6×10^6	2.7×10^6	1.3×10^6	n/a	n/a
0.5–0.7	1.2×10^5	8.9×10^4	1.4×10^5	1.1×10^5	6.6×10^6	6.2×10^6
0.7–1.0	6.0×10^4	1.7×10^4	6.7×10^4	3.7×10^4	1.8×10^6	1.6×10^6
1.0–2.0	2.9×10^4	4.0×10^3	3.0×10^4	9.5×10^3	6.5×10^5	6.6×10^5
2.0–5.0	2.0×10^3	2.3×10^2	3.3×10^3	7.1×10^1	5.2×10^4	3.2×10^4

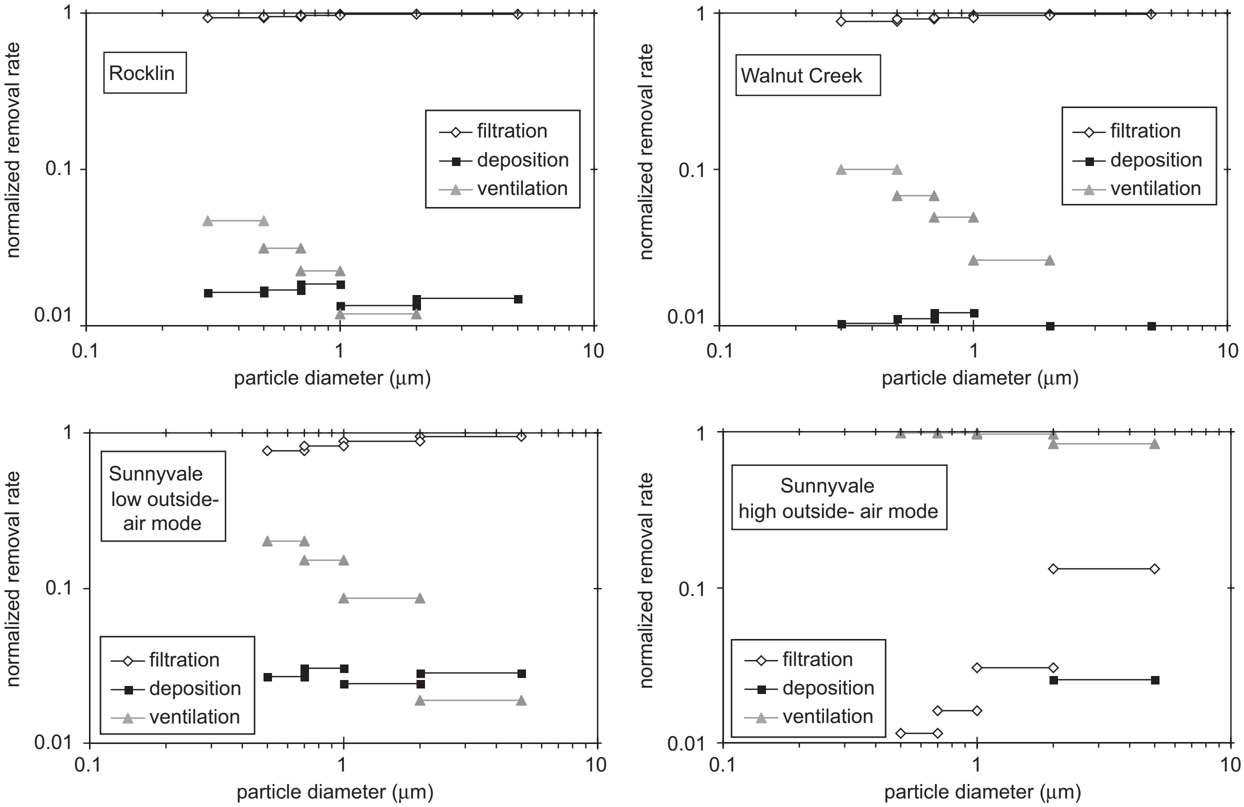

Fig. 10. Modeled particle fates at each study site.

airborne particles. A potential source is the CRAC-unit fan belts. Reconciling model predictions to measurement results suggests an indoor emission source of approximately 1 $mg \, h^{-1}$ per fan belt at each of the two study sites, which would correspond to a 1–5% loss of fan-belt mass over the typical fan-belt lifetime of 6 months.

Once particles enter the data center, their possible fates are to be exhausted with the ventilation, captured during filtration, or deposited onto an interior surface. The sum of these three potential loss terms make up the denominator in Eq. (1), with λ_{out} representing the ventilation loss-rate coefficient, β_i representing surface deposition, and the product of $\eta_{rec,i}\lambda_{rec}$ representing removal via filtration of recirculated air. The relative contribution of these particle sinks varies with particle size and among the data centers. The normalized rate of particle removal by each loss mechanism is presented in Fig. 10 for each particle-size range at each study site. Filtration dominates particle removal at the Rocklin and Walnut Creek sites. ASHRAE (2005) recommends 40% filters in data centers that use minimal outside air. This type of filter was observed in the CRAC units and in most of the outside-air handlers at the data centers monitored in this study. Even though the CRAC units have filters with modest efficiency, the large rate of recirculating flow through the CRAC units relative to the amount of outside air introduced into the data center results in high relative particle removal by this means. At the Sunnyvale site, when the HVAC system is in the "high" outside-air mode, ventilation is the dominant removal mechanism owing to the relatively high proportion of indoor air exhausted from the data center. Filtration dominates during the "low" outside-air mode at the Sunnyvale site and the relative contribution of the loss terms is similar to that found at the other two sites.

3.3. Sulfate predictions

The modeled indoor particle concentration and corresponding IPOP values depend on the size distribution of outdoor particles. Within the particle-size range studied (0.3–5 μm), outdoor concentrations that have greater proportion of their mass in larger particles will result in lower modeled IPOP values, since larger particles are more efficiently removed by filtration and by surface deposition. Conversely, a greater contribution of total mass from smaller particles would reduce interior loss rates, resulting in a higher IPOP value. The size distribution of outdoor particles varies by time and location and also by particle chemical composition. Since sulfate represents a particle type of particular concern for equipment reliability, its mass distribution was applied to the model to predict the IPOP of sulfate at the Rocklin and Sunnyvale sites. At the Rocklin site, the modeled IPOP increases from $<1\%$ for total outdoor particle mass to about 2% for sulfate mass. At Sunnyvale site, the modeled IPOP increases from approximately 3% (for total mass) to about 19% (for sulfate) in the "low" outside-air mode and from 36% (total mass) to 88% (sulfate) for the "high" outside-air mode.

4. Conclusions

Prudent implementation of energy-saving measures that would expose data-center equipment to more outside air requires two tiers of investigation: first, understanding how these design measures would change indoor particle concentrations, and second, understanding how such changes in concentration would influence equipment reliability. This study contributes to the former goal by presenting the first published measurements of particle concentrations in operating data centers. The data and their interpretation provide baseline information for conditions in typical data centers, revealing significantly lower particle concentrations than typically found in offices or residential buildings. Estimates using a parsimonious material-balance model match fairly well with the empirical results. This agreement indicates that the dominant particle sources and losses have been identified, increasing the basis for confidence in one's ability to predict particle concentrations in data centers under different scenarios. Measurements taken at the Sunnyvale site, where high flow rates of outside air are already deployed to save energy, show nearly an order of magnitude increase in particle concentration during "high" outside-air periods. Sulfate modeling results indicate that this increase may be even higher when including particles smaller than the size range measured in this study. While these data confirm and quantify the increase in particle concentrations caused by using more outside air, the equipment risk associated with this concentration increase remains unknown. We note that indoor particle concentrations at Sunnyvale still were well below particle limits recommended by some server manufacturers and were less than the limit suggested by ASHRAE. The results presented here provide a partial foundation for future work to investigate the risk to data-center equipment posed by expected particle levels. A more thorough understanding of the equipment reliability risks associated with supplying greater outside air in data centers will help determine what conditions are safe for this energy-saving measure. One can also explore mitigation alternatives, such as enhanced filtration, that aim to improve energy efficiency while simultaneously minimizing risk to electronic equipment from the deposition of particulate matter. Overall, such efforts can help temper the growing energy demand of data centers and thereby allow the expansion of information technology to proceed in a more sustainable fashion.

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