AIR POLLUTION IN NEW MUSEUM FACILITIES*

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ABSTRACT

Over the period July 1996 – April 1998, airborne particle concentrations and chemical composition were measured both inside and outside the new J. Paul Getty Museum outside Los Angeles, CA. The purpose of these experiments was to determine the relationship between the stages of construction and operation of the building and the soiling hazard to the collections. Particular attention was paid to tracking the concentrations of fine black soot particles and mineral dust particles. The time needed to "air out" the building following construction can be seen from the data collected, as well as the inherent particle removal efficiency of the filters within the building ventilation system, and the effect of entry of the general public into the building.

During the period of observation while the building was under construction, weekday coarse dust particle concentrations on occasion reached very high levels (600-1100 μg m^{-3}; 24-hour average), falling to relatively low values averaging 26 μg m^{-3} over weekend periods when construction activity subsided. In March, 1997, with construction largely completed and with the HVAC system in full operation, indoor coarse dust concentrations fell to 1.7% of those outdoors. Beginning at this time, indoor fine particle concentrations relative to those outdoors declined steadily over a period of about one to two months, reaching levels of 3.9% of those outdoors during the period June 3 - December 6, 1997 when construction was completed but before entry of the general public into the building. Thus, the coarse and fine particle removal efficiencies of the building HVAC system absent major indoor sources are at least 98% and 96% respectively. Following the opening of the museum to the public, indoor particle concentrations increased by approximately 1 μg m^{-3} in each of the coarse dust and fine smoke-size particle size ranges indicating that there is a small but measurable effect due to increased air infiltration as doors are opened and closed more frequently and due to particles shed by the visitors. Still, indoor particle concentrations inside the new Getty Museum in the presence of the general public are among the lowest in the world, only 3.2 μg m^{-3} of coarse dust and 1.8 μg m^{-3} of fine particles on average over the period January - April, 1998.

1 INTRODUCTION

New museum facilities have been observed to encounter a period of time following construction where air quality is impaired due to the effects of construction dust and particles shed from building materials. In Los Angeles, there is also concern that outdoor pollutants may migrate into the indoor atmosphere through heating, ventilation, and air conditioning (HVAC) system ducts, and through doors when they are opened and closed.

Airborne particles deposit onto the objects in museum collections and can also discolor building surfaces. In addition to the visual changes that accompany this soiling process, chemical reactions between the deposited airborne grime and the underlying surfaces can hasten the deterioration of many materials. Potential damage could take the form of chemical degradation from exposure to reactive gases or alkaline cement particles, or soiling due to deposition of airborne particles, particularly those containing elemental or "black" carbon.

There is concern among museum curators that works of art displayed in urban museums are subject to damage from exposure to indoor air pollution, but levels of pollution generated by new building construction are largely unknown. Damage has been reported in a newly constructed museum in Japan due to deposition of alkaline cement dust (Toishi and Kenjo, 1975). Black soot particles have also been observed to have darkened the interior surfaces of many museum facilities in Europe, and given the corrosive chemicals present in outdoor air in Los Angeles, other interactions may occur as well.

The purpose of this study is to quantify the potential for air pollution damage to museum collections that occurs due to particle exposure within the museum during the start-up transient that occurs at the end of building construction using the situation at the new J. Paul Getty Museum as an example. Over the period beginning when the air conditioning system was first started in July, 1996 through the early months of 1998, the museum changed from being under construction, through installation of the collections, to completion of the structure, and finally to visitation by the general public. There were several distinctly different conditions in the building over this time: (1) a condition with the HVAC system in operation, but with no collection housed within the building, (2) installation of a portion of the decorative arts collection within four period rooms while construction was still underway, (3) a time when the period rooms were installed but the remainder of the collection was yet to arrive, (4) a period when the remainder of the collection was being installed while some construction continued, (5) a period after construction stopped and the collection was present but before admission of the general public to the buildings, and (6) a time of full building operation with both the collection and the public present.

For 21 months beginning in July, 1996, the concentration and chemical composition of airborne particles was measured inside the Decorative Arts wing of the new Getty museum and at the outdoor air inlet to the HVAC system. The purpose of these measurements was to determine the relationship between the stages of completion of the museum's construction and operation and the airborne particle hazard to the collections as they were being installed over that time. Particular attention was paid to measuring the concentration of black elemental carbon (i.e., soot) particles that have great potential to damage the collections, particularly if they deposit onto difficult to clean surfaces such as fabric in the Decorative Arts collection. Airborne particle samples also were analyzed for organic carbon, ionic species (i.e., sulfates, nitrates, chlorides), and for a number of trace elements including silicon, aluminum and iron. From the chemical composition of the particles the source of the particles can be identified (e.g., cement dust or gypsum dust from construction activities vs. diesel soot from outdoor motor vehicle exhaust). Further purposes of the study were to examine the length of time needed for a newly constructed museum to "air out" as it sheds particles deposited previously during construction, and to document the effect of occupancy by the public on air quality within a museum having an advanced air filtration system.

This paper documents the results of this study. These data can be used in the future to support the selection of systems at other new museums that will control indoor air pollutant levels in order to protect the museum collections during periods of new construction and continued operation.

2 EXPERIMENTAL METHODS

Filter-based air pollutant samplers were used to measure airborne particle chemical composition at two locations at the Getty Center. An indoor sampler was located in the Rococo Room in the Decorative Arts section of the museum. An outdoor sampler was placed at the air intake to the HVAC system controlling the air supplied to the Decorative Arts galleries and other galleries in the museum.

Airborne particle samples were collected over 24-hour periods once every six days for approximately 21 months beginning in July, 1996. Collection of particle samples and subsequent comprehensive chemical analysis is very labor-intensive. For this reason, airborne particle monitoring networks operated according to U.S. Environmental Protection Agency guidelines collect samples every sixth day in order to obtain a representative sample of particle concentrations over long periods of time without having to sample every day.

When sampling first began, there was intensive construction underway inside and outside at the Getty Center. Between July 20, 1996 and November 5, 1996 the HVAC system at the museum operated by only recirculating indoor air in the conditioned spaces and not using a supply of outdoor air to the system. However, doors and windows (or entire walls) were not fully in place and substantial air infiltration from the outdoors could occur in the building through many loosely covered openings in the walls.

By November 11, 1996, the museum's HVAC system began supplying filtered outdoor makeup air to the conditioned interior spaces. The HVAC system passed outdoor supply air through a series of HVAC particle filters before the air entered the buildings. In addition, a very loosely woven mat of material similar to a home furnace filter was placed in front of the outdoor air intake grid in order to keep some of the largest construction dust particles out of the HVAC system ducts. This material was removed on February 3, 1997.

By March 11, 1997, construction activities inside the Decorative Arts Galleries ceased and control of the space was turned over to the museum staff. Construction activities continued outdoors at the Getty Center tapering off until the grand opening to the public in December, 1997. Sampling underwent a brief hiatus when the museum first opened to the public, then resumed for 3 months of sampling with visitors present in the galleries during February, March and April, 1998.

The sampling system used during this experiment has been described previously in the technical literature (Salmon et al., 1994; Ligocki et al., 1993) and is only briefly summarized here. Our sampling methods separate the airborne particles measured into two size ranges: fine particles (less than 2 μm in diameter) and total particles (no size discrimination). Coarse particle concentrations ($d_p > 2$ μm) are calculated by subtracting the fine particle concentrations from the total particle concentrations.

The coarse particles usually are described as various types of dust (e.g., soil dust, road dust, plaster dust, etc.). Coarse particles generally deposit onto horizontally-oriented surfaces as they settle under the influence of gravity. The fine particles contain any smoke or soot from combustion processes and the reaction products of atmospheric acids (e.g., sulfate or nitrate particles) as well as a fraction of the smallest dust particles in the air. Fine particles deposit more slowly than coarse dusts, but they can also deposit onto vertically-oriented surfaces, and when they do they are difficult to remove. Museum collections are particularly vulnerable to damage because certain objects (e.g., fragile tapestries) are very difficult, if not impossible, to clean completely if they become soiled by imbedded soot.

In each particle size range, samples were taken simultaneously and in parallel on three 47mm diameter filter substrates – one pre-baked quartz fiber filter (Pallflex 2500 QAO) and two Teflon membrane filters (Gelman Teflo, 2.0 μm pore size). A tandem filter pack was used for collection of gas-phase ammonia. In the filter pack, or tandem filter method, gas-phase species are collected on treated backup filters after particles are removed by Teflon pre-filters that are held in open-face filter holders. NH_3 was collected using oxalic acid impregnated glass fiber backup filters. A schematic diagram of the sampler used is shown in Figure 1.

2.1 Sample Analysis

Samples collected on quartz fiber filters were subjected to thermal evolution and combustion analysis (Birch and Cary, 1996) to measure the ambient concentration of carbonaceous particles (i.e., organic carbon, elemental (black) carbon, and carbonate carbon). Prior to sample collection these filters were heat treated at 550° C in air for at least 8 h to lower their carbon blank levels. The separate determination of organic and elemental carbon is important because of the effect that elemental carbon can have on the soiling of objects.

All Teflon filters used for particle collection were weighed before and after sampling using a Mettler model M-5S-A microgram balance to determine airborne particle mass concentrations gravimetrically. Unexposed and collected Teflon filters were equilibrated at 21 $\pm$ 1° C and 40 $\pm$ 3 percent relative humidity for at least 24 h prior to weighing each filter. To track the calibration of the balance between initial and final weighings, a set of control filters was weighed during each daily weighing period. High precision metal calibration weights also were weighed periodically to check the performance of the balance. Teflon filters were deployed in pairs, and the mass concentrations determined from the side-by-side filters were averaged.

Samples collected on one Teflon filter from each pair were analyzed by ion chromatography (IC) for nitrate, sulfate, and chloride ion concentration (Derrick and Moyers, 1981; Weiss, 1986), for ammonium ion concentration by colorimetry (Bolleter et al., 1961), and for water-soluble sodium and magnesium by atomic absorption spectroscopy (Varian, 1972). The second Teflon filter from each set was analyzed by X-Ray fluorescence (XRF) to determine the airborne concentrations of 38 trace elements: Ag, Al, As, Au, Ba, Br, Ca, Cd, Cl, Co, Cr, Cu, Fe, Ga, Hg, In, K, La, Mn, Mo, Ni, P, Pb, Pd, Rb, S, Sb, Se, Si, Sn, Sr, Ti, Tl, U, V, Y, Zn, and Zr. The elemental concentrations were converted into the concentrations of their stable oxides where appropriate. Mineral (soil, rock or cement) dust concentrations then were estimated by summing the oxides of aluminum, silicon, iron, titanium, manganese, calcium and potassium.

3 RESULTS

It is useful for purposes of discussion to divide the data into five time periods with characteristically different types of activity within the building. Table 1 shows the average particle concentrations measured indoors and at the outdoor air supply for the Getty Museum during each of the five time periods defined below. Average chemical composition data from the five phases from Table 1 representing different building conditions are presented in some detail in the bar graphs shown in Figures 2 and 3.

1. August 1, 1996 – November 5, 1996. During the first time period heavy construction activity was underway within the building, there were many openings to the outdoors through the building shell, and the HVAC system operated by recirculating only indoor air. This is illustrated by high indoor concentrations of both fine and coarse airborne particles. Both coarse and fine indoor particles are enriched in mineral components and sulfate-containing particles, suggesting high levels of gypsum dust ($CaSO_4$). Organic carbon-containing particles also are found at high concentrations in the coarse dust which could be generated by working with a variety of building materials (e.g., saw dust from cutting wood).

2. November 11, 1996 – March 5, 1997. At the start of this period, the outdoor air supply to the HVAC system began operation while heavy construction activity continued within the building. Indoor fine particle concentrations are very similar to outdoor fine particle concentrations on a daily basis during this period. Indoor coarse particle concentrations generally are lower than during the August 1 - November 5, 1996 period with the exception of one extreme event when coarse dust concentrations exceeded 1100 μg m^{-3} over a single 24-hour averaging time. Both this construction period and the previous period show a larger fraction of mineral dust present in indoor air than in later periods.

3. March 11, 1997 – May 28, 1997. The third significant period of observation began in early March, 1977 when construction activity in the Decorative Arts galleries was

finished and operation of these galleries was turned over to the museum staff. Some installation work continued in the building until the end of May, 1997. Indoor air is now substantially cleaner than outdoors where construction continues. Nearly all fine particle substances other than carbon particles are removed from the indoor air, indicating high filtration efficiency for fine particle emissions.

4. June 3, 1997 – December 6, 1997. Installation of the Decorative Arts collection in the galleries is completed followed by several months of the museum being closed to the public while construction continues outside and elsewhere at the Getty Center. The interior of the museum is very effectively protected from the high outdoor mineral dust concentrations at this time as well as from outdoor pollutant-derived carbon particles and corrosive sulfates and nitrates. During this fourth period of observation, fine and coarse particle concentrations indoors remain at very low levels. From the data taken during the June 3 - December 6, 1997 period when construction was completed indoors but before admission of the public, an estimate can be made of the filtration efficiency of the HVAC system particle filters in the absence of major indoor particle sources. The indication is that the filtration system used is able to remove at least 98% of the coarse particles and 96% of the fine particles present in outdoor air. The actual removal efficiency must be somewhat higher as it is certain that at least small emissions occur indoors caused by activities of the staff working in the building.

5. January - April, 1998. Construction is complete and the building is open to the general public. Sample collection was halted during the first round of receptions held for visitors in order to avoid disturbing these activities. The first fine particle concentration measurements made thereafter show a slight increase in indoor particle concentrations in January and February, 1998. The January 1998 measurements were made only on Mondays when the museum is closed to the general public and museum staff perform work in the galleries. The February 1998 and following measurements were made on days of the week when the museum was open to the general public and experiencing very high numbers of visitors. In March and April,

1998 particle concentration levels drop back to pre-opening levels. The proportion of carbon particles indoors is now higher than in the outdoor air supplied to the building, reflecting particles generated indoors by the visiting public, although in an absolute sense the air is still very much cleaner indoors than outside. It should be emphasized, however, that the elevated indoor fine particle mass loadings reported for January and February, 1998 are still extremely low, averaging approximately 3.5 μg m^{-3}. For comparison, average fine particle concentrations outdoors on San Nicolas Island (a very clean offshore site over the ocean upwind of the museum) are approximately 7 μg m^{-3} (Christoforou et al., 1998).

Table 1. Indoor and outdoor particle concentrations at the Getty Museum (μg m^{-3})

	Average Coarse Particle Conc.		Average Fine Particle Conc.	
	Outdoor	Indoor	Outdoor	Indoor
Construction underway and HVAC recirculating indoor air only (Aug 1, 1996 - Nov 5, 1996)	146	252	22	35
Construction underway and HVAC with outdoor air supply (Nov 11, 1996 - Mar 5, 1997)	82	143	12	10
Museum with no indoor construction (Mar 11, 1997 - May 28, 1997)	112	1.9	17	1.6
Museum closed to the public (Jun 3, 1997 - Dec 6, 1997)	107	2.3	18	0.7
Museum open to the public (Jan 5, 1998 - Apr 29, 1998)	15	3.2	18	1.8

Time series graphs for major individual chemical species have been plotted. The daily variation in airborne fine particle organic compounds is shown in Figure 4. Organic carbon data in this figure has been multiplied by 1.2 to convert from measured organic carbon mass concentration to an estimate of the mass concentration of the organic compounds present. The effect of entry of the general public into the museum is easily seen in Figure 4 by comparing indoor fine carbon particle concentrations experienced in the January - April, 1998 period to the situation during June - early December, 1997 when the museum was closed to the public.

Plots of coarse and fine particle sulfate concentrations measured by ion chromatography are shown in Figure 5a and b. From the period March, 1997 onward, nearly all fine particle sulfates should be of outdoor origin, and their removal (shown in Figure 5) attests to the high fine particle removal efficiency of the HVAC system filters.

Figure 6a and b show mineral dust (crustal oxides) concentrations in both coarse and fine particles. The concentration of crustal material is estimated by converting the elements Si, Al, Fe, Ti, Mn, Ca, and K to their common oxides and then summing the concentrations (Solomon et al., 1988).

Airborne fine particle nitrate concentrations measured by ion chromatography are shown in Figures 7. It is not uncommon to see particulate nitrate concentrations inside cooled buildings in the summer that are higher than outdoors due to NH_4NO_3 formation by reaction betweeen HNO_3 and NH_3 in the air. Figure 7 shows that this is not happening inside the Getty Museum even though ammonia is present in the indoor air. The conclusion is that the activated carbon filters in this HVAC system must be removing HNO_3 vapor, as they should.

Finally, a time series plot of fine particle elemental carbon concentrations measured by thermal evolution and combustion analysis is shown in Figure 8. During the period June 3 - December 6, 1997, when the building was closed to the public, the air filtration system was able to reduce the concentration of these key fine black carbon particles to 6% of their outdoor concentration. During the January - April, 1998 period with the public present and more frequent opening and closing of doors, the indoor fine black carbon particle concentrations rise to 43% of those outdoors.

4 DISCUSSION

From the experimental data just presented it is seen that the indoor particulate matter concentrations at the new J. Paul Getty Museum after the museum was completed are among the lowest in the world. During the construction phase of the project, however, the indoor particle concentrations were often much higher than the outdoor concentrations and varied greatly from day to day.

Figure 9 illustrates some of the types of construction activity that occurred during the period beginning July 20, 1996 through the end of May, 1997. It can be seen that indoor particle concentrations vary greatly from day-to-day during this period, with peak coarse dust concentrations periodically reaching or exceeding 600 μg m^{-3}. For example, the very high indoor concentration on August 1 occurred during a major burst of construction activity that included installation of a subfloor, workmen building a scaffolding in the Rococo Room, and ceiling work that included sanding. This intense construction activity was accompanied by increased floor sweeping of construction debris. The indoor peak on August 13 coincided with carpentry work and the use of a table saw in the Rococo Room while samples were being taken. By comparison, outdoor coarse particle concentrations in West Los Angeles under normal conditions average approximately 40 μg m^{-3}.

The first part of the Getty collection began to arrive at the beginning of August, 1996 when the New York firm Traditional Line started installing restored panels of the Rococo Room. The high indoor particle concentrations on September 12 occurred during the pack-up and departure of the New York restorers and the arrival of gilders from the Paris firm Les Ateliers Robert Gohard. The gilding work continued through October and November, 1996 contributing dust from sanding and compounds from simmering pots of rabbit skin glue cooking in the Rococo Room. Skin glues release sulfur compounds which can tarnish silver. There was also an increase in finely divided airborne gold particle concentrations during the time that the gilders were present as seen in the data in the appendix.

The highest indoor fine particle concentration (145.5 μg m^{-3}) of the entire 21 month sampling period occurred on October 30, 1996 during a time when painting occurred in the Rococo Room. The peak indoor coarse particle concentration (1,107 μg m^{-3}) was measured on January 9, 1997 when the sampler was located in the hallway outside the Rococo Room while flooring was being installed and stained inside the Rococo Room. In contrast, even during construction, the indoor fine particle levels drop to an average of approximately 3.6 μg m^{-3} on weekends and holidays, indicating that the HVAC filters are capable of removing most of the fine particles as long as indoor sources are kept to a low level. (See Table 2.)

Particle concentrations at the outdoor air supply ducts for the building also fluctuate depending on outdoor construction activity in the vicinity of the outdoor sampler. Prior to February 3, 1997 a loosely woven mat of filter material was temporarily installed over the outdoor air inlet to the HVAC system (and in front of our air sampler in the outdoor air supply duct to the building) to reduce dust accumulating in the ventilation ducts. The peak coarse particle concentration in the outdoor air supply to the building occurred on October 12 when the filter material used to protect the inlet air ducts to the building was removed for one day. After February 3, 1997, the filter material on the outdoor air intake grid was permanently removed because by this time most outdoor construction had ceased. Still, the remaining fluctuations in coarse particle concentrations (see Figure 9) at the Getty Museum were highly correlated with construction activity in the vicinity of the outdoor particle sampler. For example, increased activities both indoors and outdoors in preparation for the December, 1997 grand opening of the museum led to increased coarse particle concentrations in November, 1997.

Average coarse particle concentrations outdoors in West Los Angeles in general are approximately 40 μg m^{-3}, with fine particle concentrations of about 20 μg m^{-3}. By comparison, outdoor coarse particle concentrations at the museum site during the major phase of construction activity (August, 1996 through February, 1997) averaged 124 μg m^{-3}. Indoor coarse particle concentrations were even higher, averaging 274 μg m^{-3} over this same time period. To put this in perspective, the outdoor coarse particle concentration at the Yungang Grottoes in China (where there is a very serious particulate soiling problem) averages 378 μg m^{-3} (Salmon et al., 1994). Outdoor fine particle concentrations at the construction site during August, 1996 through February, 1997 averaged 19 μg m^{-3}, about the same as would be expected for West Los Angeles as a whole, while indoor fine particle levels were higher, about 31 μg m^{-3}.

Table 2. Indoor and outdoor particle concentrations at the Getty Museum (μg m^{-3})

	Average Coarse Particle Conc.		Average Fine Particle Conc.	
	Outdoor	Indoor	Outdoor	Indoor
Weekday periods during heavy construction phase (Aug 1, 1996 - Feb 3, 1997)	124	274	19	31
Weekend periods during heavy construction phase (Aug 25 & 31; Oct 6 & 12[a]; (Nov 29; Dec 23 & 29; 1996)	26	26	14	3.6
Museum after construction while closed to the public (Mar 11, 1997 - Dec 6, 1997)	108	2.1	17	1.0
Museum after completion and open to the public (Jan, 1998 - Apr, 1998)	15	3.3	18	1.8

a. Outdoor data for October 12 not included in average due to work being performed near outdoor sampler on that day.

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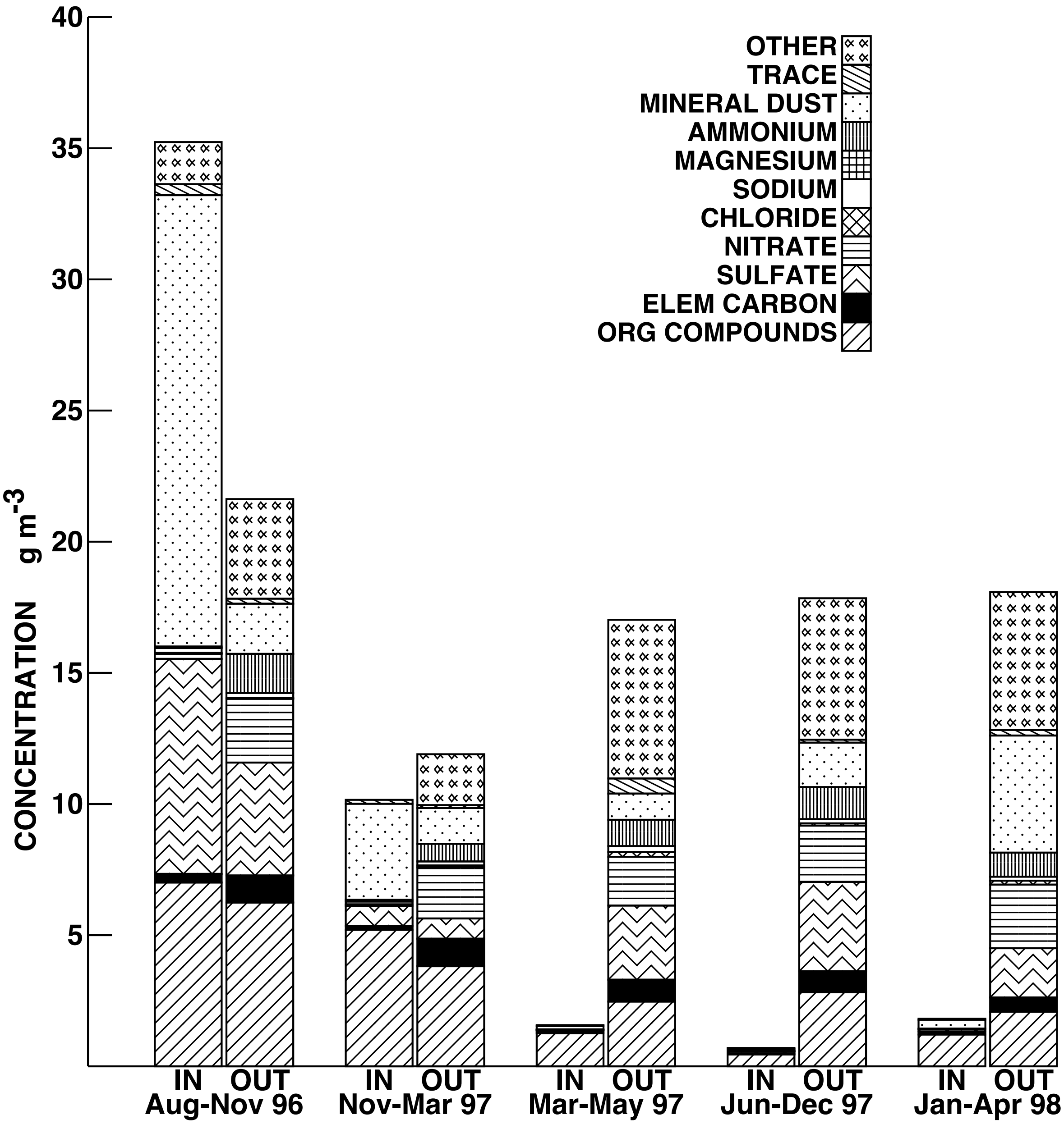

Figure 1: Average chemical composition of fine airborne particles at the Getty Museum.

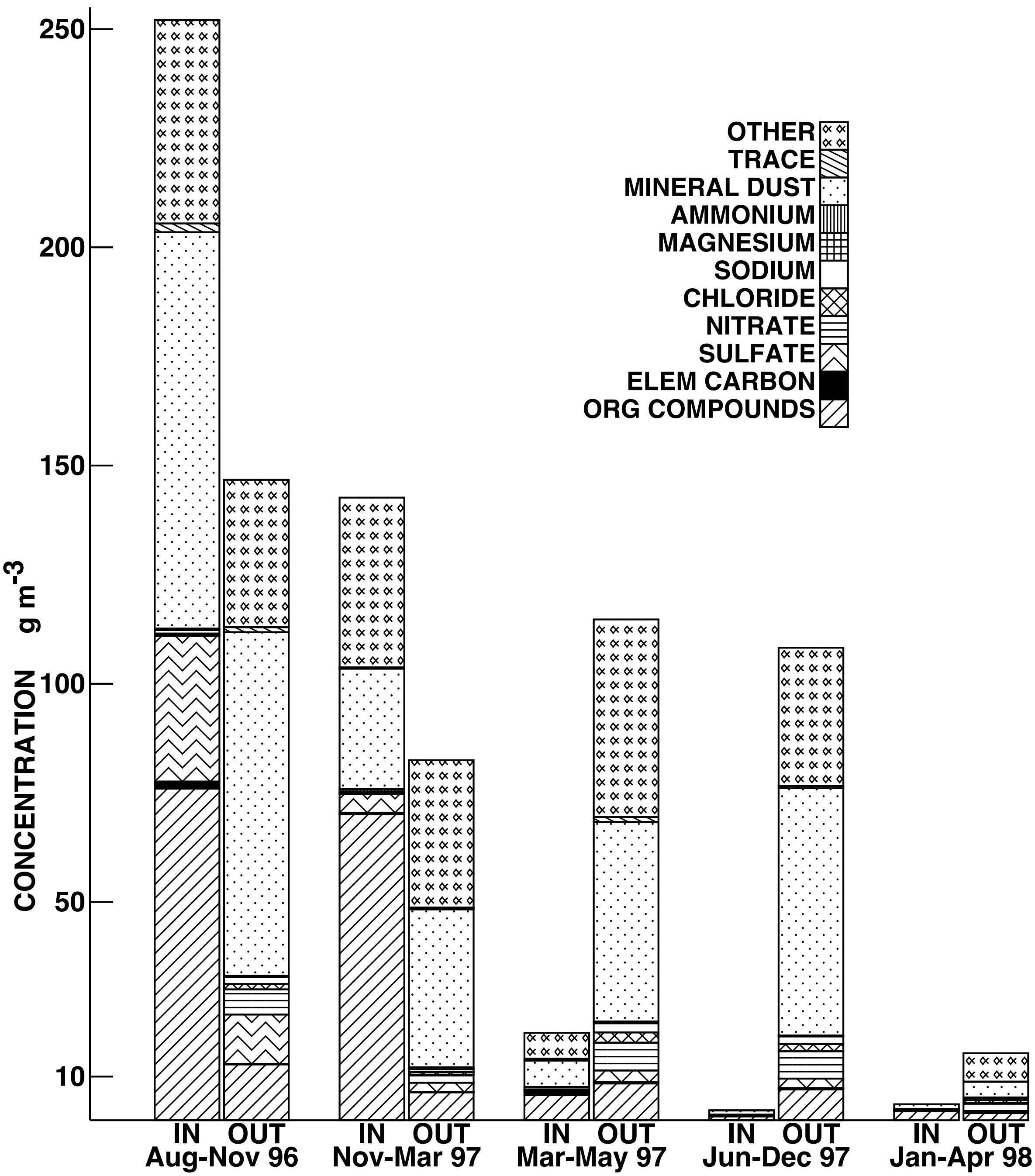

Figure 2: Average chemical composition of coarse airborne particles at the Getty Museum.

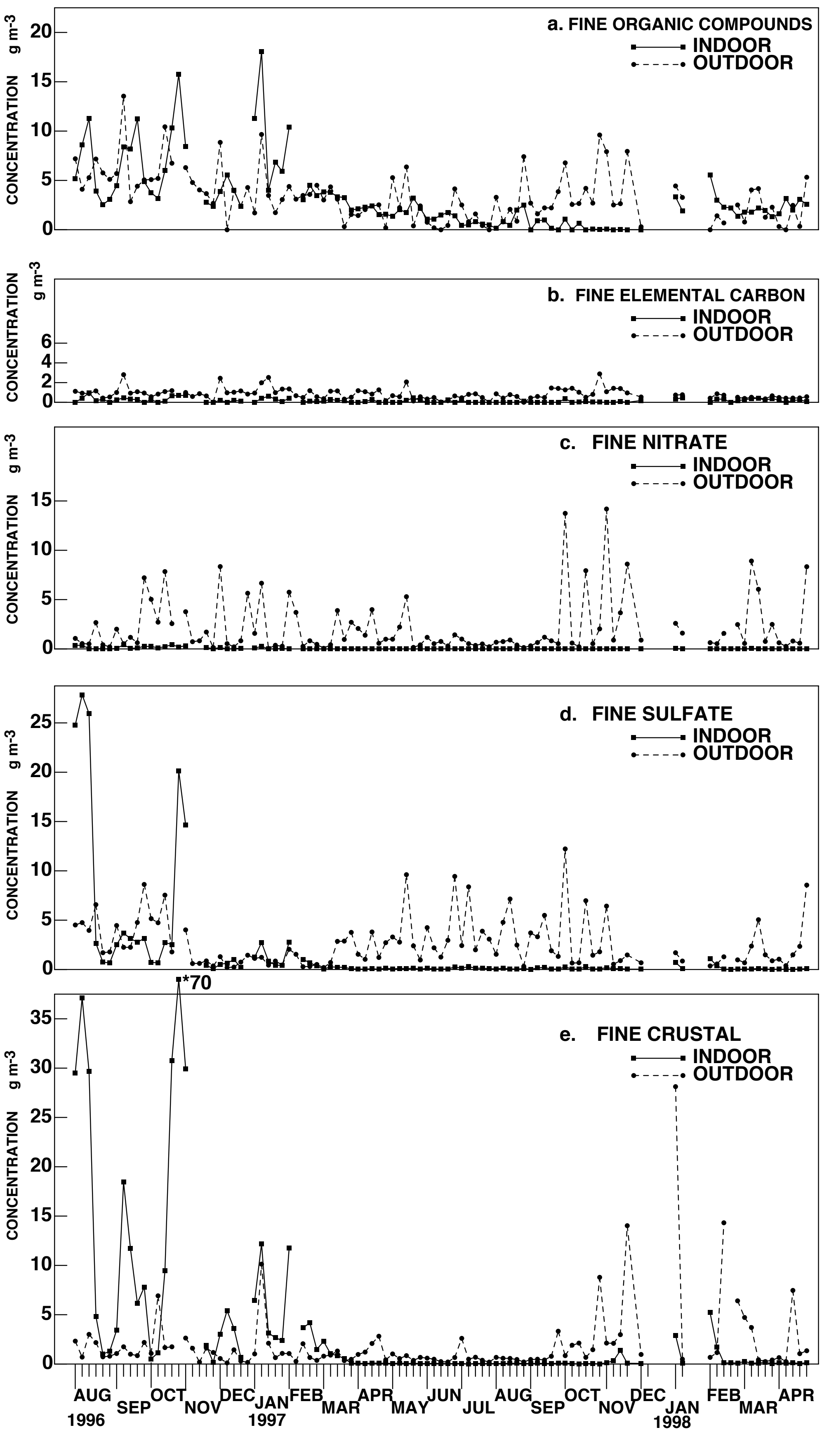

Figure 3: Airborne fine particle compounds at the Getty Museum: (a.) organic compounds, (b.) elemental carbon, (c.) nitrate, (d.) sulfate, and (e.) crustal material.

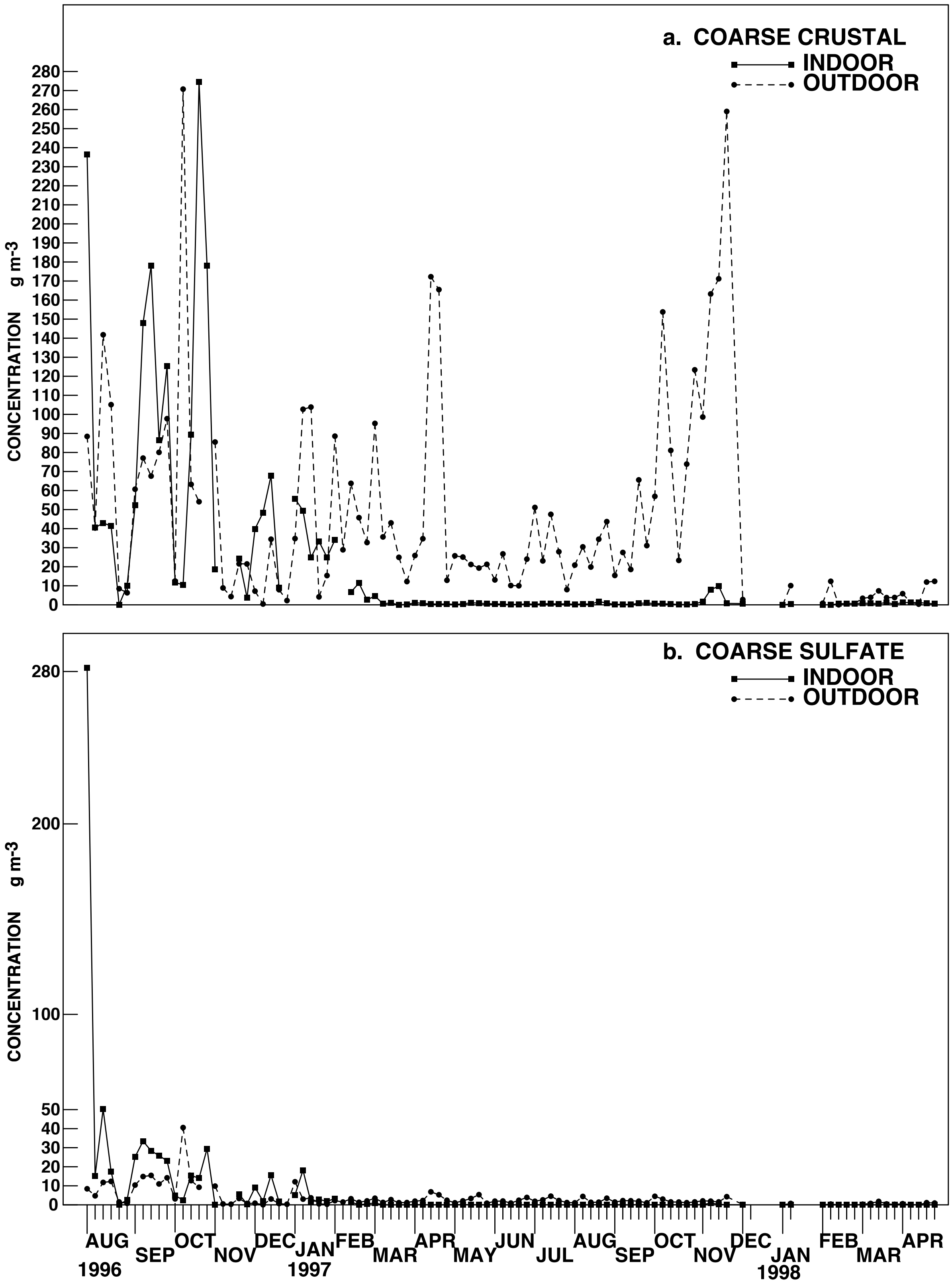

Figure 4: Airborne (a.) coarse crustal material and (b.) coarse sulfate concentrations at the Getty Museum.

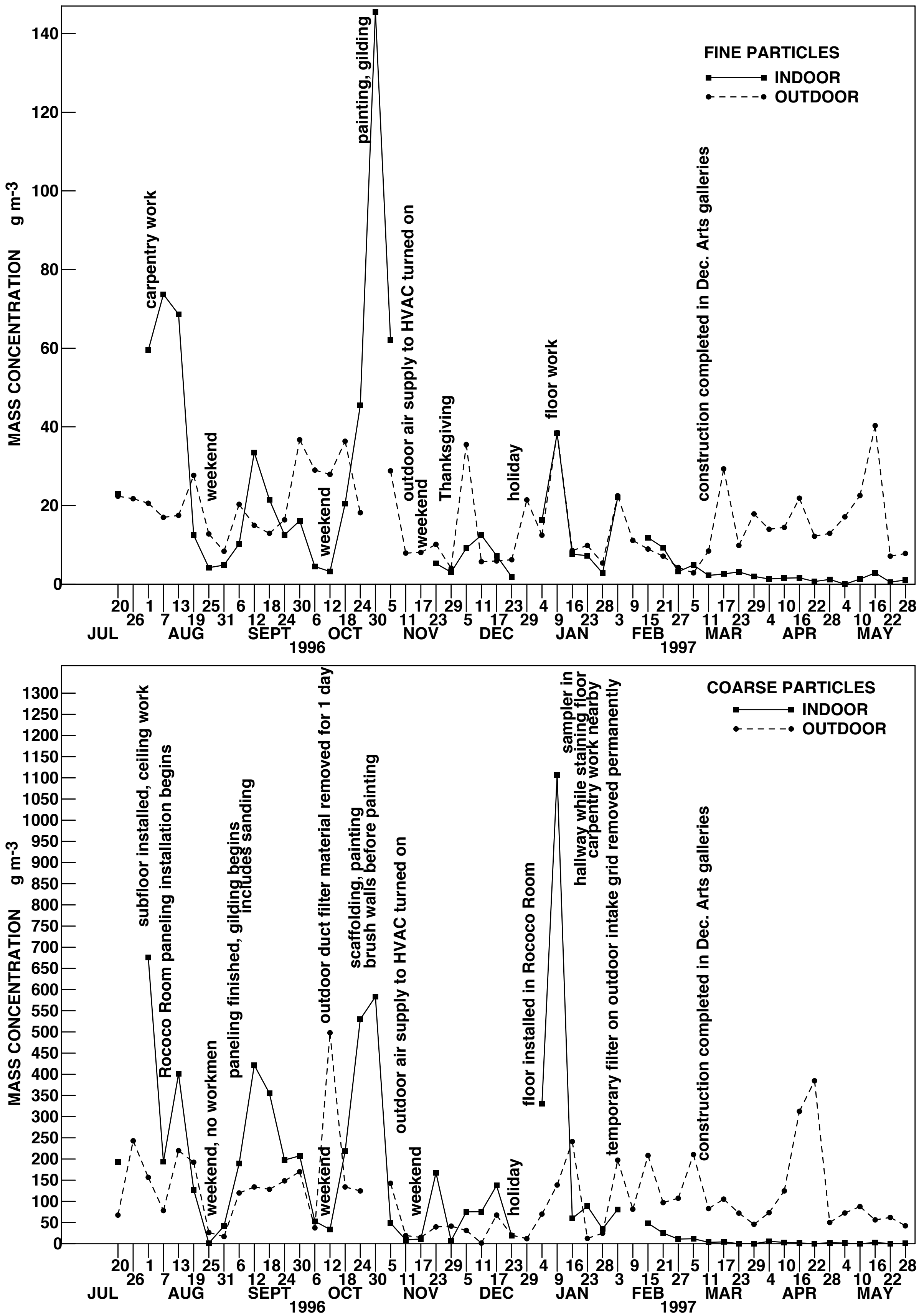

Figure 5: Construction activity effects on coarse and fine particle mass concentrations.