NUMERICAL SIMULATION OF INDOOR AIR POLLUTION LEVELS IN A CHURCH AND IN A MUSEUM IN GREECE

G. Drakou, Ch. Zerefos, I. Ziomas and V. Ganitis

Summary—*Using the Nazaroff and Cass model, indoor air pollutant concentrations were predicted inside two buildings which house valuable cultural properties. Both are located in the centre of Thessaloniki, Greece. One building is an eighth-century Byzantine church, Agia Sofia, which is naturally ventilated; the other is an exhibition hall at the Archaeological Museum of Thessaloniki, with a conventional air-conditioning system. Model predictions were based on outdoor air pollutant concentration measurements, on meteorological data and on the design, use and operation of each building. The results, which cover a typical wintertime two-day period for each building, show that in these buildings, despite their differences, the indoor concentrations of air pollutants such as* O_3*, NO,* NO_2*, HCHO, PAN and* HNO_3 *were generally higher than those recommended by most air quality standards. Changes in the ventilation of the buildings, to mitigate air pollution, are also discussed.*

Introduction

Indoor concentration measurements of reactive photochemical oxidants, such as ozone (O_3) and nitrogen dioxide (NO_2), in buildings housing works of art showed that in many cases these concentrations are higher than the air quality standards specified for museums, archives and galleries, to prevent damage to sensitive material. The effect of a pollutant on the indoor surfaces depends on the material of the surfaces, in conjunction with the prevailing indoor temperature and relative humidity conditions, indoor air flow near the surfaces, the synergistic effects of other pollutants, as well as the mixing ratio of the various pollutants present indoors [1–9].

The air pollutants may infiltrate into buildings from outdoors and/or they are generated from indoor sources. Total indoor air pollution depends on outdoor environmental conditions but, mainly, is affected by the design, use and operation of the building [8, 9].

In Mediterranean countries, such as Greece, due to the elevated solar radiation, high temperature, low relative humidity and an ever increasing number of vehicles, photochemical air pollutants are serious agents that threaten works of art. Many works of art in these countries are housed in old buildings with natural ventilation, and others in modern buildings with an HVAC (heating, ventilation and air-conditioning) system. This work aims to investigate indoor air pollution in two buildings which are representative of the types of building housing valuable artifacts. One is a traditional eighth-century Byzantine church and the other a new museum with an HVAC system.

Indoor photochemically-related air pollutant concentrations were predicted using the Nazaroff and Cass model [10], based on measured outdoor pollutant concentrations, meteorological data, and the building characteristics. Model results are compared with the specified standards for indoor air quality in buildings which house cultural property. Assuming that the deterioration of works of art is proportional to the fluxes of the reactive species to their surfaces, an example is given of how to estimate, from the model results, the potential risk of damage to the works of art housed. Following on from this, it is shown how changes in the ventilation of the building can prevent damage to sensitive material.

Model applications

The Nazaroff and Cass mathematical model [10], which predicts the indoor concentrations of photochemically-related air pollutants, was validated by comparing model results with experimental data through two independent experiments [5, 10]. Having acquired validation, the model was run for the buildings described below. Two versions of this model were used throughout this work:

(i) The simplified version, treating pollutant species as chemically independent, hereafter referred to as 'no chemistry' (NC) case [10–12]

(ii) The complete version, which explicitly incorporates reactive chemistry, hereafter referred to as 'full chemistry' (FC) case [10].

The indoor air pollutant concentrations which were calculated are: NO (nitrogen monoxide), NO_2

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Table 1 Simulation input parameters

Institution	*Surface area m^2*	*Volume m^3*	*Lighting*	*Indoor pollutant sources*
Agia Sofia	7575	9539	natural	none
Vergina	1065	1065	artificial	none

Full chemistry case (FC)	*Deposition velocity ($cm.sec^{-1}$)* Agia Sofia	Vergina
O_3	0·051	0·036
NO_2	0·011	0·006
NO	0·003	0·0
HCHO, RCHO	0·005	0·005
PAN	0·035	0·035
HNO_2, HNO_3, HNO_4, HO_2, H_2O_2		
NO_3, N_2O_5, RCO_3, RNO_4, RONO, RO_2	0·07	0·07
ALK, ARO, CO, C_2H_4, OLE	0·0	0·0

Air exchange rate	*Make-up outdoor air flow*		*Total air flow*		*Recirculation air flow*	
	night	*day*	*night*	*day*	*night*	*day*
Agia Sofia						
M		0·30	2·00			
A	0·10	0·50	2·17		1·67	2·07
Vergina						
M	0·00	3·60	14·40		10·80	
B	0·00	1·80	14·40		12·60	
C*	0·00	1·80	14·40		12·60	

*The HVAC system starts four hours later in the morning.

(nitrogen dioxide), O_3 (ozone), HCHO (formaldehyde), H_2O_2 (hydrogen peroxide), HNO_3 (nitric acid), HNO_2 (nitrous acid), PAN (peroxyacetylnitrate), RCHO (aldehydes more complex than formaldehyde), ALK (alkanes), ARO (aromatics), OLE (olefins).

Description of the sites

Agia Sofia church is located in the centre of the old part of the city of Thessaloniki. It is a traditional vaulted basilica, constructed in the eighth century A.D.. The church underwent many modifications through the ages. It is constructed with local green stone and bricks. The floor covering is marble. There are many large windows with simple panes of glass. The artificial lighting is provided by electric light bulbs. There are important Byzantine icons and frescoes, as well as old sacerdotal vestments and old rare books and wall paintings. The church is open to the public between 6:30 a.m. and 7:00 p.m. The whole church is naturally ventilated and has a central heating system.

Vergina is an exhibition hall at the Archaeological Museum of Thessaloniki, which is a concrete construction, built in 1989. This hall is separated from the rest of the building and it has its own heating, ventilation and air-conditioning (HVAC) system. There are no windows, only artificial light provided by 120W fluorescent lamps, with UV filters. The HVAC system works between 6 a.m. and 5 p.m, for reasons of economy. Until 1998 this hall housed the finds from the tombs at Vergina in Macedonia, Greece.

Input data for the indoor air quality model

Table 1 summarizes the input parameters used in the model simulations.

For the church, estimates of the air flow rates from outdoors were based on:

(a) Calculations of air flow into and out of each building based on multiple measurements of air velocity with a hot-wire anemometer at the windows and at the front door of the building

(b) Evaluations of air exchange rates from standard engineering estimates for infiltration based on the building blueprints and the data for wind velocity and direction outside the building [13, 14].

For the museum, the engineer who was responsible for the HVAC system gave information about the make-up air flow rate and the air recirculation rate.

The deposition velocities reported in the literature for O_3, NO, NO_2 and HCHO have been used, taking into account the construction materials of the interior space and the relative humidity levels at each building [10, 11, 15–18].

Data on outdoor concentrations of the pollutants required by the model were specified by the following approach. For the church, hourly data on O_3, NO, NO_2* (= NO_x–NO), carbon monoxide and hydrocarbon concentrations were obtained from the monitoring station of the Municipality of Thessaloniki, which is situated outside Agia Sofia. For the museum, the same data were obtained from the Laboratory of Atmospheric Physics of the Aristotle University of Thessaloniki, located within 1·5km of the museum. All other species (HNO_3, PAN, H_2O_2, HNO_2) concentrations were calculated according to the methodology described by Nazaroff and Cass [10]. The contribution of other nitrogen-containing species to the NO_2* measurements is assumed to be 15% of the outdoor ozone concentrations [10]. Hence the outdoor NO_2 values used in the model are $NO_{2*outdoor} - O_{3outdoor}$.

Cases denoted M refer to measured *in situ* air exchange rate (ach) with outdoors, in each building.

Cases A, B and C investigate the effect of reducing the outdoor make-up air by changing the ventilation scenario of the buildings.

In case A, for the church, it was assumed that a common mechanical ventilation system is installed. So, the total air flow rate remains the same as before the installation, but the infiltration of fresh air is now reduced. The minimum recommended outdoor make-up air flow rate is $8{\cdot}5 m^3 h^{-1}$ per person occupying the building [14, 19]. If we assume an occupancy of 600 persons, the resulting minimum outdoor air exchange rate is 0·5 ach.

Case B, for the Vergina exhibition hall, investigates the case in which the make-up air flow rate is reduced and the air recirculation rate is increased to obtain the same total air flow rate as before. The selected value of outdoor air exchange rate is the minimum recommended value for an occupancy of 150 persons. In case C the air flow rates are the same as in case B, but the ventilation system began to work four hours later in the morning.

Results and discussion

Figure 1 shows the model predictions of indoor air pollutants (NO, NO_2 and O_3) for the two buildings during a two-day period in the winter of 1995.

The simulations presented in Figure 1 show that predicted indoor NO_2 concentrations in each building exceeded the outdoor NO_2 levels for many hours. This result appeared when the outdoor NO_2 levels were increased and the air exchange rate of the buildings during this time was also elevated. This is caused by the much reduced indoor photolysis inside the buildings, as well as indoor NO_2 generation through chemical reactions [6, 10, 16].

It should be noted here that winds changed from a north-northwest to a southerly direction from the first to the second day of this experimental period. The wind velocity and direction affected the air exchange for Agia Sofia (a building with a permanently open front door during the day). Due to the orientation of this building the air exchange with outdoors was increased on the first day and this fact resulted, as is shown by the model, in high indoor air pollutant concentrations, equal to the outdoor values. In contrast, the following day there were lower air exchange and lower indoor pollutant levels, if one compares them with the outdoor values.

The Vergina exhibition hall is not connected with the outdoors, except through its ventilation system. Consequently, indoor air pollutant levels depended mainly on the make-up air flow rate by which outdoor pollutants were transferred indoors. It is crucial at what time during the day and how much fresh air infiltrated into the room. During the night hours the ventilation system was off, as were the lights, so the pollutant levels were extremely low. While the system was working, the predicted indoor pollutant levels were high due to the absence of any pollutant-removing air-filter in the HVAC system. Note that during the period under study, the forced air infiltration was elevated when outdoor O_3 levels were high and the outdoor hydrocarbon levels were also high; these facts, combined with the strong

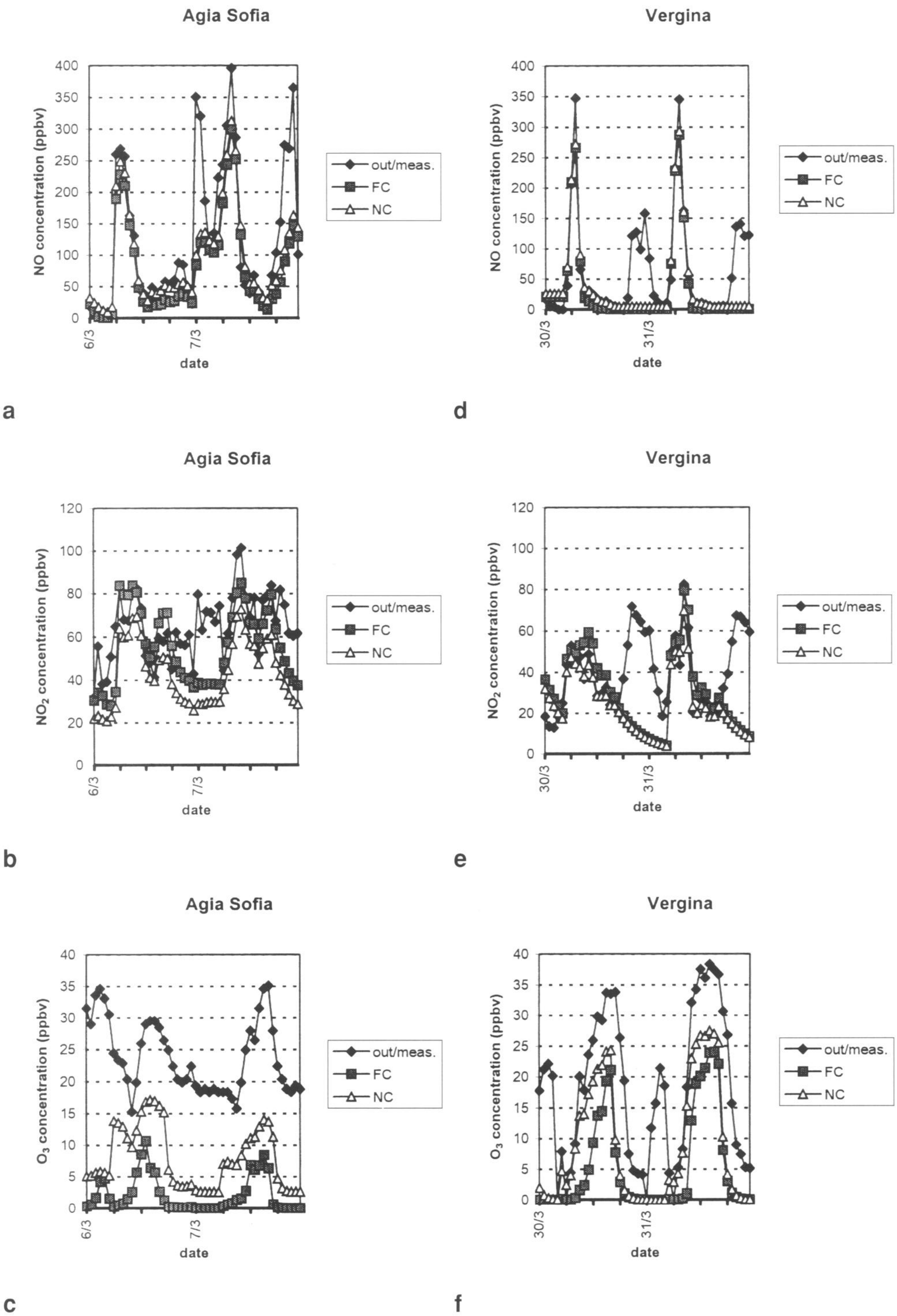


Figure 1 *Indoor and outdoor NO, NO_2 and O_3 concentrations in Agia Sofia and Vergina.*

indoor lighting, resulted in high indoor calculated O_3 levels for many hours. So the common HVAC system is estimated to be ineffective to protect the collection from air pollutants. It should be noted that actual indoor levels of O_3 are expected to be lower than the modelled values because of O_3 losses at surfaces within the ventilation system, which are not calculated in this work [3, 6]. On the other hand, NO_x levels are expected to be as high as the model predicts. These calculations show that modifications have to be made in this building to improve its indoor air quality, particularly when there are elevated outdoor air pollution levels [3, 8, 20, 21].

Figure 2 shows the two-day averaged indoor/outdoor (I/O) pollutant concentration ratios in these two buildings (FC case). As can be seen, the indoor/outdoor pollutant concentration ratios are comparable in these buildings and for some species these ratios are very high in both buildings. It should also be noted that for O_3 the maximum I/O concentration ratios as predicted by the NC case are 49% for Agia Sofia and 72% for the Vergina exhibition hall (not presented in Figure 2). These maximum ratios are consistent with the experimental ratios found by Druzik *et al.* [7] in museums in Los Angeles with construction and air exchange rate similar to those of these two buildings.

Therefore, irrespective of the building and its ventilation system, it appears that indoor air pollutant levels are expected to be high inside these buildings and measures should be taken to preserve the important and irreplaceable works of art which are housed within them.

One of the most common measures that is suggested to reduce indoor air pollutants is to control their intrusion through changes in the ventilation scenario of the buildings. If we assume no air pollutant sources inside the two buildings, by reducing the fresh air infiltration, the indoor air quality will be improved. Figure 3 corroborates this, by comparing the indoor NO, NO_2 and O_3 concentration ratios, as predicted based on measured ventilation rate, with the predicted ratios under the assumption of reducing outdoor fresh air. On the other hand, when indoor air pollutant sources are present (for example, tourists), the ventilation rate must be increased.

The cost of installing an HVAC system in the church is counterbalanced by the protection of materials sensitive to air pollution. For the museum, a serious study has to be made to manage the HVAC system for the well-being of the works of art.

These buildings are representative not only of Greece but of all the Mediterranean countries. The example of the church covers not only the numerous churches existing in these countries, but also the case of private art collections. Many valuable objects are kept in naturally ventilated buildings which experience bright sunlight. To show the potential damage to materials in these buildings, an example follows.

Let us consider a naturally ventilated building in Thessaloniki, Greece, which houses a private art collection. Let us assume that this building has a ratio $A/V = 1{\cdot}8\text{m}^{-1}$ and construction materials such that the NO, NO_2 and O_3 decomposition rates on the indoor surfaces, $r = v_g \times (A/V)$, are 0·04, 0·40 and $3{\cdot}3\text{h}^{-1}$, respectively. The air pollutant deposition velocities are taken from the published data in the literature. Let us assume that the building has natural lighting. Also, let us consider a very hot and sunny day. During this day the windows of the building are half-open and the air exchange rate with outdoors is 2·4 ach. Under these assumptions the indoor NO, NO_2 and O_3 concentrations, according to the model results (FC case) for the church, are about 77, 66 and 33%, respectively, of the corresponding outdoor values. In this season in Thessaloniki, a very probable 24-hour averaged value of the NO outdoor concentration is 70ppb, whilst for NO_2 it is 40ppb and for O_3, 20ppb (Laboratory of Atmospheric Physics, Thessaloniki, Greece). The corresponding 24-hour averaged indoor concentrations of these pollutants are: $70 \times 0{\cdot}77 = 53{\cdot}9$ppbv for NO, $40 \times 0{\cdot}66 = 26{\cdot}4$ppbv for NO_2 and $20 \times 0{\cdot}33 = 6{\cdot}6$ppbv for O_3. Therefore, the 24-hour averaged flux of an air pollutant to interior surfaces (F) is given by the equation:

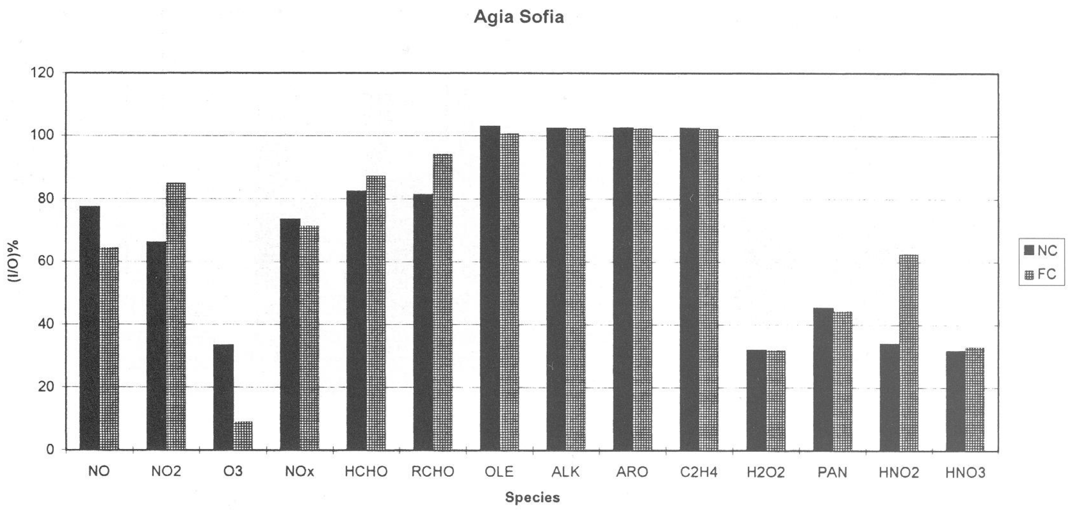
$$F = v_g \times C = r \times (V/A) \times C \qquad (1)$$

where C is the 24-hour averaged concentration quite far from the surface, v_g is the pollutant deposition velocity and r the corresponding decomposition rate on indoor surfaces.

Based on equation (1), the 24-hour averaged flux of NO_2 and O_3 to interior surfaces of this building is: for NO_2, $11\mu\text{gm}^{-2}\text{h}^{-1}$ and for O_3, $24\mu\text{gm}^{-2}\text{h}^{-1}$.

If this building houses valuable objects which are sensitive to pollution, the 24-hour averaged indoor NO, NO_2 and O_3 concentrations exceed by far the recommended values for these concentrations, which are 1ppb for O_3 and below 2·5ppb for NO_2 [1–3, 6, 7]. This translates to $4\mu\text{gm}^{-2}\text{h}^{-1}$ flux for O_3 and $1\mu\text{gm}^{-2}\text{h}^{-1}$ flux for NO_2, values much smaller than those estimated for this building.

The 24-hour averaged flux of an air pollutant to interior surfaces (F) gives an indication of the soiling or potential degradation of sensitive materials housed in the building. Taking into account that the effects of the pollutants on these objects are cumulative and synergistic, it is very clear that in these buildings the cultural heritage is unprotected against air pollution.



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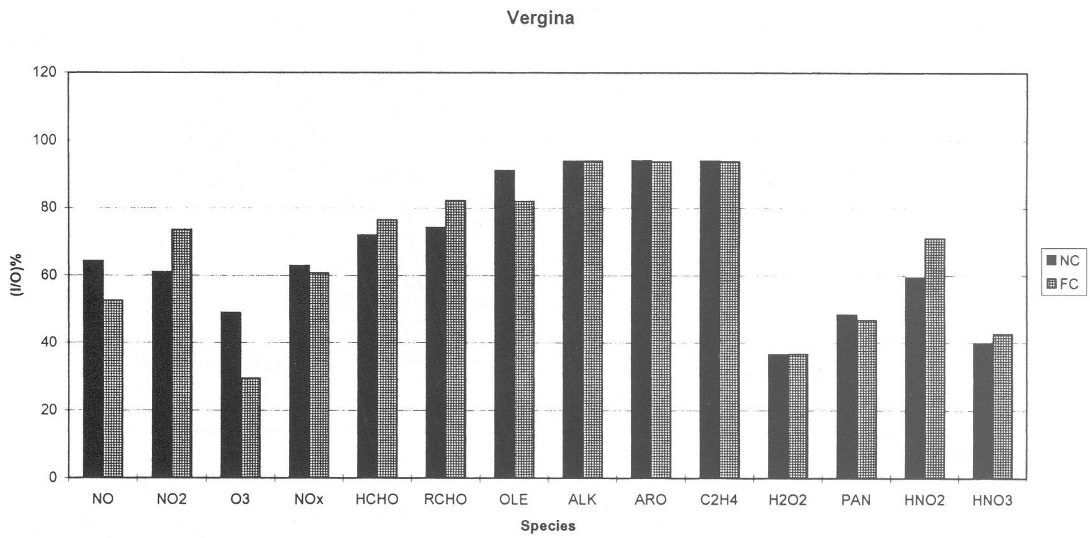

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Figure 2 Average indoor/outdoor pollutant concentration ratios for a two-day period.

The situation in museums, libraries and archives like the museum studied is also very usual. The common HVAC system protects the collections only from dust. Indoor air pollution is similar to that in a naturally ventilated building, like the church. Furthermore, the use of this system can be detrimental rather than beneficial, if it is not working according to the needs of the works of art and the intake and uptake dampers are located in the wrong places [21].

Indoor air pollutant sources are not investigated here because there were no available data. But, for example, tourists visiting both buildings, and the burning of candles in the church, generate indoor air pollution and make the picture even worse. A special study has to be undertaken to investigate the situation thoroughly and to propose measures to prevent material damage.

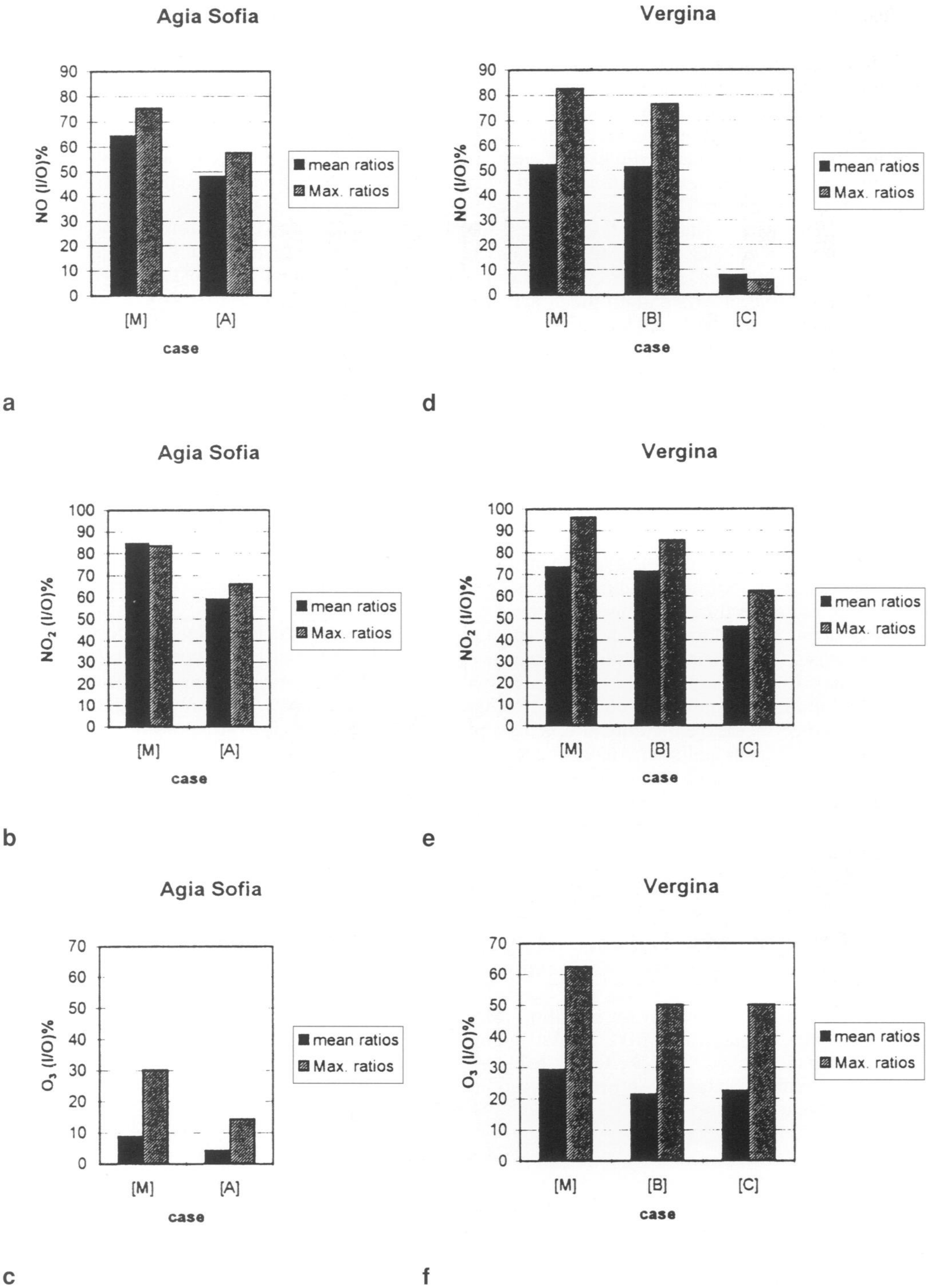

Figure 3 *Comparisons of indoor/outdoor air pollutant concentration ratios under different building ventilation scenarios.*

Conclusions

The indoor air pollutant concentrations were predicted for a two-day wintertime period in two representative buildings in Greece, which house valuable cultural artifacts. One building is an eighth-century Byzantine church, Agia Sofia, with natural ventilation; the other is an exhibition hall at the Archaeological Museum of Thessaloniki, with a conventional HVAC system. The predictions were made using the Nazaroff and Cass model and were based on outdoor air pollutant concentration measurements, on meteorological data and on the design, use and operation of each building. The results demonstrate that in these buildings, despite their differences, the indoor concentrations of air pollutants such as O_3, NO, NO_2, HCHO, PAN and HNO_3 were generally higher than most recommended air quality standards. The church studied gives an estimation of the potential damage to the works of art which are housed in similar buildings with natural ventilation. The case of the museum shows that even when a common HVAC system exists, the indoor air pollutant levels are high; only the dust is less than in the case of the church. Indoor air pollutant sources exist but they were not studied here because there were no available data, so the indoor air quality is expected to be even worse. Changes in the ventilation scenario of the buildings is a measure to control the intrusion of the air pollutants originating outdoors. But before selecting a change in the ventilation rate, a careful study of the outdoor air pollutant trend, the indoor air pollutant emissions and the occupancy of the buildings has to be made, at the very least.

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Authors

REA DRAKOU graduated in 1979 in physics from the Aristotle University of Thessaloniki and obtained a PhD in atmospheric physics from the same university in the year 1998. She is currently working on the problems of indoor air quality, studying the modelling and control of indoor pollutants and their effects on artifacts. She is also a lecturer on indoor air quality at the Demokritus University of Thrace, Department of Environmental Engineering. *Address: Demokritus University of Thrace, Department of Environmental Engineering, Laboratory of Atmospheric Pollution Science and Technology, Vas. Sofias 1, 67100 Xanthi, Greece.*

CHRISTOS S. ZEREFOS graduated in physics from the University of Athens and obtained an MSc in meteorology and PhD in physics-meteorology from the same university. In 1978 he was elected Director of the Research Centre for Atmospheric Physics of the Academy of Athens and in 1979 Professor of Atmospheric Physics at the Physics Department of the Aristotle University of Thessaloniki, Greece. Since 1981 he has been the Director of the Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki. Presently he is directing the WMO Ozone Mapping Centre following the decisions of WMO Congress RA VI decision (1995) and the Balkan Environmental Research and Development Institute which is part of the Balkan Physical Union. In 1992 he was unanimously elected by the Balkan Physical Union (BPU) as Director and in 1997 he was elected President of BPU. *Address: Aristotle University of Thessaloniki, Physics Department, Laboratory of Atmospheric Physics, Thessaloniki 54006, Greece.*

IOANNIS C. ZIOMAS is an associate professor in the Department of Physics, Aristotle University of Thessaloniki. He has over 15 years of research and management experience in the field of atmospheric physics. He has coordinated numerous international and national research projects and he is a member of the EU (DGXII) Science Panel for tropospheric physics and chemistry. *Address: as for Zerefos.*

VAIOS GANITIS was born in 1951. He studied conservation at the Technical School of Athens 1976–1979, architectural studies at the University of Rome 1981–1984 and scientific principles of conservation at ICCROM, Rome, 1992. He has been a conservator of icons and wall paintings at the Greek Ministry of Culture since 1979. He is head of the icons conservation department at the Museum of Byzantine Culture, Thessaloniki. Currently, he is teaching and is responsible for the course on conservation principles of painted surfaces on organic substrates, in the conservation postgraduate programme at the Aristotle University of Thessaloniki, Greece. *Address: Museum of Byzantine Culture, 2 Stratou Ave., PO Box 50047, 54013 Thessaloniki, Greece.*

Résumé—*On a calculé, en utilisant les modèles de Nazaroff et de Cass, les valeurs prévues pour les polluants de l'air à l'intérieur de deux édifices à caractère historique. Tous deux sont situés au centre de Thessalonique, en Grèce. L'un est une église byzantine du 8ᵉ siècle, Agia Sofia, qui possède une ventilation naturelle; l'autre est un hall d'exposition au Musée archéologique de Thessalonique, et dispose d'un système conventionnel d'air conditionné. Les prévisions des modèles étaient fondées sur les mesures de la pollution à l'extérieur, sur les* *données météorologiques, et sur la conception, l'usage et le fonctionnement de chacun des édifices. Les résultats, qui couvraient une période représentative de deux jours d'hiver pour chaque bâtiment, montre que dans ceux-ci, malgré leurs différences, les concentrations de polluants tels que O_3, NO, NO_2, HCHO, PAN et HNO_3 étaient généralement plus élevées que celles recommandées par la majorité des standards de la qualité de l'air. Cet exposé constitue une base de discussion relative à la modification éventuelle de la ventilation des édifices en vue de diminuer la pollution.*

Zusammenfassung—*Die Autoren beschreiben den Einsatz des sog. Nazaroff und Cass Modells zur Beurteilung der in Innenräumen in der Raumluft vorhandenen Schadstoffe. Das Verfahren kam für die hier zusammengefasste Studie in zwei Gebäuden mit wertvoller kulturhistorischer Innenausstattung im Zentrum von Thessaloniki in Griechenland zur Anwendung, nämlich in der Hagia Sofia, einer byzanthinischen Kirche aus dem 8. Jahrhundert, und in einem Ausstellungsraum im archäologischen Museum der Stadt. Während in der Hagia Sofia eine natürliche Durchlüftung stattfindet, besitzt das Museum, in dem der untersuchte Ausstellungsraum liegt, eine konventionelle Klimaanlage. Die Vorhersagen, denen das beschriebene Modell zugrunde liegt, basieren auf der Messung des Schadstoffgehaltes der Außenluft, auf meteorologischen Daten und auf Bauart, Funktion und Gebrauch der untersuchten Gebäude. Die Resultate, gemessen über zwei Tage bei typischem Winterwetter, zeigen, daß trotz der aufgezeigten baulichen und technischen Unterschiede der Bauwerke die Konzentrationen von Luftschadstoffen in den Innenräumen wie Ozon (O_3), Stickstoffoxiden (NO, NO_2), HCHO, PAN und Salpetersäure (HNO_3) grundsätzlich höher lagen als die in den meisten Luftqualitätsstandards empfohlenen Richtwerte. Es werden im vorliegenden Bericht mögliche Veränderungen der Belüftungsweise der Gebäude zur Reduzierung der Luftverunreinigungen diskutiert.*

Resumen—*Usando los modelos de Nazaroff y Cass se pudieron predecir los niveles de concentración de contaminantes en el interior de dos edificios, los cuales albergan valiosos bienes culturales. Ambos están localizados en el centro de Tesalónica, Grecia. Uno de los edificios es una iglesia bizantina del siglo VIII, Agia Sofía, la cual es ventilada con aire exterior natural; la otra es una sala de exposiciones en el Museo Arqueológico de Tesalónica, con un sistema convencional de aire acondicionado. Modelos de predicciones se basaron en las medidas de concentración de contaminantes en el exterior, en datos meteorológicos y en el diseño, uso y función de cada edificio. Los resultados, los cuales cubren un periodo invernal típico de dos días para cada edificio, muestran que en éstos, a pesar de sus diferencias, las concentraciones interiores de contaminantes como el O_3, NO, NO_2, HCHO, PAN y HNO_3 eran normalmente más altas que las recomendadas por la mayor parte de los standards de calidad de aire. Se discuten, así mismo, los cambios en la ventilación de los edificios, con el fin de mitigar la polución del aire.*