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FORECASTING PEAK POLLUTANT LEVELS FROM METEOROLOGICAL VARIABLES

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Abstract—The main objective of this paper is to present analytical models relating maximum pollutant concentrations in urban areas with meteorological and other variables. The analysis is based on measurements from Greater Athens Area and is restricted in only one pollutant of special interest, namely NO_2. The meteorological variables, used in analytical modeling for forecasting pollution concentrations, cover the most important atmospheric processes favoring pollution episodes. The selection of the variables was based both on extensive correlation analysis and on the existing knowledge from the scientific literature. The evaluation of the developed forecasting models showed that their degree of success is promising. The final model equations derived are simple and they can be used easily for operational forecasts from the air quality management authorities.

Key word index: Forecasting pollutant concentrations, Athens.

1. INTRODUCTION

It has been long recognized that serious pollution episodes in the urban environment are not generally caused by sudden increases in the emission of pollutants, but result from unfavorable meteorological conditions, which diminish the ability of the atmosphere to disperse the pollutants. It is thus not surprising that during the past few decades a lot of effort has been dedicated to studying the relationship between pollution concentrations and meteorological parameters (e.g. McCollister and Wilson, 1975; Aron and Aron, 1978; Lin, 1982; Katsoulis, 1988; Robeson and Steyn, 1990).

Many of the previous studies (Sanchez *et al.*, 1990; Mantis *et al.*, 1990; Pissimanis *et al.*, Kallos *et al.*, 1993) analyzed the meteorological conditions associated with high pollutant concentrations from a synoptic perspective. These studies usually produced qualitative or semiquantitative results and shed light on the relation between the synoptic meteorological conditions and the pollutant concentration. Using various criteria, suitable classifications are established, which describe the relation of synoptic meteorological conditions to urban atmospheric pollution.

Another well-established approach is to determine a relationship between the peak pollutant concentration and various meteorological parameters (Aron, 1984; Lalas *et al.*, 1985; Robeson and Steyn, 1990). Some of these models are purely empirical and do not attempt to explain the mechanisms involved. Using a historic record of air quality data, an empirical model is constructed by fitting air quality data with a probability density function. A drawback of this approach is that it is not possible to utilize a new variable, which was not included in the initial derivation of the empirical formulation. Analytical models try to avoid this problem by employing physical arguments to decide in advance which input variables to use. However, even if the form of the model is analytical, the model coefficients are determined by statistical optimization techniques and therefore are stochastic models. Even in this case, the input parameters must be chosen from the available data and it is necessary to make some assumptions based on empirical arguments.

In the present study, an attempt is made to develop an analytical methodology, which will provide both

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qualitative and quantitative predictions of pollution levels. The methodology is based on observations taken in the Greater Athens Area (GAA). As in many cities worldwide, the concentrations of air pollutants in the GAA exceed frequently the threshold limits established by the Greek Ministry of Environment (PERPA, 1989). The only safe way to avoid pollution episodes is of course the reduction of pollutant emissions from all kinds of sources. However, since effective permanent reduction of emissions is not foreseen for the coming years, a special effort is given to improve the existing procedure for the temporal reduction of emissions. Our interest was focused on forecasting maximum NO_2 levels at the downtown area of Athens due to the fact that whenever emission reduction measures were taken by the responsible authorities the decision was based on NO_2 levels at this area. The semi-empirical approach proposed by Mantis *et al.* (1990) was the first successful (Spyropoylos, 1992) approach for the prediction of the possibility of the occurrence/continuation of a pollution episode. However, this methodology does not provide a quantitative estimate of the next day's maximum pollutant concentrations. Moreover, the degree of success of this methodology strongly depends on the experience of the involved personnel.

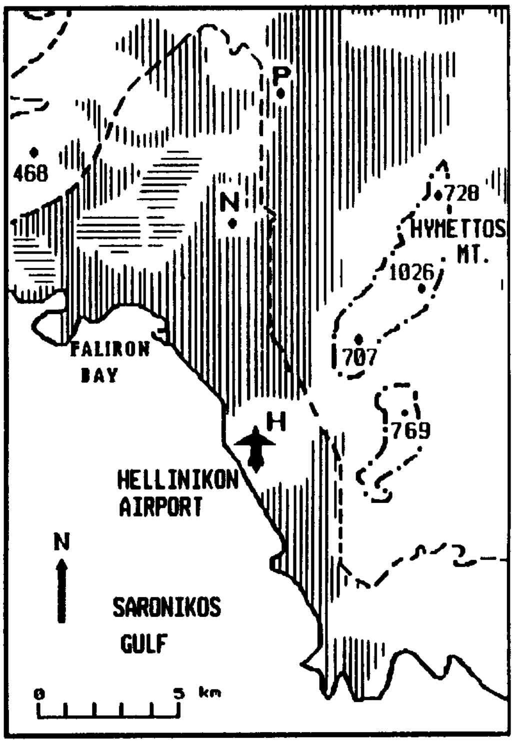


Fig. 1. Map of the Athens area. The monitoring station at Patision is indicated by P, the National Observatory of Athens by N and the Hellinikon Airport by H.

2. DESCRIPTION OF THE ATHENS AREA AND OF THE DATA USED

Air pollution in the Athens area has been the subject of many investigations and the main features of the problem are well documented in the literature (see, e.g. Mantis *et al.*, 1992). Therefore only a brief summary will be presented here.

Athens basin is located on the west coast of the Attica peninsula (Fig. 1). The city of Athens is surrounded by moderately high mountains, forming a channel, with only one major opening toward the sea to the southwest. The mountains are acting as physical barriers with only small gaps between them. The most important is the channel leading to the northeast coast of Attica peninsula, which gives the Athens basin access to the Etesians, the system of semipersistent northerly winds, which reduce the likelihood of prolonged pollution episodes. Multistorey buildings almost cover the floor of the valley for a distance of 20 km inland.

Mantis *et al.* (1992) point out that pollutant density emission in central Athens is sufficiently large to create a constant threat of a pollution episode whenever there is poor ventilation and dilution. A network of 14 pollution monitoring stations (not all of them operating presently) has been established in the Athens basin, which provides information on pollutant concentrations and meteorological conditions. Pollution levels vary considerably over the city and the monitoring station of Patision, indicated by P in Fig. 1, shows consistently the highest NO_2 concentrations (Mantis *et al.*, 1992).

The sampling inlet, at Patision station is about 8 m above ground level, facing the heavy traffic street with six lanes of traffic (about 62,000 transpassing vehicles per day) (PERPA, 1989). Whenever emission reduction measures were taken by the responsible authorities, the decision was mainly based on the pollution levels at the monitoring station at Patision. For this reason, the present analysis for forecasting maximum NO_2 concentrations, is limited to this station only. It must be noted that although pollution levels at the Patision station are affected by local sources, the independent variables used in the developed models are more or less regional in nature. The reason for this is that local variables are not likely to be available by routine meteorological forecasts. Moreover, the variables used in the present analysis represent the conditions over the entire urban area and the same methodology can be used to predict air pollution levels in other parts of the Greater Athens area. On the other hand, it is anticipated that using regional instead of local variables will increase the data scatter and diminish somewhat the accuracy of the analytical models.

The pollution data used in the present study cover the period 1987–90 and were provided by PERPA. Although meteorological measurements are presently performed at five of the air pollution monitoring stations, the meteorological data that have been used in this study have been obtained from the station operated by the National Observatory of Athens (NOA). This is because only the NOA station provided continuous data for the entire time period (1987–90), covered by the present analysis. The NOA site (indicated by N in Fig. 1) is located at the top of a small hill, 107 m above MSL and about 5 km from the shoreline. Continuous observations of all meteorological parameters have been carried out at this site since 1870 and are published in the Climatological Bulletin of NOA. Meteorological data obtained at NOA are considered to be of very good quality. The only exception is wind speed measurements which may exhibit an overspeeding due to hill effects. Radiosonde ascents are available twice a day, i.e. 0200 LST and 1400 LST at the Athens airport, Hellinikon (indicated by H in Fig. 1).

For the purposes of the present study, 95 NO_2 pollution periods, from the years 1987–90, were selected, each one covering a total of seven days. The criterion applied for selecting these episodes was that the maximum hourly NO_2 concentration of the fourth day should have exceeded or been equal to the assumed limit of 250 $\mu g\ m^{-3}$. This limit is somewhat higher than the alert limit for NO_2 (200 $\mu g\ m^{-3}$). Following previous recommendations (Robeson and Steyn, 1990; Hanna and Paine, 1989) the data were divided into two parts, a development database (comprising measurements from the period 1987–89) and an evaluation database (measurements from the year 1990).

3. VARIABLES CONSIDERED

Special effort has been given so that the meteorological variables, used in analytical modeling for forecasting pollution concentrations, cover the atmospheric processes favoring pollution episodes. The selection of the variables was based both in extensive correlation analysis between the different variables and in the existing knowledge from the scientific literature. The detailed presentation of the correlation analysis results is out of the scope of this paper. However, as an illustrating example, in Fig. 2 there are presented the mean day to day variations calculated from all the selected 95 NO_2 pollution periods for (a) the daily maximum mean hourly NO_2 concentration, (b) the air temperature change at 850 hPa, (c) the wind speed and (d) the index for the wind direction defined by

$$\mathrm{WD} = 1 + \sin(\psi + \pi/4), \tag{1}$$

where ψ is the wind direction expressed in radians (see also Section 3.2 for further explanations). The bars indicate the standard deviations about the mean quantities. From this figure, it is obvious that, as a general pattern, the increase of NO_2 concentrations is accompanied by an increase of the 850 hPa air temperature and low winds coming from southern

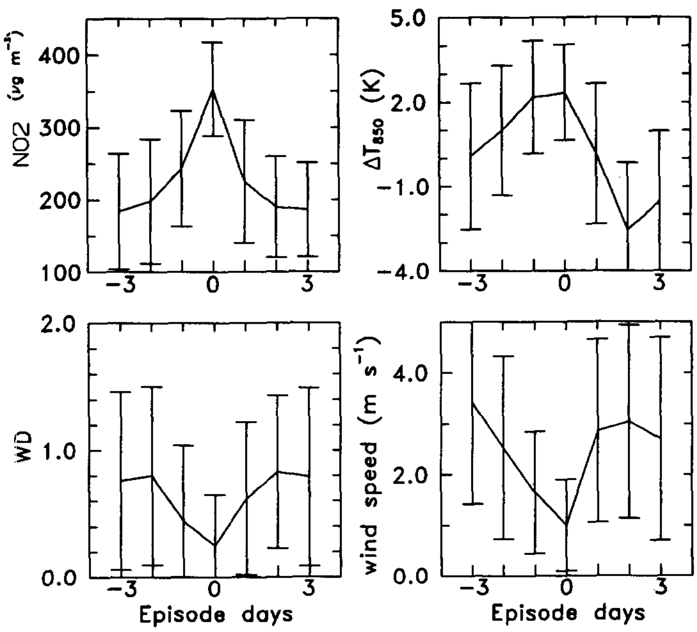


Fig. 2. The mean day to day variation of the daily maximum mean hourly NO_2 concentration (NO_2), the air temperature change at 850 hPa (ΔT_{850}) in the proceeding 24 h, the index for the wind direction (WD) defined by equation (1) and wind speed. Vertical bars indicate the standard deviation of the mean. Day 0 is the day with the highest NO_2 concentrâtion exceeding 250 $\mu g\,m^{-3}$. The index for wind direction is 0 for winds coming from SW and becomes equal to 2 for winds coming from NE.

directions. It is worth mentioning that the standard deviations during day 0 (the day with the highest NO_2 concentration) are always smaller than the corresponding standard deviations during the other days indicating that there is a frequent meteorological pattern associated with high NO_2 concentrations.

In the following sections the discussion is confined to these variables which were found to affect significantly the success of the forecast. Other variables such as the ambient temperature near the surface, relative humidity, cloudiness, etc., were excluded, since their use did not improve the forecast.

3.1. *The* 850 hPa *air temperature*

Dilution by vertical mixing is confined within the boundary layer which is alternatively referred to as the mixing layer (Pasquill and Smith, 1983). In the daytime convective boundary layer, vertical diffusion is mainly carried out by large eddies limited by the height of the well-mixed layer. The height of the mixing layer is therefore an important scale in air pollution meteorology and a delicate task is the choice of location, time and method for mixing height determinations. Several authors (e.g. Lin, 1982) proposed that the study of the change of 850 hPa air temperatures may provide a rough measure of the stability of the layer above the Planetary Boundary Layer (PBL). The stability of this layer is of great importance in reducing the mixing height during the day and the 24 h temperature change at 850 hPa should be a rough measure of mixing height variations.

3.2. *Horizontal wind*

The basic meteorological parameters determining the horizontal transport and dispersion of air pollutants are the mean wind speed and the wind direction. In addition, mechanically produced turbulence contributes to vertical diffusion of pollutants in the lower part of the PBL.

The horizontal and vertical wind pattern is the combined result of thermally induced local circulation systems superposed on the mesoscale and synoptic wind field. The prevailing winds in the Athens basin are along the axis of the valley (either N–NE or S–SW). A semipersistent circulation system, consisting of a northern wind flow, is unique to the eastern Mediterranean during the warm part of the year. This system is called Etesians and in the Athens basin it appears as a north-easterly flow. During the appearance of the Etesians, the mean vector wind is strongest and gives maximum ventilation of the basin and thus pollution episodes are not favored. However, the weakening of the synoptic wind allows the development of local circulation systems, such as sea/land breezes along the axis of the basin (NE to SW) and anabatic/catabatic flows from the surrounding mountains. In such cases the ventilation of the basin is poor, the PBL is shallow and the air pollution potential increases. This is illustrated in Fig. 3, where the mean

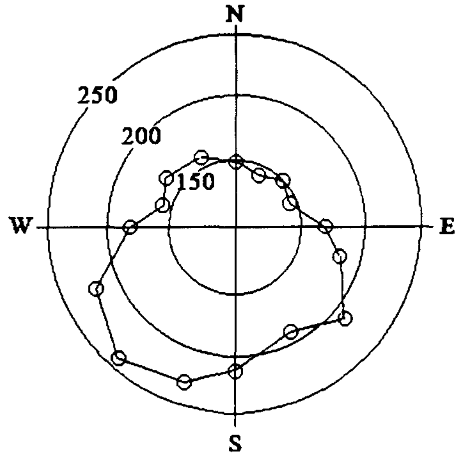


Fig. 3. The mean daily maximum NO_2 concentrations ($\mu g\, m^{-3}$) as a function of the corresponding prevailing wind direction.

daily maximum NO_2 concentrations are plotted as a function of the corresponding prevailing wind direction (determined from the wind direction at 13:00–14:00 h at NOA). In the calculation of the mean values, all days in the data set were used (four years of data). As shown in this figure, maximum NO_2 concentrations are observed when the wind is coming from the southwest, which is the prevailing wind direction under sea breeze conditions, while the NO_2 concentrations are significantly lower during northerly winds. It is also worth mentioning that the standard deviations are rather small ranging between 20 and 39% of the mean values.

In the present study we have selected the hourly mean wind speed at 08:00–09:00 h as a ventilation index because:

(i) Due to the city activities, the peak NO_x emissions from traffic occur a few hours after the sunrise.

(ii) If low winds are observed during the morning hours, there is an indication that the prevailing wind pattern shall be a southern see breeze circulation.

Since during the morning hours of a pollution episode day, the frequency of calms is rather high and so the wind direction cannot be accurately defined, it has been necessary to utilize the wind direction during some other hour of the day. For this purpose the prevailing wind direction at 13:00–14:00 h has been selected. Additionally, the purpose for selecting these hours is that the sea breeze is well established by that time.

Furthermore, instead of using the wind direction angle which is linear from 0 to 360°, being discontinuous at 360°, the wind direction index, WD (defined by equation (1)), has been selected as a measure of the wind direction suitable in the study. From the definition of this index it emerges that when the wind is SW then WD = 0 (minimum value of WD) and when the wind is NE then WD = 2 (maximum value of WD). These wind directions correspond to the maximum and minimum average NO_2 concentration, respectively (see Fig. 3).

3.3. *Precipitation*

Wash out by precipitation is a most effective process of removal of both particulate and chemical pollutants. However, there is not enough knowledge about the exact relation between the amount of rainfall and the dilution of pollutants and at the same time it is very difficult to forecast the exact amount of precipitation. For these reasons, in this study, we have used a precipitation index, which is based on empirical assumptions. The values of this index are presented in Table 1. When the same conditions (rain or no rain) are expected to prevail during both the day of interest and the previous day, then the precipitation index takes the value 0 which indicates negligible effects. When rain is expected during the day of interest and no rain was observed during the previous day, or *vice versa*, then the NO_2 concentrations are expected to decrease or increase, respectively (precipitation index = 0.1 or − 0.1, respectively).

3.4. *Persistency of high pollution levels*

Earlier studies (e.g. Robeson and Steyn, 1990) have shown that the possibility of occurrence of pollution episodes is increased if the previous day's pollution levels were higher than normal. This is also observed in the Athens area and is seriously taken into account for the empirical pollution forecast procedure performed by PERPA (Mantis *et al.*, 1990). This is attributed to the fact that pollution episodes are "built up" when meteorological conditions favoring high pollutant concentrations occur during successive days.

In the present study the maximum hourly concentration of NO_2 of the previous day is used in the analytical model as a parameter indicating the potential of a pollution episode for the next 24 h.

Table 1. The precipitation index used in the analytical expression (2)

Conditions	Index
Precipitation was observed during the previous day and precipitation is expected for the day of interest	0
No precipitation was observed during the previous day and precipitation is expected for the day of interest	0.1
No precipitation was observed during the previous day and no precipitation is expected for the day of interest	0
Precipitation was observed during the previous day and no precipitation is expected for the day of interest	− 0.1

3.5. *Short-term variation of emissions*

Pollution episodes are strongly related with the spatial and temporal distribution of emissions. This is more obvious when dealing with urban pollution, where the variability of the city activities induce a significant short-term variation of emissions. For example, even if the meteorological conditions are favoring the trapping of pollutants in the PBL, the pollution levels are lower during Sundays, compared with the pollution levels during working days.

In order to take into account this factor in the analytical model presented in this study, an index was introduced for the parametrization of the short-term variability of emissions and especially the traffic. The values of this index are presented in Table 2 and they correspond roughly to the ratio of the traffic volume of each day versus the week average traffic volume. Unfortunately, only a few sparse data are available which do not allow the accurate determination of the proposed index as a function of the traffic volume.

4. RESULTS AND DISCUSSION

4.1. *Forecast of the possible increase or decrease of NO_2 levels*

The first step followed in the present analysis has been the development of a simple analytical method for deciding whether the next day's maximum NO_2 concentration shall increase or not. For this purpose, we performed discriminant analysis which is a statistical technique to determine functions as linear combinations of a set of variables. More details about this technique can be found in Lin (1982). The goal is to achieve the maximum differentiation between groups. In our case, the single discriminant function separates the following two groups:

(a) the days during which the maximum NO_2 concentration, compared with the corresponding concentration of the previous day increased or remained essentially constant and

(b) the days that the maximum NO_2 concentration decreased by more than 20 $\mu g\ m^{-3}$.

The discriminating variables (predictors) used in the analysis were selected using the physical reasoning outlined in Section 3. The form of the discriminant function is

$$SC = Ca_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 + a_6X_6 + a_0, \quad (2)$$

Table 2. The index characterizing the short-term variability of the emissions

Day	Index
Mondays	1.2
Tuesdays, Wednesdays, Thursdays, Fridays	1.1
Saturdays	0.8
Sundays, and official holidays	0.7

where SC is the dimensionless discriminant score, X_1 is the previous day's maximum 1 h average NO_2 concentration ($\mu g\ m^{-3}$), X_2 is the difference of the 850 hPa temperature (°C) between the previous day and the day of interest (both at 14:00 LST), X_3 is an index indicating the short-term emission variations for the day of interest (see Table 2), X_4 is the index of the forecasted wind direction for the hours 13:00–14:00 of the day of interest, as calculated from equation (1), X_5 is the forecasted wind speed ($m\ s^{-1}$) for the hours 08:00–09:00 of the day of interest, X_6 is an index characterizing the effect of precipitation during the day of interest (see Table 1). C is a variable taking the value 1 when the previous day's maximum NO_2 concentration was $\leqslant 350\ \mu g\ m^{-3}$, or $C = 0$ when the maximum NO_2 was $> 350\ \mu g\ m^{-3}$. The limit of $350\ \mu g\ m^{-3}$ has been selected empirically because it was found that when the previous day's maximum concentration exceeded $350\ \mu g\ m^{-3}$ this variable is not important any longer and therefore it is excluded from the equations ($C = 0$). $a_1, a_2, a_3, a_4, a_5, a_6, a_0$ are the discriminant coefficients calculated using the above-described discriminant variables, for the period 1987–89. The software package STATGRAPHICS (STSC, Inc.) was employed to carry out the discriminant analysis. In Table 3 the value of each discriminant coefficient depending on the value of the variable C, as well as the group centroids, are presented. In order to predict whether the next day's NO_2 concentration is expected to increase or decrease, the next steps should be followed:

(a) Selection of the model to be used. As already mentioned, the selection is based on whether the previous day's maximum NO_2 was greater or less than $350\ \mu g\ m^{-3}$ ($C = 0$ or $C = 1$, respectively).

(b) Calculation of the discriminant score SC according to equation (2).

(c) The next day's maximum NO_2 concentration is expected to increase or decrease depending on the distance of SC from the corresponding group centroids.

The evaluation of the above-described methodology, performed for the test year 1990, showed an average percentage of successful forecasts of about 80%. More details are given in the contingency Table 4.

In order to evaluate the relative importance of the controlling variables we constructed different models by alternatively excluding each one of these variables. The results are presented in Table 5. From this table it is recognized that the previous day's maximum concentration is the most important variable, while all the other controlling variables provide only a slight improvement. However, the combined effect of the other variables is very important and when excluding all of them from the derived equation the percentage of successful forecasts is reduced to 68% (when the previous day's maximum NO_2 concentration was less than $350\ \mu g\ m^{-3}$). As it was mentioned before, when the previous day's maximum concentration exceeds $350\ \mu g\ m^{-3}$, this variable is not included in the equation.

4.2. *Estimation of the next day's maximum* NO_2 *concentration*

In order to provide a quantitative estimation of next day's maximum mean hourly NO_2 concentration a multiple regression analysis was performed. From this analysis two relationships were derived. The first may be used for calculating next day's maximum NO_2 when an increase in pollution levels is expected. The

Table 3. Discriminant coefficients and the group centroids for the different models

	$C = 1$	$C = 0$
a_1	0.01856	0.00000
a_2	− 0.03862	0.27458
a_3	− 1.72250	0.22272
a_4	0.53589	− 0.52500
a_5	0.08871	0.26457
a_6	− 4.43525	9.99997
a_0	− 2.50986	− 0.66647
Increase group centroid	− 0.41653	1.16971
Decrease group centroid	1.08016	− 0.21527
Mean value of group centroids	0.33182	0.47712

Table 4. Number of days where the hourly maximum NO_2 concentration increased or decreased when compared to the corresponding of the previous day. Only data from the test year 1990 are used

	Observations (number of days)	Model (number of days)
Increasing NO_2 levels	117	114
Decreasing NO_2 levels	79	83

Table 5. Performance of different models constructed by excluding alternatively the controlling variables

Variable excluded	Successful forecasts (%)
None	80
Previous day's maximum concentration	69
Temperature change at 850 hPa	78
Index for the short-term variability of the emissions	79
Wind direction index	78
Wind speed	79
Precipitation index	79

second relationship applies when a decrease of NO_2 maximum concentration is expected. The decision of whether an increase is expected or not may be based either on discriminant analysis (see Section 4.1) or on any other method (e.g. subjective judgment by an experienced scientist).

It should be noted that the analysis revealed that not all the variables presented in Section 3 improved significantly the accuracy of the prediction. For this reason some of these variables were excluded from the final regression models. The derived analytical formulas are:

$$\max[NO_2] = 0.9604X_1 + 1.3681X_2 + 77.0855X_3 - 21.0069X_4 - 12.2 \quad \text{(increase)}, \quad (3)$$

$$\max[NO_2] = 0.4130X_1 + 2.1042X_2 + 33.0867X_3 - 11.0700X_4 - 5.3509X_5 + 57.0 \quad \text{(decrease)}, \quad (4)$$

where max $[NO_2]$ is the forecasted maximum mean hourly NO_2 concentration ($\mu g\ m^{-3}$) of the next day and X_1–X_5 are the discriminating variables defined in Section 4.1. As already mentioned, the coefficients in equations (3) and (4) were calculated using data from the period 1987–89 (see also Section 2). The values of these coefficients were found to be consistent with the physical effect of the respective variables, as outlined in Section 3.

These analytical models were evaluated against maximum NO_2 concentrations observed at the Patision station, during the test year 1990. It is clear that the accuracy of the present method heavily relies on the correct forecast of whether the daily maximum concentration of NO_2 will increase or decrease. For example, the comparison between forecasted and measured maximum NO_2 concentrations (for the year 1990) are shown in Figs 4a and b for days of decrease and increase, respectively. The results presented in these figures were derived by using equations (3) and (4), while the increase or decrease was considered *a priori* known. Although there is a slight tendency for underestimating high observed concentrations, the agreement between observed and predicted values is generally good. More specifically for days when an increase occurred, the correlation coefficient is 0.81, while for days with decrease it is 0.76. The root mean square error (RMSE) values are 45 $\mu g\ m^{-3}$ for days when pollution levels increased and 35 $\mu g\ m^{-3}$ for days when a decrease occurred.

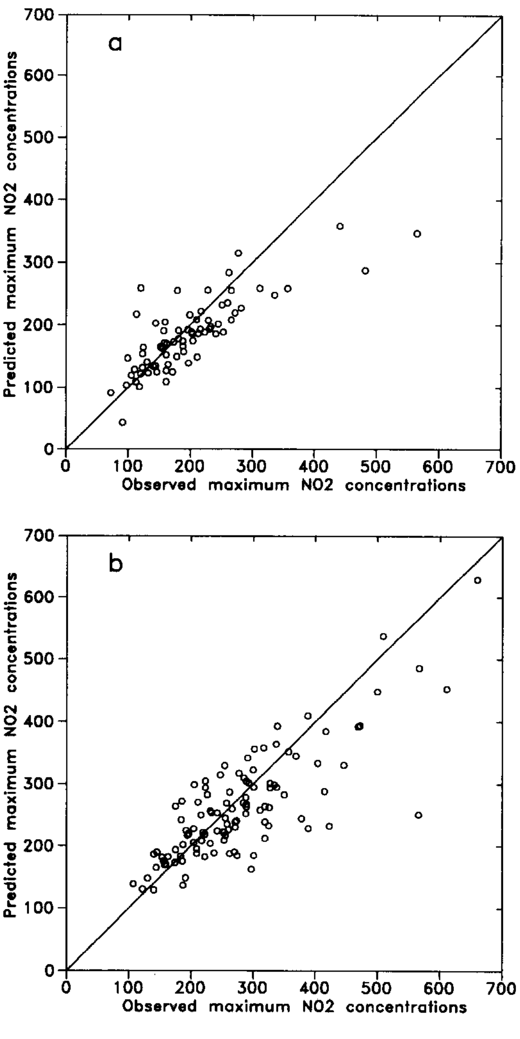
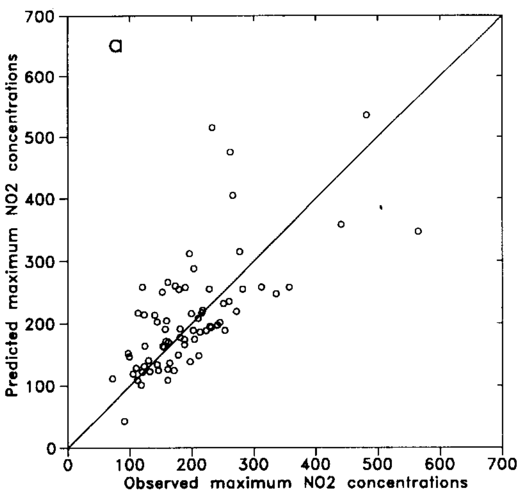


Fig. 4. Model evaluation for days when the maximum NO_2 is expected to decrease (a) or increase (b) when compared to the concentration of the previous day. The discrimination between increase and decrease days was based on observations.

For comparison purposes, respective results are shown in Figs 5a and b but this time the increase or decrease of the NO_2 concentrations was judged following the methodology described in Section 4.1. As it appears from these figures, the agreement between forecasts and observation is slightly worse ($r = 0.72$ and $r = 0.68$ for Figs 5a and b, respectively), but still encouraging. The RMSE is 51 $\mu g\,m^{-3}$ for days when an increase in pollution levels is expected and 72 $\mu g\,m^{-3}$ for days when a decrease is expected.

Some more illustrative examples for two episode periods, 10 May–29 May 1990 and 1 July–7 July 1990 are shown in Figs 6 and 7, respectively. In these figures forecasted maximum NO_2 concentrations (asterisks), calculated by means of equations (3) and (4) are plotted together with observations (solid curve). Whether a decrease or an increase occurred was considered *a priori* known. For comparison, in the same figures the respective results (circles) are shown for the same time periods but this time calculated by first making the discrimination between increase or decrease days by using the methodology described in Section 4.1. As it appears from these figures the agreement between forecasted and observed maximum NO_2 concentrations is rather good, regardless of whether the increase or decrease was known or predicted. In any case, according to our opinion, the accuracy of the predictions must be considered sufficient for operational use.



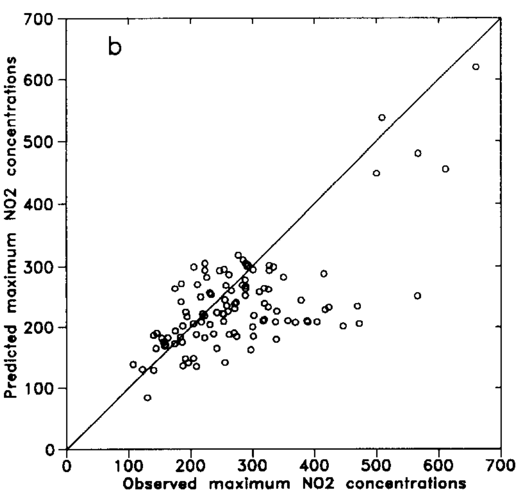


Fig. 5. Same as in Fig. 4 but this time the increase or decrease of the NO_2 concentrations was judged following the methodology described in Section 4.1.

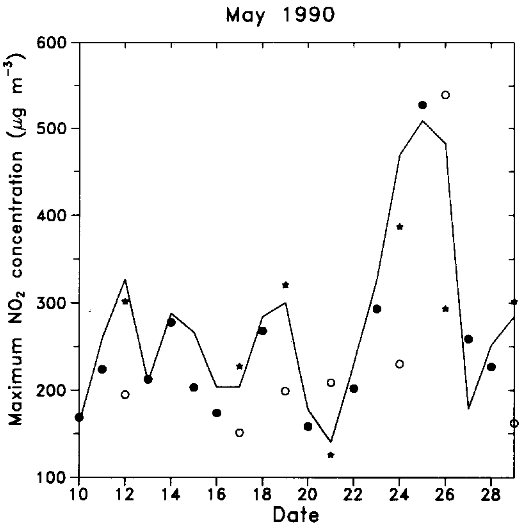


Fig. 6. Time series of maximum NO_2 concentrations at Patision station for the period 10–29 May 1990. (Solid line: observations, circles: predictions based on equations (3) and (4) when the possible increase or decrease was based on equation (2), asterisk: predictions based on equations (3) and (4) when the possible increase or decrease was considered as *a priori* known.)

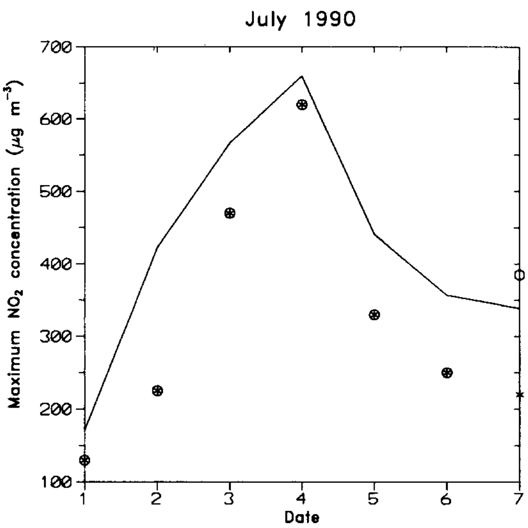


Fig. 7. Same as Fig. 6 but for the period 1–7 July 1990.

5. CONCLUDING REMARKS

In the present paper, there are presented analytical models in order to:

(a) discriminate days in which an increase of maximum NO_2 concentrations was observed from those in which a decrease occurred (equation (2));

(b) calculate the maximum NO_2 concentration of the next day (equations (3) and (4)).

It was found that the use of simple meteorological variables, available from routine measurements, together with pollution measurements, may give rather good predictions. The final model equations derived are simple and they can be used easily for operational forecasts from the air quality management authorities. The evaluation of the developed forecasting models showed that their degree of success is rather promising. It is therefore expected that the use of the developed analytical models together with other prognostic systems will enable the responsible authorities to issue warnings and take restrictive measures in advance.

When using the analytical models presented in this study operationally, the success of the predictions, depends strongly on the accuracy of the meteorological forecast. However, since forecasted meteorological data were not available, this factor of uncertainty was not possible to be further examined in our study.

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