Computation of long-term average SO_2 concentration in the Venetian area

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(Received 18 February 1976)

This study tests the possibility of describing the dispersion of a non-reactive atmospheric pollutant in a complex coastal zone, such as the Venetian area, by means of a Gaussian type diffusion model. The basic assumption of the model is that the pollutant has a Gaussian distribution along the vertical and is uniformly distributed crosswind in each sector of the wind rose. With the use of meteorological data recorded on an hourly basis and average evaluation of urban and industrial emission, three-monthly average SO_2 concentrations as well as the annual ones were computed for the period February 1973 to January 1975. The surface roughness and the heat island effect have been taken into account by modifying Pasquill's stability classification. The results were compared with the concentration values recorded at ten monitoring stations. The general agreement between the model results and the measured data proved the validity of the applied technique for simulating long-term average concentrations and its applicability for land planning purposes.

Introduction

The problem of the dispersion of a non-reactive gaseous pollutant released in the atmosphere has been extensively investigated during recent years because of the occurrence of high pollution levels both in industrial and urban areas, causing damage to the environment and to human health.

The main purpose of such investigations is the formulation of a model relating the concentrations of air pollutants to the rate of emissions as well as to the meteorological conditions and local effects due to the geography of the area and the position of the sources.

The dilution of non-reactive gaseous effluents is mainly affected by the state of turbulence of the lower atmosphere, which is not yet a very well understood phenomenon. Therefore, semi-empirical models have been developed in order to calculate the dispersion of a pollutant. Of these models, the most known one is based on the formulation that Sutton[1] proposed by developing Taylor's statistical concepts and is at present commonly known as 'Gaussian plume model'[2]. Such a formulation has been used with more or less significant modifications by several authors in order to compute short-term average SO_2 concentrations, i.e. hourly concentrations[3] and daily concentrations[4] as well as long-term average SO_2 concentrations, i.e. monthly[5] and seasonal[6,7].

The models developed up to now have proved to work well in situations in which the parameters affecting the dispersion were rather uniform over the whole area of application. In more complicated areas, on the other hand, further implementations of diffusion models are needed in order to formulate a satisfactorily precise idea of their reliability as well as of their limits. Venice and its surroundings are a typical example of an area in which dispersion of atmospheric pollutants is greatly affected by the non-uniformity of its geographic characteristics. Furthermore, the study of the air pollution problem in Venice is made urgent by the damage that pollution causes to its priceless artistic patrimony.

For the above reasons the applicability of a Gaussian type model for computing three-monthly and annual average concentration in the Venetian area has been tested.

Area of interest

The investigated area (*Figure 1*) is situated at the eastern side of the Padana Plain. This area includes a part of the Venetian Lagoon, which is located in the north-eastern side of Italy at the upper shore of the Adriatic Sea, from which it is separated by two narrow strips of land: The Lido and Pellestrina.

It consists of the urban centres of Mestre, Marghera and Venice and of the largely industrialized area of Porto Marghera. The urban centres of Mestre and Marghera are situated in the mainland and cover a surface of about

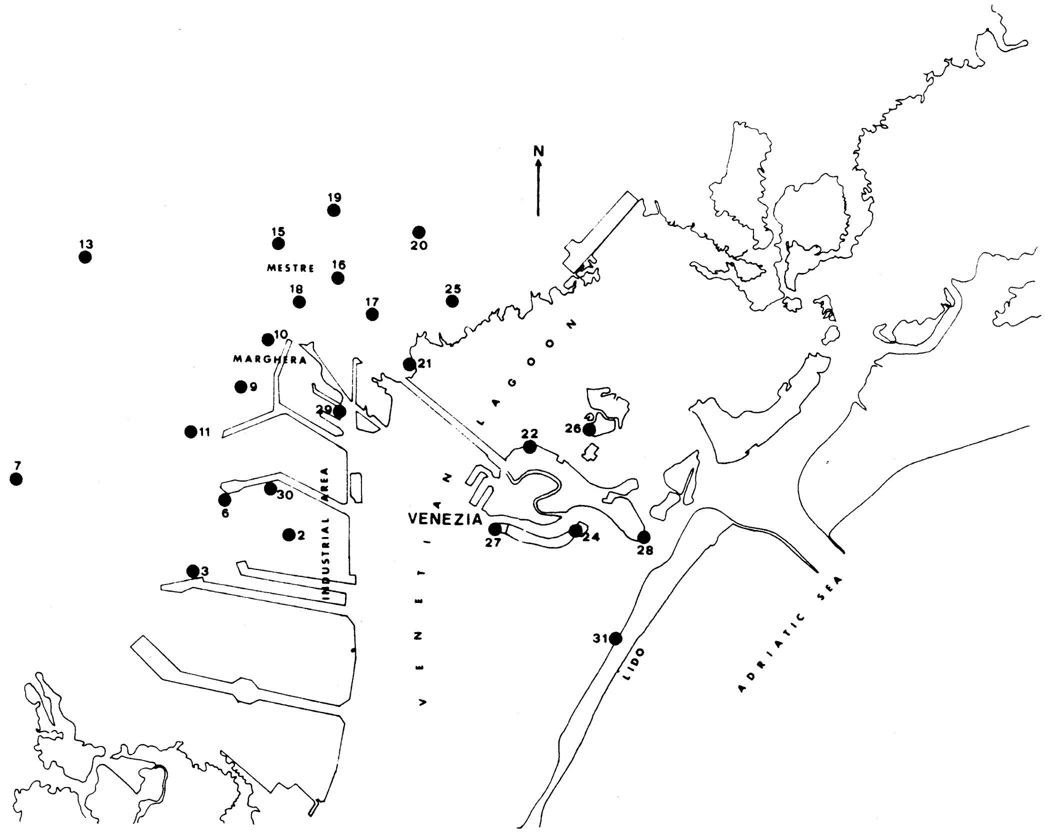

Figure 1 Venetian area. • indicates the location of the SO_2 monitoring stations (2, 6, 9, 10, 16, 17, 22, 24, 29, 30 were operating since Feb. 1973)

10 km². Close to them a large industrial area of about 22 km² is found, whose main activities concern oil-refining, petrochemicals production, production of electric energy, metallurgy of iron and other metals.

Five kilometers from the mainland, in the middle of the lagoon is the historical centre of Venice, standing on a cluster of small islands separated by a network of small canals and interconnected by many bridges. Owing to such a peculiar situation and to its history the urban texture has undergone neither significant modifications nor the growth typical of other cities. Its surface area is of about 6 km².

The presence of the above mentioned urban and industrial settlements causes great variations in surface roughness and large heat fluxes, which strongly influence the dynamics and the state of turbulence of the atmosphere. In addition, the contiguity of different surfaces (i.e. land–lagoon and sea) produces breeze-effects which interact with the general meteorological situation. Therefore, the description of atmospheric pollutant dispersion in such an area cannot be achieved in full detail by applying a simple model such as the Gaussian one. For these reasons the application of a model based on Gaussian formulation can be oriented only towards a simulation of the average aspects of the phenomenon, i.e. the computation of seasonal and annual average concentration.

Data

The application of a diffusion model for simulating the concentration field in a certain area requires the knowledge of data concerning the emissions and of meteorology. On the other hand, data concerning the pollution level are needed in order to test the validity of the model.

Industrial emissions

In accordance with the National Law on Pollution promulgated on 15 April 1971, an inventory of SO_2 emissions resulting from industrial activities was carried out in 1972 by the local government. The inventory led to the identification of 74 main continuously emitting stacks and to the estimation of their average emission rates. The range of the heights of such sources varies from 10 to 120 m and the overall SO_2 emission is of 160 000 tonnes per year.

The knowledge of the average emission rate is obviously an error source in the computation, but since the model was oriented towards the calculation of long-term average concentrations it can be assumed that the time variation of the emissions would not greatly affect the applicability of the model.

Urban emission

Evaluation of the emissions. In order to evaluate the spatial distribution of domestic heating, emissions data gathered in the last national general census, taken in 1972, were used. In the special form used on that occasion people were required to indicate the type of fuel used in their domestic heating system. The urban districts of the Venetian area were divided into 272 sections (*Figure 2*) for each of which the number of inhabitants as well as the

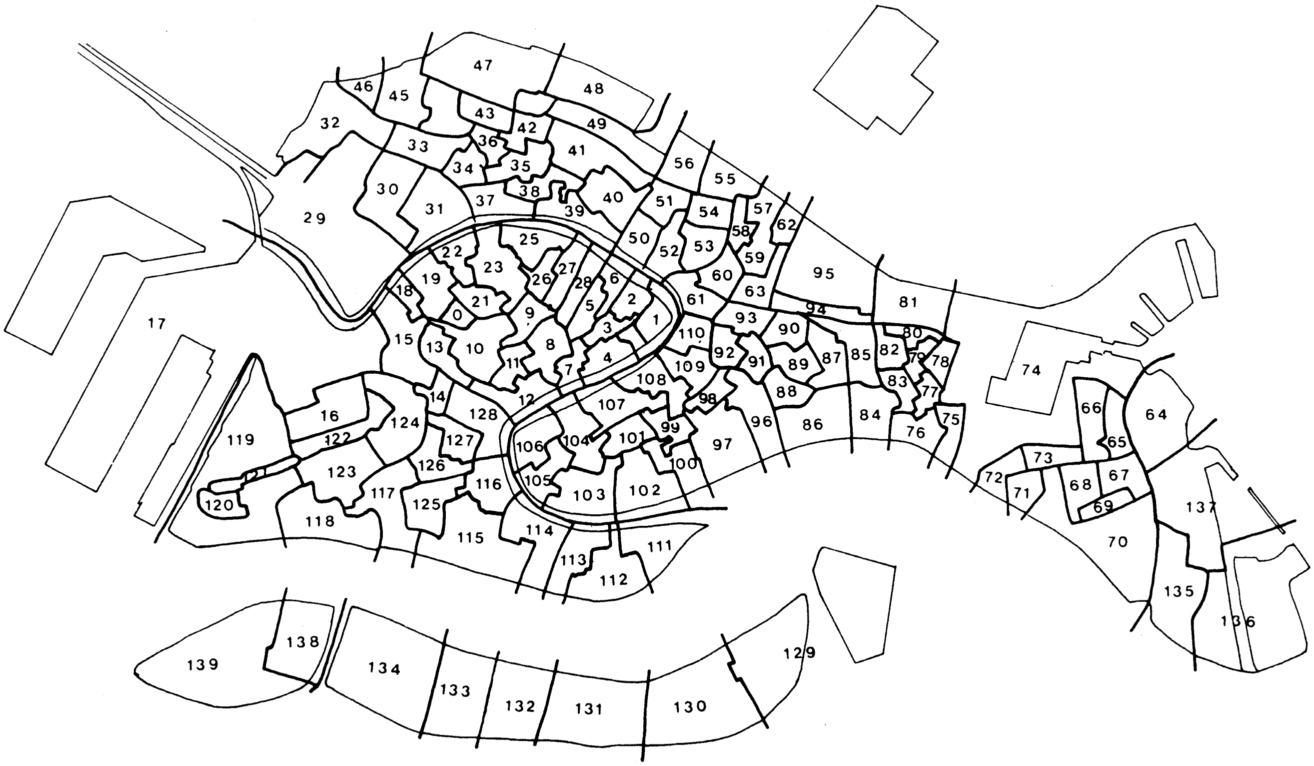

Figure 2 Map of the historical centre subdivided into census sections

various percentages regarding the use of different fuels were determined.

The fuels used in the Venetian area for urban activities are natural gas, oil, coal and wood. Since only the overall consumption of natural gas was known, the problem arose of determining the consumption of the other fuels in order to evaluate the urban emission of sulphur dioxide. The solution was found by defining an 'individual thermal consumption', i.e. the average yearly number of calories required by an individual, which was evaluated on the basis of the consumption of natural gas for which a good estimate was known.

Such an 'individual thermal consumption' made it possible to calculate the total consumption of other fuels (the polluting ones such as oil, coal, etc.) as well as the overall yearly emission of SO_2 for each of the 272 sections considered. The computed values turned out to be in good agreement with the estimates made by the fuel wholesalers (personal communications).

Distribution in time of the emissions. The distribution in time of the domestic heating emissions was achieved on the basis of the concept of day/degree. A day/degree (*dd*) is defined, as is well-known, by:

$$dd = T_b - \frac{\sum_{i=1}^{24} T_{h,i}}{24}$$

where T_b is the temperature at which heating starts, and $T_{h,i}$ is the average hourly temperature at ith hour of the day. For the Venetian area $T_b = 15.5°C$. The total number of days/degree was computed for the whole year as well as the number of days/degree for every month of the year.

In order to evaluate the SO_2 emission rate of the ith section during a certain period for which the model should be run the following equation was applied:

$$q_i = \frac{E_i g}{G N_s}$$

where q_i is the emission rate of the ith section in the considered period (kg/sec)

E_i is the yearly amount of SO_2 emitted by the ith section (kg)

g is the number of *dd* in the considered period (°C)

G the total number of *dd* in a year (°C)

N_s number of seconds in the considered period

Every area emission was introduced in the model as an equivalent constant strength point source, located in the barycentre of the corresponding section. The height of the urban emissions, including plume rise, was estimated to be ~ 30m for the historical centre of Venice (where the buildings are generally old and low) and ~ 45 m for the urban areas of the mainland, which have developed during the last three decades and show taller buildings.

Meteorological and concentration data

Both the meteorological and concentration data used for the application of the model have been provided by the monitoring network that Tecneco (*Figure 1*) has installed in the Venetian area by appointment of the Istituto Superiore di Sanità (Governmental Department of Health). This network consists of one meteorological station and 24 SO_2-monitoring sensors.

The meteorological station, situated in the historical centre, 15 m above the ground, records on an hourly basis the speed and direction of wind, temperature, pressure, humidity, rainfall, cloud amount and fog. Wind direction is recorded according to the eight sectors of the compass, which introduces an indetermination of ± 22° 30′ into the measure. As a consequence of this approximation the model can only be used for the computation of concentration average over a long period (i.e. a season or a year), for which the assumption of a uniform distribution of wind direction in each sector is correct.

Concentration data recorded by the 24 monitoring sensors are transmitted to a small computer which elaborates the data and prints the hourly average values as well as daily statistics. In addition, every time the 30 min average SO_2-concentration 'standard' (0.30 ppm) imposed by Italian law is exceeded in a station the computer gives an alert. Since only 10 stations were regularly operating from February 1973, the model has been tested on the data recorded by them for the period February 1973 to January 1975. Nevertheless, some results will also be given for the other operating sensors in the year 1974.

Diffusion equation

For the computation of the concentration at a receptor point P, at ground level, owing to a certain distribution of N point sources, the following formula was used:

$$C_p = \left(\frac{2}{\pi}\right)^{3/2} \sum_{k=1}^{N} \frac{Q_k}{D_{p,k}} \sum_{\substack{id=1\\ iw=1\\ is=1\\ it=1}}^{8,6,6,4} \frac{F(id, iw, is, it)}{u(id, iw, is, it) S_z(D_{p,k}, is)} \times \left[\Lambda\left\{-\frac{h}{2H}, \frac{S_z^2}{2H^2}\right\} + \Lambda\left\{\frac{h}{2H}, \frac{S_z^2}{2H^2}\right\}\right] \quad (1)$$

where the function Λ is defined by:

$$\Lambda\left(\frac{h}{2H}, \frac{S_z^2}{2H^2}\right) = \sum_{n=-\infty}^{+\infty} \exp\left\{-\frac{(h(u,T)/2H + n)^2}{S_z^2(D_{p,k}, is)/2H^2}\right\} \quad (2)$$

and the symbols have the following meaning:

- C_p concentration at receptor point (μg/Nm^3),
- Q_k emission rate of the kth source (μg/Nm^3),
- N number of sources (industrial and urban),
- $D_{p,k}$ distance of point P from the kth source, projected on the wind direction (m),
- S_z vertical standard deviation obtained from Pasquill's graphs[8] (m),
- $F(id, iw, is, it)$ frequency of wind blowing into a given 45° sector of the compass (id), for a given wind speed class (iw), atmospheric stability class (is) and temperature class (it),
- $u(id, iw, is, it)$ representative wind speed for a given meteorological situation having a frequency $F(id, iw, is, it)$ (m/s),
- $T(id, iw, is, it)$ representative temperature for a given meteorological situation having a frequency $F(id, iw, is, it)$ (°C),
- h effective height of the kth source (m),
- H inversion layer depth (m).

Equation (1) is the classical Gaussian plume formula[2], written according to the proposal of Martin[6] and Calder[7], which has been modified here by the introduction of a fourth parameter, air temperature, into the joint frequency distribution of meteorological conditions. This has been done in order to take into account the influence of air temperature on the plume rise.

The above mentioned hourly meteorological data were used to determine the joint frequency distribution of meteorological conditions.

As to wind speed the following six classes were used:

0 ⟶ 1.57, 1.57 ⟶ 3.14, 3.14 ⟶ 5.24,

5.24 ⟶ 8.38, 8.38 ⟶ 11.0

and greater than 11 m/s; the representative speed $u(id, iw, is, it)$ was computed as the arithmetic mean of the measured values in a meteorological situation having a frequency $F(id, iw, is, it)$. In order to take into account the variation of the wind speed with the height, an exponential law was used, whose exponent was assumed equal to 0.25 for neutral and unstable classes and equal to 0.5 for the stable ones. Although low wind speed were the most frequent ones, frequencies of calms were so low that it was decided to disregard them. Wind directions were grouped into 8 classes corresponding to the standard 8 compass-directions (N, NE, ... , NW).

Atmospheric stabilities were grouped into 6 classes as Pasquill suggested by performing experiments in a flat and open area[2]. Pasquill's categories can therefore result in being inadequate to characterize the atmospheric stability of a more complex area. However, since no better criteria for defining atmospheric stabilities are available, as a first step the computation was carried out by assuming that Pasquill's criteria could be applied to the Venetian area.

As a further step a modification of Pasquill's categories, based on empirical considerations, was introduced in order to take into account the effects of surface non-uniformity and heat islands on the atmospheric turbulence state. Stability was diversified for every receptor point as a function of wind direction and time of day (day/night). For winds blowing from areas showing changes in surface roughness and fluxes of heat, the stability was moved towards the next unstable class (sometimes it was moved by two classes). For station 29, for instance, the stability was modified as follows:

Direction	N	NE	E	SE	S	SW	W	NW
Day	1	1	1	0	1	1	1	1
Night	2	2	2	1	2	1	2	1

(Digit 1 means one-class move towards instability)

The changes proposed for station 29 depend on its location at the centre of a highly industrialized area where, mainly in the night, atmospheric stability cannot be described by Pasquill's criteria, which assume that a neutral condition cannot be exceeded. Therefore, for some wind directions the stability in the night was moved by two towards unstable classes.

As to air temperature, the following classes were introduced: less than 0, 0→10, 10→20, and greater than 20°C; the representative temperature $T(id, iw, is, it)$ has been evaluated as the arithmetic mean of the measured values in a meteorological situation of frequency $F(id, iw, is, it)$. The effective height has been calculated according to the equation

$$h = h_g + \Delta h$$

where h_g is the geometrical height of the source, and Δh is the plume rise. The plume rise Δh has been evaluated by using the formula proposed by Concawe[9]:

$$\Delta h = 0.047 \frac{Q_h^{0.56}}{u^{0.76}}$$

where Q_h is the heat rate (cal/sec), defined as $Q_h = c_p Q_v \times (T_g - T_a)$, where c_p = specific heat at constant pressure of effluent gases (cal/m^3 °C); Q_v = overall emission rate (Nm^3/sec); T_g = gas temperature (°C); T_a = air temperature (°C).

Since no suitable information was available the height of the inversion layer was not introduced in the model, consequently equation (2) reduces to:

$$\Lambda \left(\frac{h}{2H}, \frac{S_z^2}{2H^2} \right) = \exp \left\{ - \frac{h^2(u,T)}{2S_z^2\,(D_{p,k}, is)} \right\} \qquad (3)$$

which is the case of an infinite mixing height. Besides it was assumed that the decay rate of SO_2 could be disregarded for the purpose of this computation.

Results

The monitoring stations were divided into three groups according to their geographical location. *Figures 3–5* show measured three-monthly average concentration as well as the calculated one for two stations chosen out of each group. *Figure 3* refers to sensors 6 and 30, located at the southern edge of the industrial area, while stations 10 and 29 (*Figure 4*) are situated between the industrial area and the urban centres of Mestre and Marghera and finally *Figure 5* shows the results for sensors 16 and 22 located in Mestre and in Venice respectively.

The plots reproduce the computed values obtained both by classifying the atmospheric stability according to Pasquill's criteria and by modifying such a classification as discussed above. The model simulates fairly well the spatial distribution as well as the time evolution of the concentration field. A strong improvement can be observed for station 29 owing to the introduction of the modified Pasquill's classification of stability.

Such results lead to the conclusion that a classification of stability adequate to the Venetian area is needed in order to obtain more satisfactory results with the application of a Gaussian model. In addition, it must be pointed out that for stations very close to the strongest emissions such as 10 and 29 noticeable errors are introduced by possible inaccuracies in the evaluation of their mutual locations.

The model was also used to calculate annual average SO_2 concentration for the years 1973 and 1974; the relative results are plotted with the experimental ones in

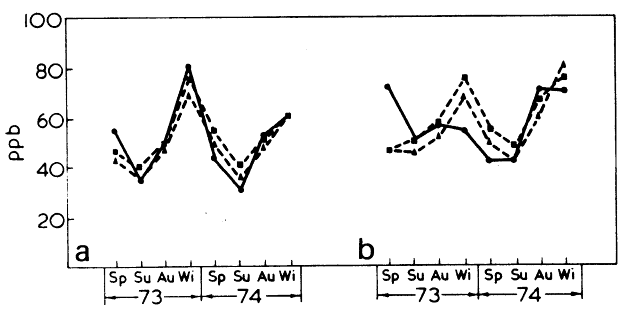

Figure 3 Observed and calculated three-monthly average SO_2 concentration at stations 6 (a) and 30 (b) (Sp: March, April, May; Su: June, July, August; Au: September, October, November; Wi: December, January, February). ●, observed; ▲, calculated (Pasquill's categories); ■, calculated (modified Pasquill's categories)

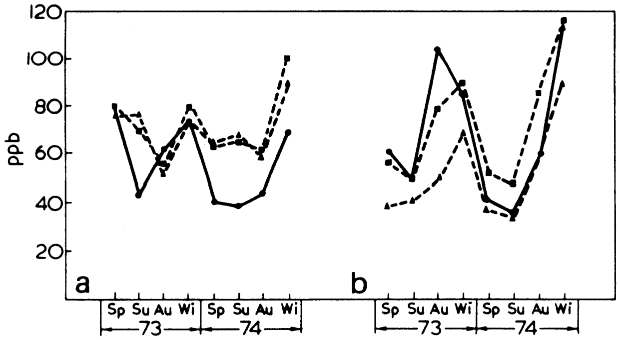

Figure 4 Observed and calculated three-monthly average SO_2 concentration at stations 10 (a) and 29 (b) (symbols as in *Figure 3*)

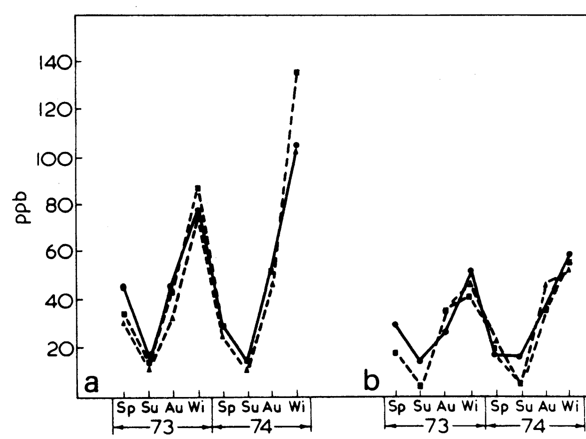

Figure 5 Observed and calculated three-monthly average SO_2 concentration at stations 16 (a) and 22 (b) (symbols as in *Figure 3*)

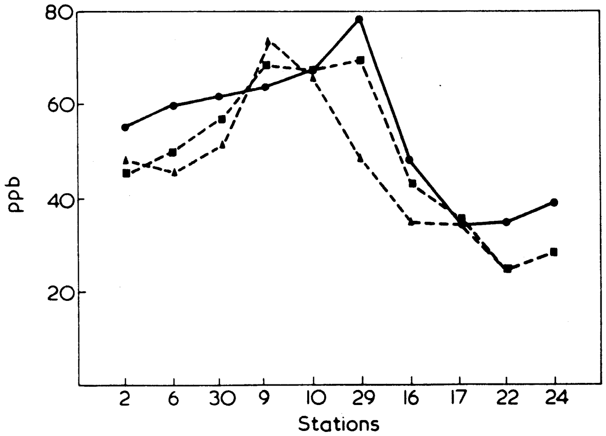

Figure 6 Observed and calculated annual average SO_2 concentration for the year 1973 (symbols as in *Figure 3*)

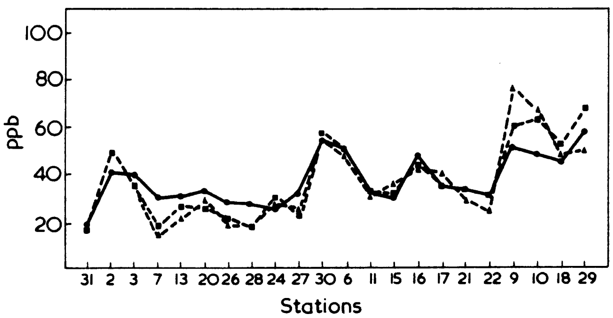

Figure 7 Observed and calculated annual average SO_2 concentration for the year 1974 (symbols as in *Figure 3*)

Table 1 Correlation coefficients and slopes and intercepts of the regression lines

	1973		1974	
	Modified	Unmodified	Modified	Unmodified
		Correlation coefficient		
Annual	0.940	0.743	0.927	0.845
Three-monthly	0.809	0.718	0.880	0.799
		Slope of the regression line (measured vs. calculated)		
Annual	0.862	0.715	0.607	0.540
Three-monthly	0.741	0.675	0.668	0.659
		Intercept of the regression line (ppb)		
Annual	12	22	14	18
Three-monthly	14	19	8	10

Figures 6 and *7*. As was expected, the model proved to give better results if the period of calculation was extended.

The correlation coefficients as well as the slopes and intercepts of the regression lines have been computed for three-monthly and annual averages. The results are summarized in *Table 1*.

The encouraging results obtained by applying the model led to extending the calculations over the whole area of interest in order to get a visible description of the spatial distribution of the pollutant. This made it possible to draw the isolines of concentration, shown in *Figures 8* and *9*, for the periods June–August 1973 and December 1973 to February 1974, respectively. By comparing the two maps the conclusion can easily be drawn that because of the local meteorological conditions[10], in summer SO_2 'keeps away' from the historical centre, and concentrates itself near the industrial sources. In winter, the different meteorology prevailing over the area, as well as the presence of urban emissions causes a wider spread of the SO_2 and consequently raises the pollution level in the urban centre of Venice.

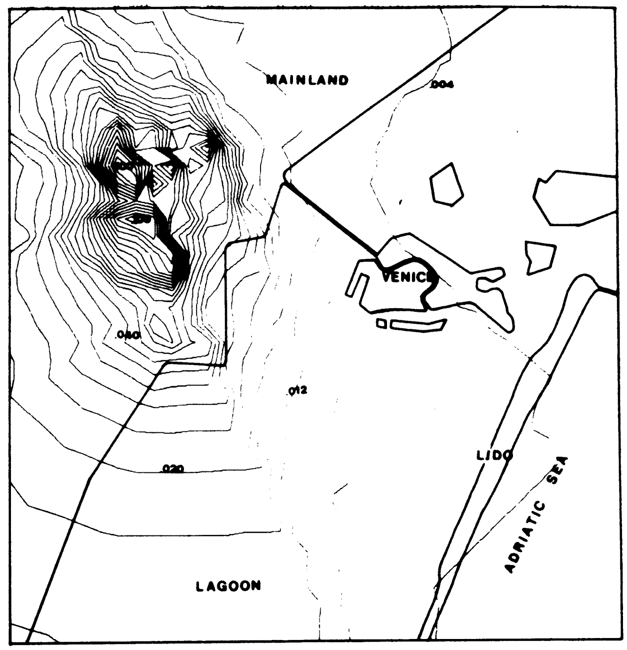

Figure 8 Isolines of average SO_2 concentration for the period June–August 1973 (concentration values are in ppm)

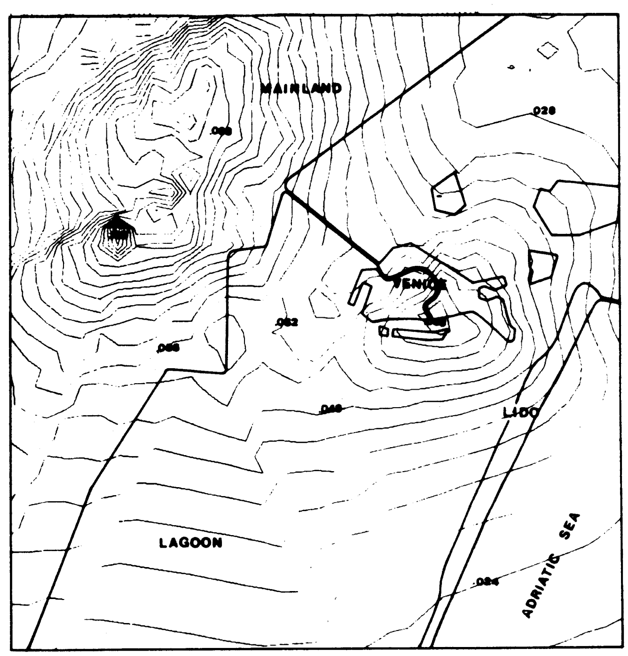

Figure 9 Isolines of average SO_2 concentration for the period December 1973–February 1974 (concentration values are in ppm)

Conclusions

The application of a Gaussian-type model for computing long-term average SO_2 concentration in Venice and its surroundings has been presented. Although it is difficult to describe the local meteorology, the choice of characterizing the atmospheric stabilities according to Pasquill's categories as well as the assumptions concerning height variation of the wind and the plume rise proved to be satisfactory. Since the obtained results showed that the seasonal patterns of SO_2 concentration can be described by the model, it has been used to illustrate the influence of seasonal climate on the SO_2 dispersion over the area and the contributions of urban and industrial emissions to the pollution level in the historical centre of Venice.

Improvements can be brought to the model by introducing in it a proper definition of the atmospheric stabilities on the basis of a more detailed knowledge of the local meteorology as well as by better defining the industrial emissions rates and locations. In such a way the model would become a valid tool for land planning purposes and for optimizing the monitoring network.

Acknowledgements

The authors are indebted to Tecneco, Regione Veneta, Coses and Veneziana Gas which supplied the basic data used in this study.

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