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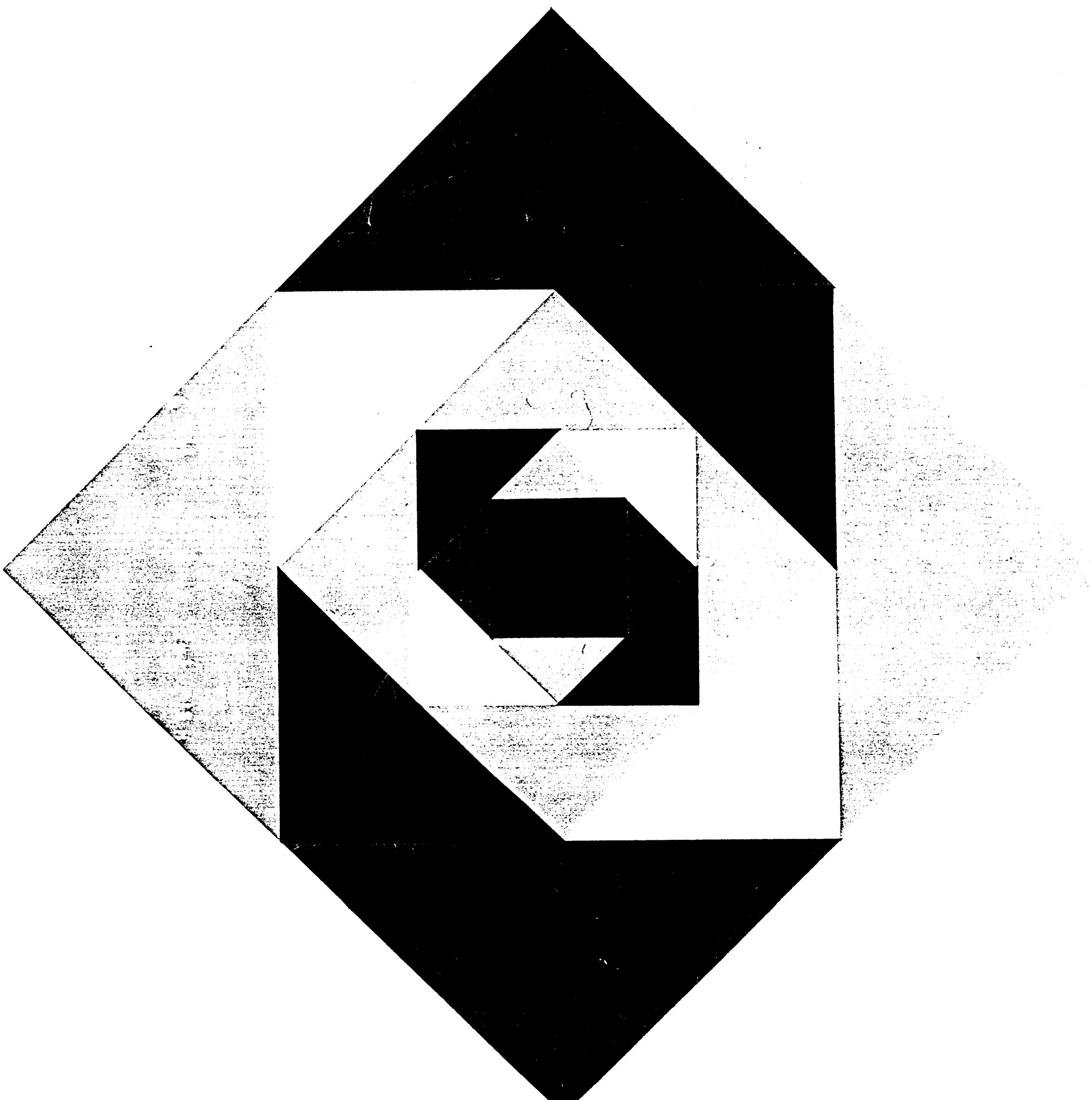

Seminar on Air Pollution Modelling

AN APPLICATION OF AIR POLLUTION MODELS TO THE VENETIAN AREA

by

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ABSTRACT

This study tests the possibility of simulating the dispersion of a non-reactive atmospheric pollutant in a complex coastal zone, such as the Venetian Area, by means of a diffusion model.

The simulation is carried out by developing two different models. One is a Gaussian type model, the other one is based on the numerical integration of the diffusion equation written according to the K-theory.

The basic assumption of the Gaussian 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 emissions, SO_2 three-monthly average concentrations, as well as the annual ones, were computed for the period Feb.'73-Jan.'75. The surface roughness changes and the heat islands effects 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.

The model based on K-theory integrates the time-dependent diffusion-convection equation according to the method of fractional steps. It has been designed with the purpose of simulating short term SO_2 average concentrations and complementing the Gaussian model.

The implemented numerical technique allows for variable grid spacing and time steps. Comparison between numerical and analytical solutions, as well as preliminary applications for simulating the real phenomenon in the Venetian Area, proved enough satisfactory.

INTRODUCTION

The problem of the dispersion of a non-reactive gaseous pollutant released in the atmosphere has been extensively investigated during the last 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 air pollutants concentrations 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 effluents is mainly affected by the state of turbulence of the lower atmosphere, which is not yet a very well understood phenomenon. Therefore semiempirical 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 (1932-1947) proposed by developing Taylor's statistical concepts (1935) and is at present commonly known as "Gaussian plume model" (Pasquill 1962). 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 (Shieh 1971) and daily concentrations (Turner, 1964) as well as long term average SO_2 concentrations, i.e. monthly (Pooler, 1961) and seasonal (Martin, 197 and Calder, 1971).

The models up to now developed 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 contrary, 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.

In order to give a practical contribution to this problem an application of diffusion models is being carried out. The problem was tackled by applying, as a preliminary attempt, a Gaussian type model, by which three -monthly average concentrations, as well as the annual ones, were simulated for the years 1973 and 1974. The results obtained are discussed in the first part of this presentation, after which a diffusion model based on the numerical integration of the diffusion-convection equation, written according to the K-theory, will be analyzed. Such a model was built in order to take into account the local characteristics which cannot be included in the previous model.

AREA OF INTEREST

The investigated Area (fig.1) is situated at the Eastern side of the Padana Plain. This area includes a part of the Veneta 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 centers of Mestre, Marghera and Venice and of the largely industrialized area of Porto Marghera. The urban centers of Mestre and Marghera are situated in the mainland and cover a surface of about 10 Km^2. Close to them a large industrial area of about 22 Km^2 is found, whose main activities concern oil-refining, petrochemical production, production of electric energy, metallurgy of iron and other metals.

Five Km from the mainland, in the middle of the lagoon is the historical center of Venice, standing on a cluster of small islands separated by a network of small canals and interconnected by many bridges. Due to such a peculiar situation and to its history the urban texture has not undergone neither significant modifications nor the growth typical of other cities. Its surface is of about 6 Km^2.

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 the 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.

APPLICATION OF THE GAUSSIAN MODEL

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

DATA

Industrial emissions

In accordance with the National Law on Pollution promulgated on April 15,1971, an inventory of SO_2 emissions due to 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 goes from 10 to 120 m. and the overall SO_2 emission is of 160.000 tons 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

a) 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 in that occasion people were required to indicate the type of fuel used in their domestic heating ystems.

The urban districts of the Venetian area were divided in 272 sections (Fig.2) for each of which the number of inhabitants as well as the various percentages regarding the use of different fuels were determined.

The fuel 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 and was assumed to be independent of the type of fuel used.

Such an "individual thermal consumption" enabled us 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 (private communications).

b) 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 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_{hi} is the average hourly temperature at i-th hour of the day. For the Venetian area $T_b = 15.5^{o}C$.

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 i-th 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 i-th section in the considered period (Kg/s)
E_i	is the yearly amount of SO_2 emitted by the i-th section (Kg)
g	is the number of dd in the considered period (^{o}C)
G	the total number of dd in a year (^{o}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 around 30 m. for the historical center of Venice (where the buildings are generally old and low) and around 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 (Fig.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 center, 15 m. above the ground, records on an hourly basis the speed and direction of wind, temperature, pressure, humidity, rainfall, cloudiness and fog. Wind direction is recorded according to the eight sectors of the compass, which introduces an indetermination of $\pm 22^{\circ}30'$ 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 minutes average SO_2-concentration "standard" (0.30 ppm) imposed by the 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 in the period February 1973 - 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, due to a certain distribution of N point sources, the following formula was used:

$$C_P = \left(\frac{2}{\pi}\right)^{3/2} \sum_{K=1}^{N} \frac{Q_K}{D_{P,K}} \sum_{\substack{id=1\\ iw=1\\ is=1\\ it=1}}^{8,6,6,4} \frac{F(id,iw,is,it)}{u(id,iw,is,it)\, S_z(D_{P,K},is)} \left[\Lambda\left\{-\frac{h}{2H},\frac{S_z^2}{2H^2}\right\} + \Lambda\left\{\frac{h}{2H},\frac{S_z^2}{2H^2}\right\}\right] \qquad (1)$$

Where the function Λ is defined by:

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

and the symbols have the following meaning:

C_p	concentration at receptor point P (mmg/Nm^3)
Q_k	emission rate of the K-th source (mmg/Nm^3)
N	number of sources (industrial and urban)
$D_{p,k}$	distance of point P from the K-th source, projected on the wind direction (m)
S_z	vertical standard deviation obtained from Gifford's plots (Slade, 1968) (m)
F (id,iw,is,it)	frequency of winds blowing into a given 45^o 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) (^oC)
h	effective height of the K-th source (m)
H	inversion layer depth (m)

Eq. 1 is the classical Gaussian plume formula (Pasquill 1962), written according to the proposal of Martin (1971) and Calder (1971), which has been here modified 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 :

$0 \rightarrow 1.57$, $1.57 \rightarrow 3.14$, $3.14 \rightarrow 5.24$, $5.24 \rightarrow 8.38$, $8.38 \rightarrow 11.0$

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. Though 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 (Pasquill, 1962). Pasquill's categories can therefore result 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 reception 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 center 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 instable classes.

As to air temperature, the following classes were introduced: less than 0, 0—10, 10—20, and greater than 20^{o}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

Δh is the plume rise

The plume rise Δh has been evaluated by using the formula proposed by Concawe (Detrie,1969)

$$\Delta h = 0.47 \frac{Q_h^{0.56}}{u^{0.70}}$$

where :

Q_h : is the heat rate (cal/s) , defined as:

$$Q_h = c_p \cdot Qv \cdot (Tg-Ta)$$

where :

c_p specific heat at constant pressure of effluent gases (cal/m^3 ^oC)

Qv overall emission rate (Nm^3/s)

Tg gas temperature (^oC)

Ta air temperature (^oC)

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

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

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 of Gaussian model application

The monitoring stations were divided into three groups according to their geographical location. Figs. 3-4-5 show measured three-monthly average concentration as well as the calculated one for two stations chosen out of each group. Fig.3 refers to sensors 6-30, located at the southern edge of the Industrial Area, while stations 10-29 (Fig.4) are situated between the Industrial Area and the urban centers of Mestre and Marghera and finally Fig.5 shows the results for sensors 16-22 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 due to the introduction of the modified Pasquill's classification of stability.

Such results, although incomplete, 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 SO_2-annual average concentration for the years 1973 and 1974; the relative results are plotted with the experimental ones in Figs.6-7. As was expected, the model proved to give better results if the period of calculation was extended.

The encouraging results obtained by applying the model led to extend the calculation 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 Figs. 8-9, for the periods June-August 1973 and December 1973-February 1974, respectively. By comparing the two maps the conclusion can easily be drawn that because of the local meteorological conditions (Runca and Zannetti,1973), in summer SO_2 "keeps away" from the historical center, 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 center of Venice.

DESCRIPTION OF THE NUMERICAL MODEL

The application of a model based on Gaussian plume formula has a few severe limitations. This approach can give erroneous results in low wind conditions. In addition it cannot incorporate the complex effects induced by the local geography and their influence on the distribution of pollutants. Though the Gaussian formulation has the above limitations it is nevertheless widely used. First because it offers a practical method for calculation and secondly, because the present availability and accuracy of input data is generally inadequate to develop a more sophisticated model.

On the other hand , if the diffusion of atmospheric pollutants has to be described in detail the model must accomodate temporal and spatial variations of meteorological parameters, effects of the inhomogeneous surface conditions and other features. Since models based on the numerical integration of the diffusion convection equation, such as those developed by Randerson 1970, Sklarew 1970, Lamb 1971, Shir and Shieh 1973, proved capable of dealing with the previously mentioned features, the study which is being carried out tests the application of a model of this kind for simulating short term average SO_2 concentration in the Venetian Area.

The basic assumption of the model is that the equation governing local changes in SO_2 in the atmosphere can be written, disregarding the decay term, as follows:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(K_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial C}{\partial z}\right) + S \qquad (4)$$

Where:

- C — mean concentration of SO_2 (mmg/m^3)
- u, v, w — horizontal and vertical components of the wind velocity (m/s).
- K_x, K_y, K_z — coefficients for eddy diffusion along the x, y, z, directions (m^2/s)
- S — source of SO_2 $(mmg/m^3 s)$

Eq. 4 is numerically solved with the method of fractional steps (Yanenko, 1971) in a three-dimensional grid system with the x-axis oriented W-E the y-axis oriented S-N and the z-axis extended vertically to the height of the mixing layer.

At present the grid system consists of 21x21x15 points.

Along the x and y-axes the grid points are spaced 1000 m. apart. As yet a final decision on the vertical subdivision has not yet been taken. In this preliminary and testing phase the model runs with a mixing height variable from 280 to 360 m. and a vertical grid size ranging from 15 to 40 m. The orientation of the grid system is such that the industrial emissions as well as the urban emissions are as far as possible from the edges of the grid framework.

Boundary conditions for the vertical diffusion range are specified, assuming that ground and mixing layer base are impermeable to the SO_2 as follows:

$$K_z \frac{\partial C}{\partial z} = 0 \qquad z = 0, H(t)$$

where H (t) is the mixing height. The lateral boundary conditions cannot be well posed. At present the model is testing a few different boundary conditions which are not discussed here; the simplest one assumes that the concentration level can be neglected. Anyway it results that, if the grid framework is large enough , computation is not affected by the lateral boundary conditions.

As far as the initial conditions are concerned, since the computation shows (Shir and Shieh,1973) that the observed concentrations values are reached within two hours under average wind speed conditions, the concentration field at the beginning of the simulation can be set to zero over the whole region.

Numerical Scheme

According to the method of fractional steps the concentration field at the time t +Δt is obtained from that at the time t by separating the contribution due to the source, convection and diffusion terms of equation (4). Hence at every time step the equation $\frac{\partial C}{\partial t} = S$ and the remaining six one-dimensional time dependent equations (3 for the convection and 3 for the diffusion) are solved separately by a finite-difference technique.

The numerical scheme applied to the convection equations is the one devised by B.Carlson (Richtmyer and Morton,1967) and it is illustrated for convection along the x-axis in Fig. 10.

The diffusion equations are solved with an implicit space-centered difference scheme allowing for a variable grid spacing. With respect to the x-axis the difference equation is:

$$\frac{C_i^{t+\Delta t} - C_i^{t}}{\Delta t} = \frac{2}{\Delta X_i \, (\Delta X_i + \Delta X_{i-1})} \left\{ \vartheta D[C_i^{t+\Delta t}] + (1-\vartheta) D[C_i^{t}] \right\}$$

with :

$$D[C_i] = \frac{\Delta X_i}{\Delta X_{i-1}} K_{x_{i-1/2}} C_{i-1} - \left(\frac{\Delta X_i}{\Delta X_{i-1}} K_{x_{i-1/2}} + K_{x_{i+1/2}} \right) C_i + K_{x_{i+1/2}} C_{i+1}$$

where x_i is the interval between the i and i+l grid point and ϑ is a parametric constant. This method is always stable for $1/2 \leq \vartheta \leq 1$

Since Carlson's scheme is unconditionally stable, assuming $1/2 \leq \vartheta \leq 1$, the choice of the time step and grid spacing in solving equation (4) is limited only by accuracy. With the application of Carlson's scheme it is not necessary to observe the stability condition $u \Delta t \leq \Delta x$ therefore allowing for a time step such that $u \Delta t = \Delta x$ in the area of maximum concentration gradients.

The numerical scheme has been tested by comparing analytical with numerical solutions of equation (4), obtained respectively from the explicit relation used by Roberts to represent the diffusion of a puff of smoke (Sutton, 1953) and from calculations with the proposed method (Fig.11 shows some of the obtained results).

Another remarkable feature of the implemented numerical scheme is the possibility of using different time-steps in order to integrate the different equations into which the original equation was fractioned. By doing this, it is possible to take into account more appropriately the scales of the different mechanisms (i.e. transport, horizontal diffusion, vertical diffusion, etc....) affecting the dispersion phenomenon.

As an example, we compare the analytical solution for the case of Fig. 12 with the numerical ones obtained by using a uniform time step of 200 s. (dashed line) and by using a diversified time step, 200 s for the diffusion and 400 s for the transport respectively (dotted line). The improvement for the numerical integration performed with diversified time steps must be ascribed to the elimination of the error in the solution of the transport equation.

Application of the numerical model

As a preliminary investigation the model has been applied with the same input data used in the Gaussian model and with rough assumptions such as constant mixing height, no surface discontinuities, vertical exchange coefficient expressed by a power law and constant emission rate (urban sources enter the model as point sources, see the Gaussian model).

Some results are shown in Figs. 13-14, where daily average computed values are compared with the measured ones.

An application of the model will be soon developed in which the meteorological factors affecting SO_2-dispersion are provided by experiments carried out by CNR (Italian National Research Council) and EURATOM. This application will be the subject of a future article.

CONCLUSIONS

The application of a Gaussian-type model to compute long term SO_2-average 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 center 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.
In addition, a model based on the diffusion concentration equation has been briefly described. The devised numerical scheme allows for variable grid spacing and time step. Since the model's spatial resolution can be increased in the areas where the emission are located and the advection distance per time steps can be made equal to the grid spacing in the region of maximum concentration gradient, a substantial reduction in numerical errors should result.
Preliminary results of an application of this model with the same data used in the Gaussian model have been presented. Better results are expected from an application which is being developed with a set of more appropriate data.

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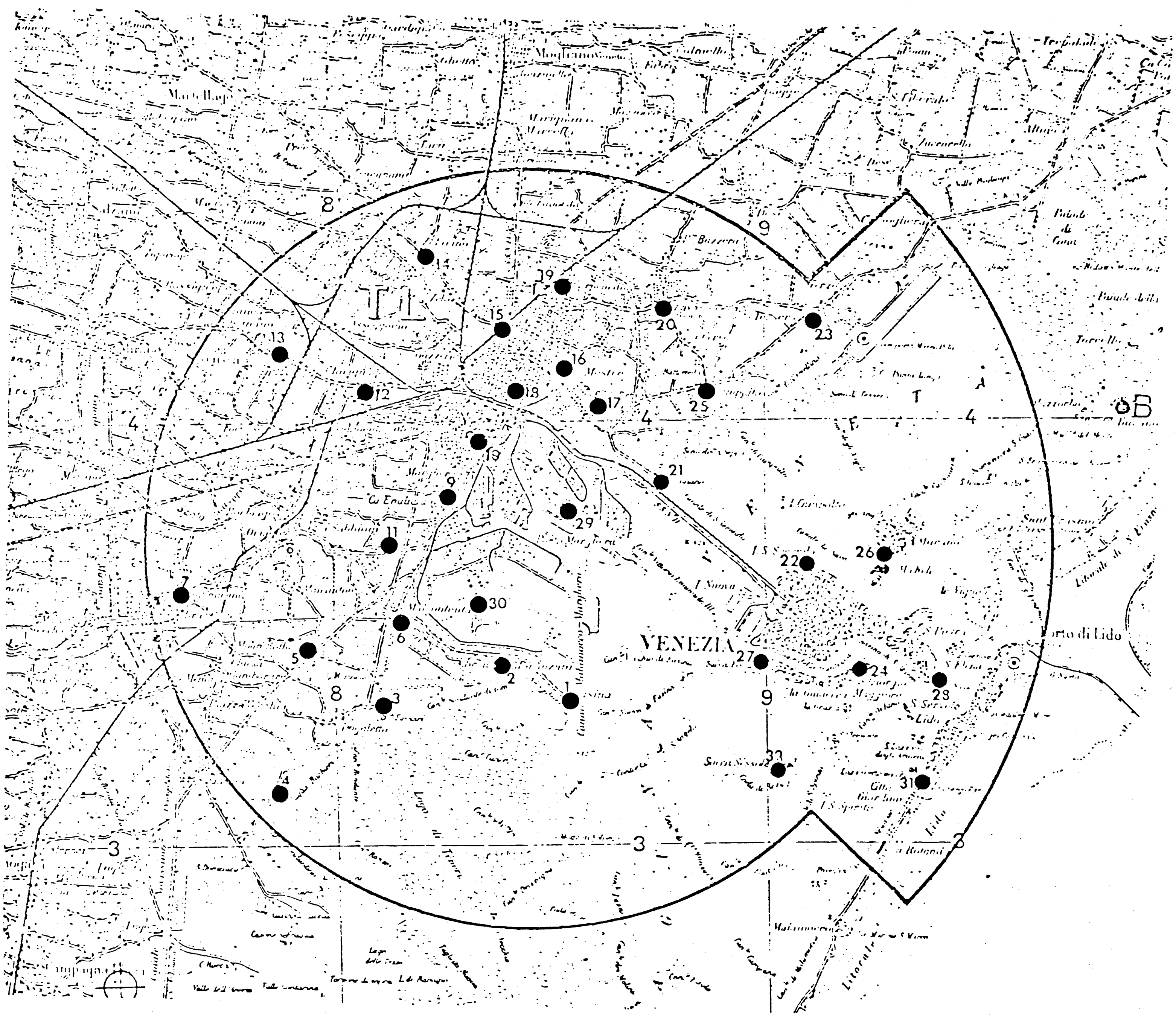

Fig. 1 Venetian Area - Dots indicate the location of the SO_2 monitoring stations (2,6,9,10,16,17,22,24,29,30 were operating since Feb. '73)

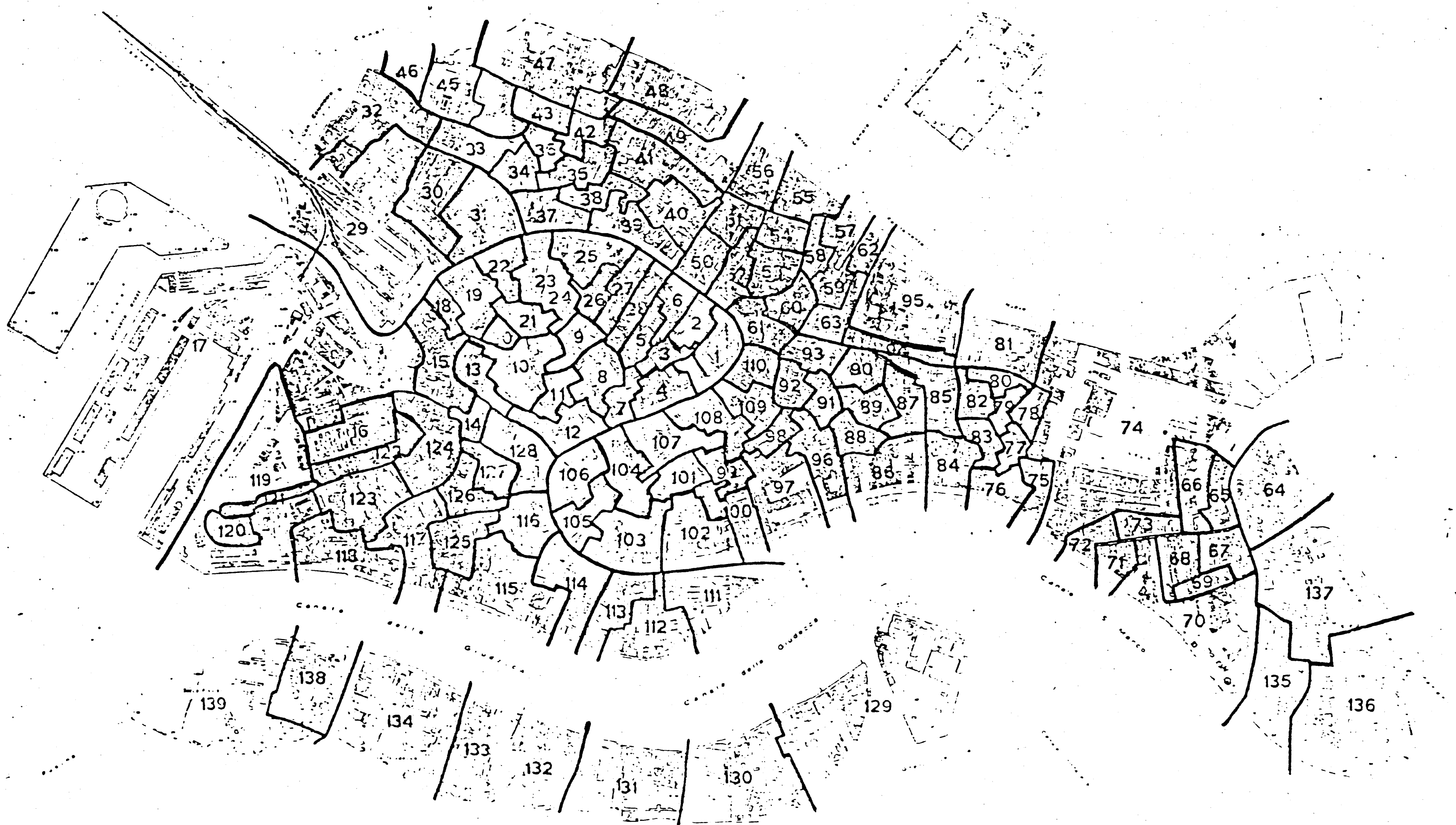

Fig. 2 Map of the historical center subdivided into census sections

SO_2-SEASONAL AVERAGE CONCENTRATION

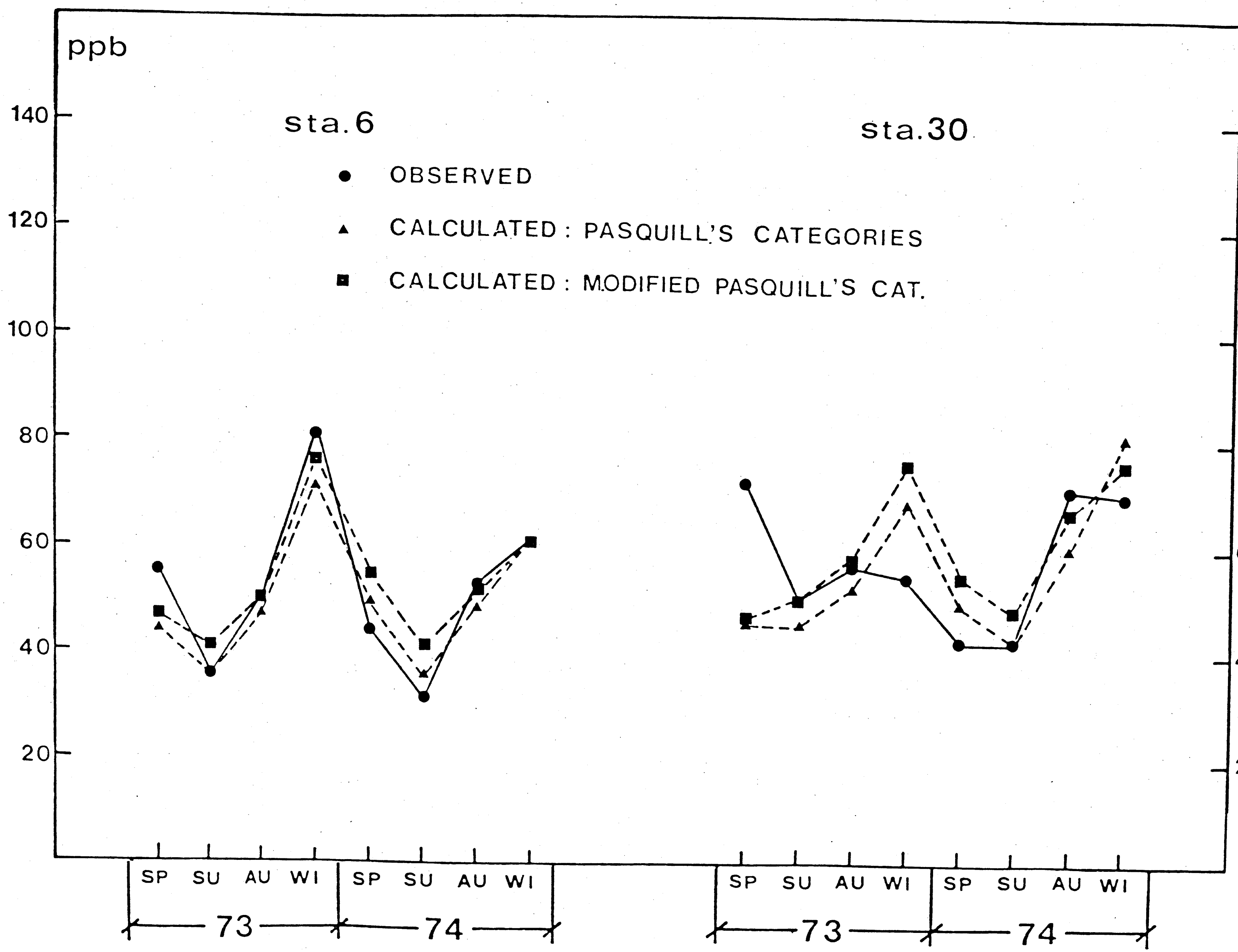

FIG 3

SO_2-SEASONAL AVERAGE CONCENTRATION

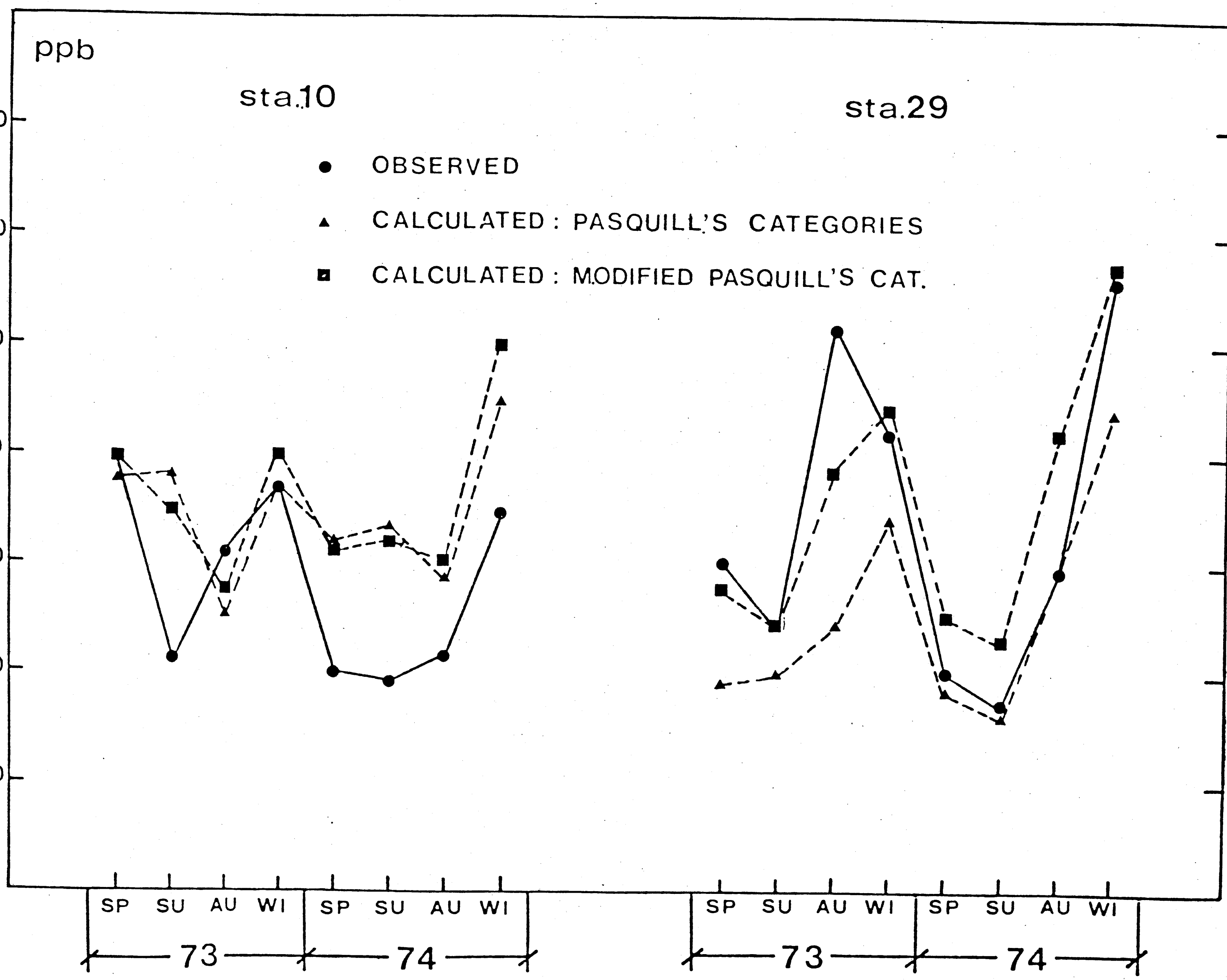

FIG. 4

SO_2-SEASONAL AVERAGE CONCENTRATION

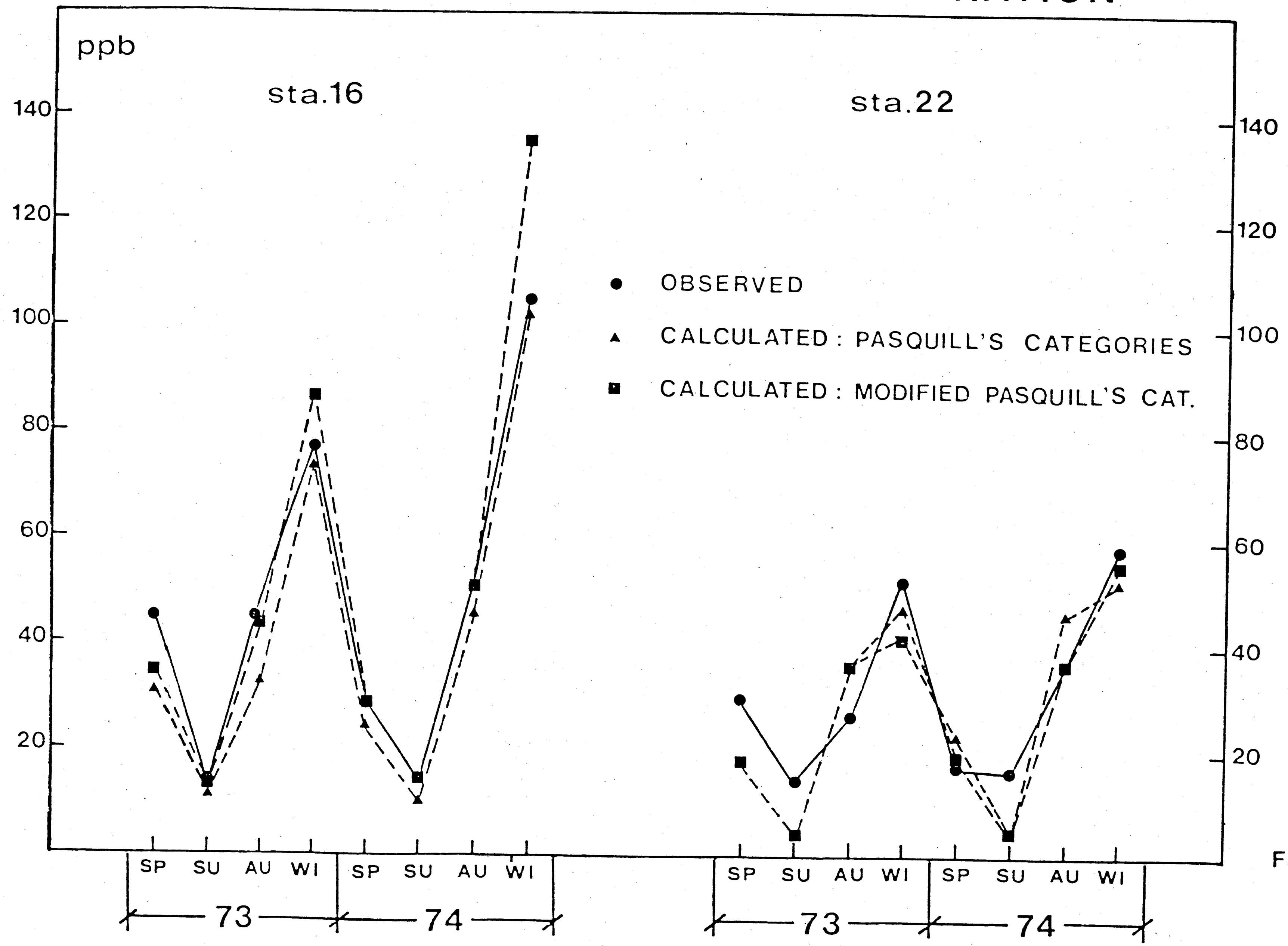

FIG.5

SO_2 - ANNUAL AVERAGE CONCENTRATION 1973

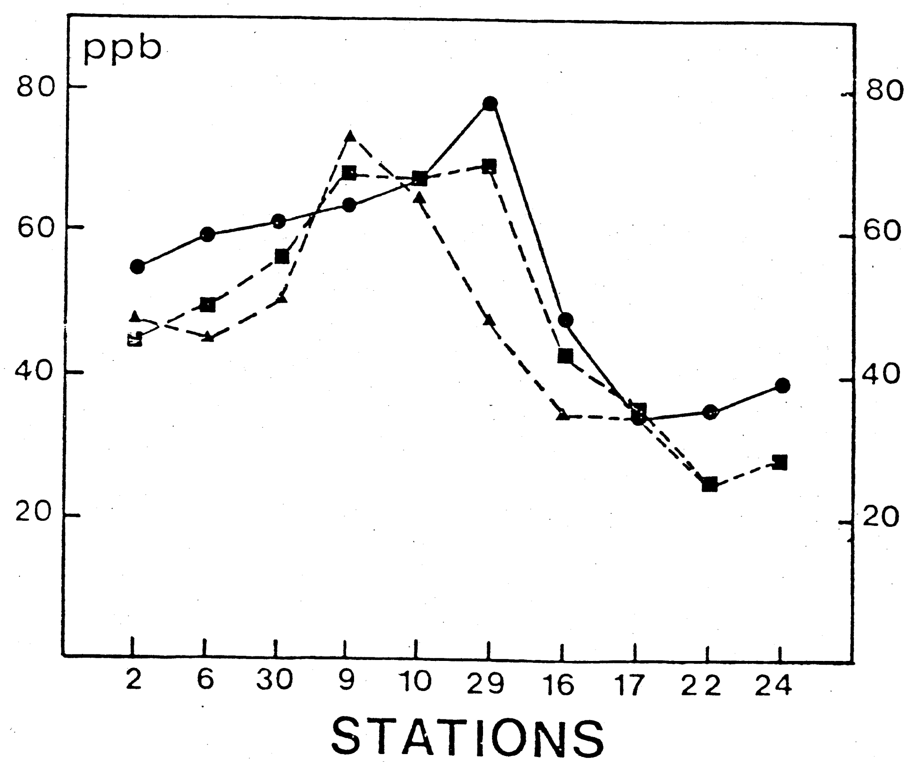

FIG. 6

● OBSERVED

▲ CALCULATED : PASQUILL'S CATEGORIES

■ CALCULATED : MODIFIED PASQUILL'S CAT.

SO_2-SEASONAL AVERAGE CONCENTRATION

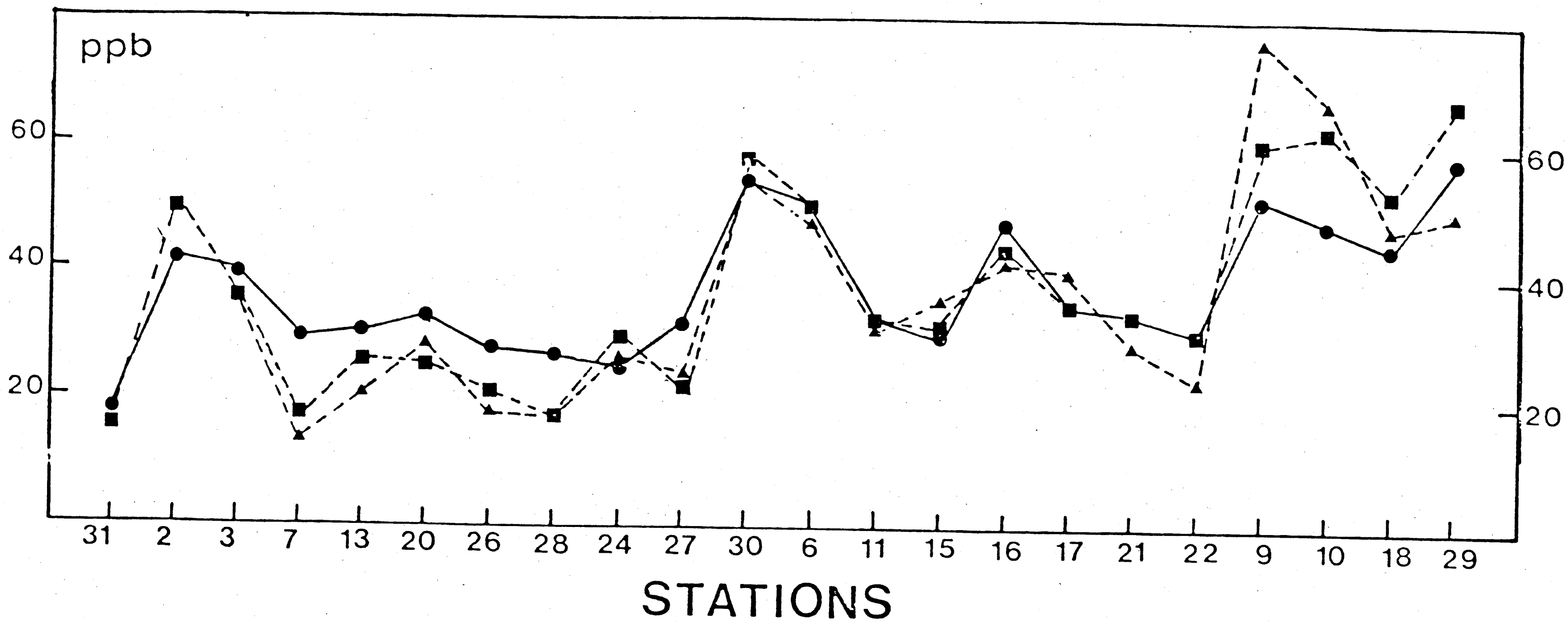

FIG.7

- ● OBSERVED
- ▲ CALCULATED : PASQUILL'S CATEGORIES
- ■ CALCULATED : MODIFIED PASQUILL'S CAT.

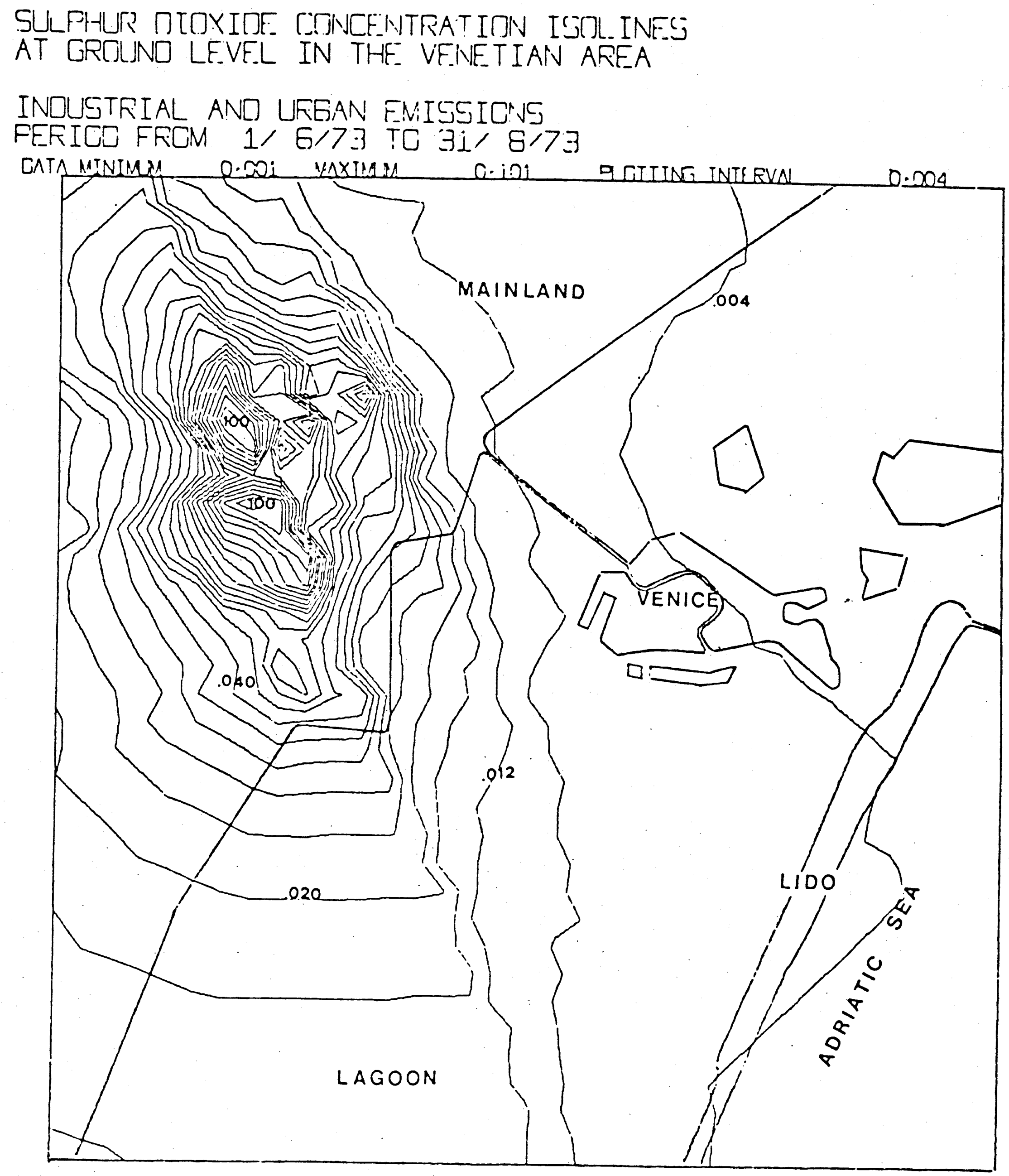

Fig. 8 Concentration values are in ppm.

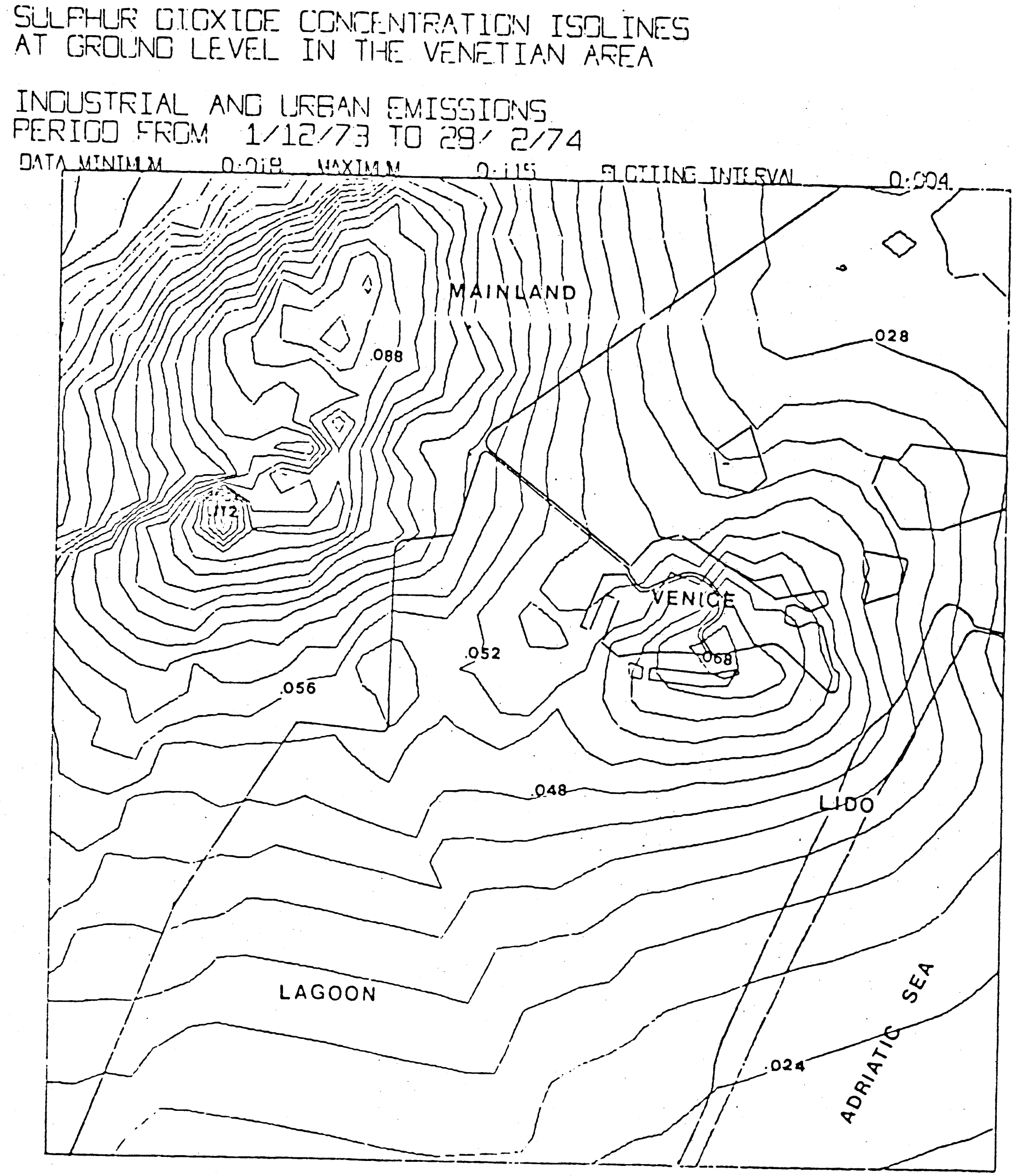

Fig. 9 Concentration values are in ppm.

characteristic a $\quad u\Delta t < \Delta X \quad C_i^{t+\Delta t} = \dfrac{C_i^t \cdot (\Delta X - u\Delta t) + C_{i-1}^t u \Delta t}{\Delta X}$

characteristic b $\quad u\Delta t > \Delta X \quad C_i^{t+\Delta t} = \dfrac{C_{i-1}^t \Delta X/u + C_{i-1}^{t+\Delta t} \cdot (\Delta t - \Delta X/u)}{\Delta t}$

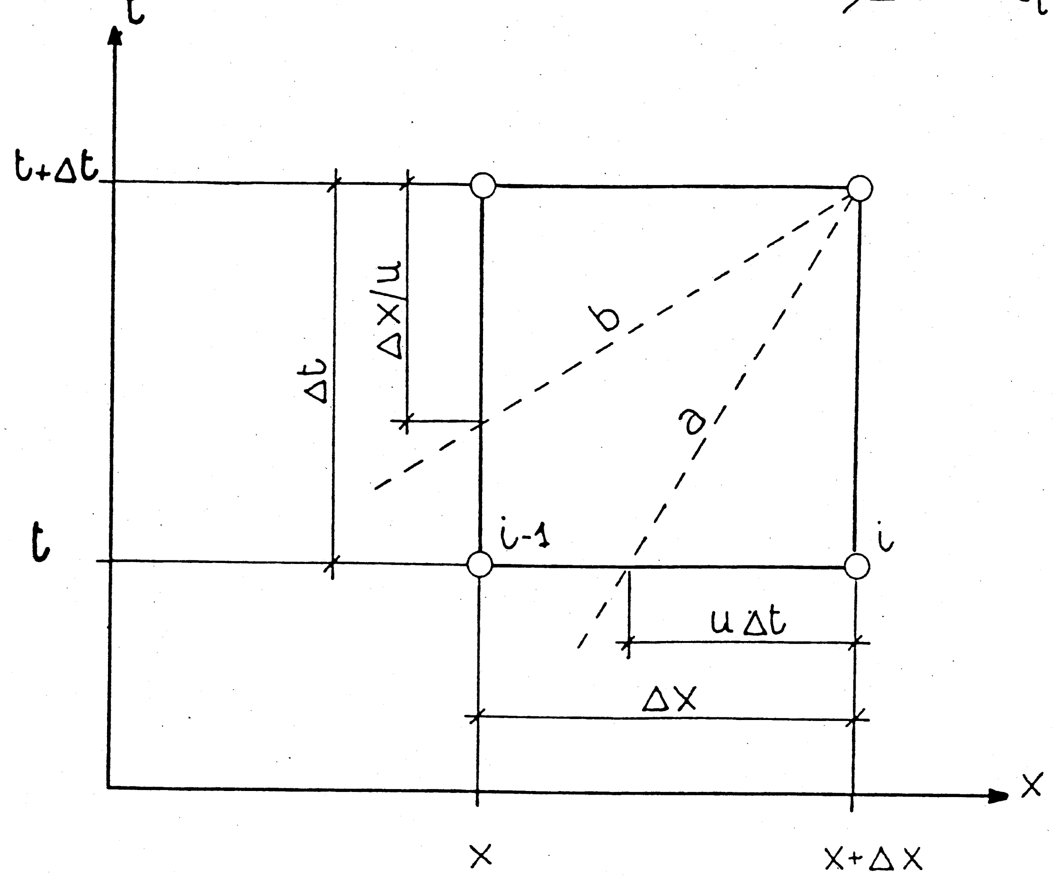

FIG. 10 Carlson's scheme applied to convection along x-axis

$K_x = K_y = K_z = 500\ m^2/s$

$U = 2\ m/s\ ,\ V = W = 0$

$\Delta X = \Delta Y = \Delta Z = 1000\ m$

$\Delta T = 500\ sec$, Instantaneous source = 1 Kg

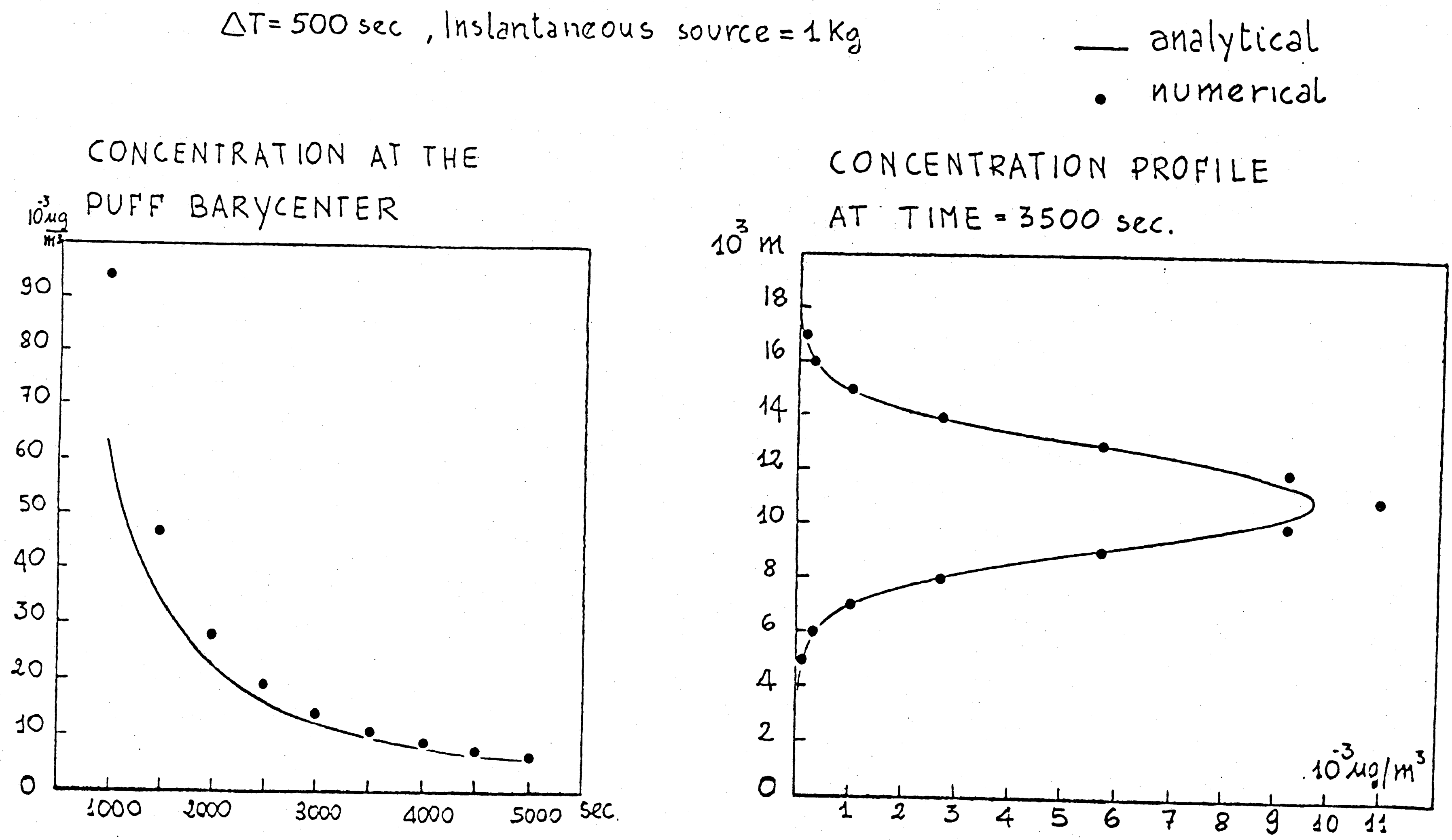

FIG.11 Comparison of analytical with numerical solution

CONCENTRATION AT THE PUFF BARYCENTER

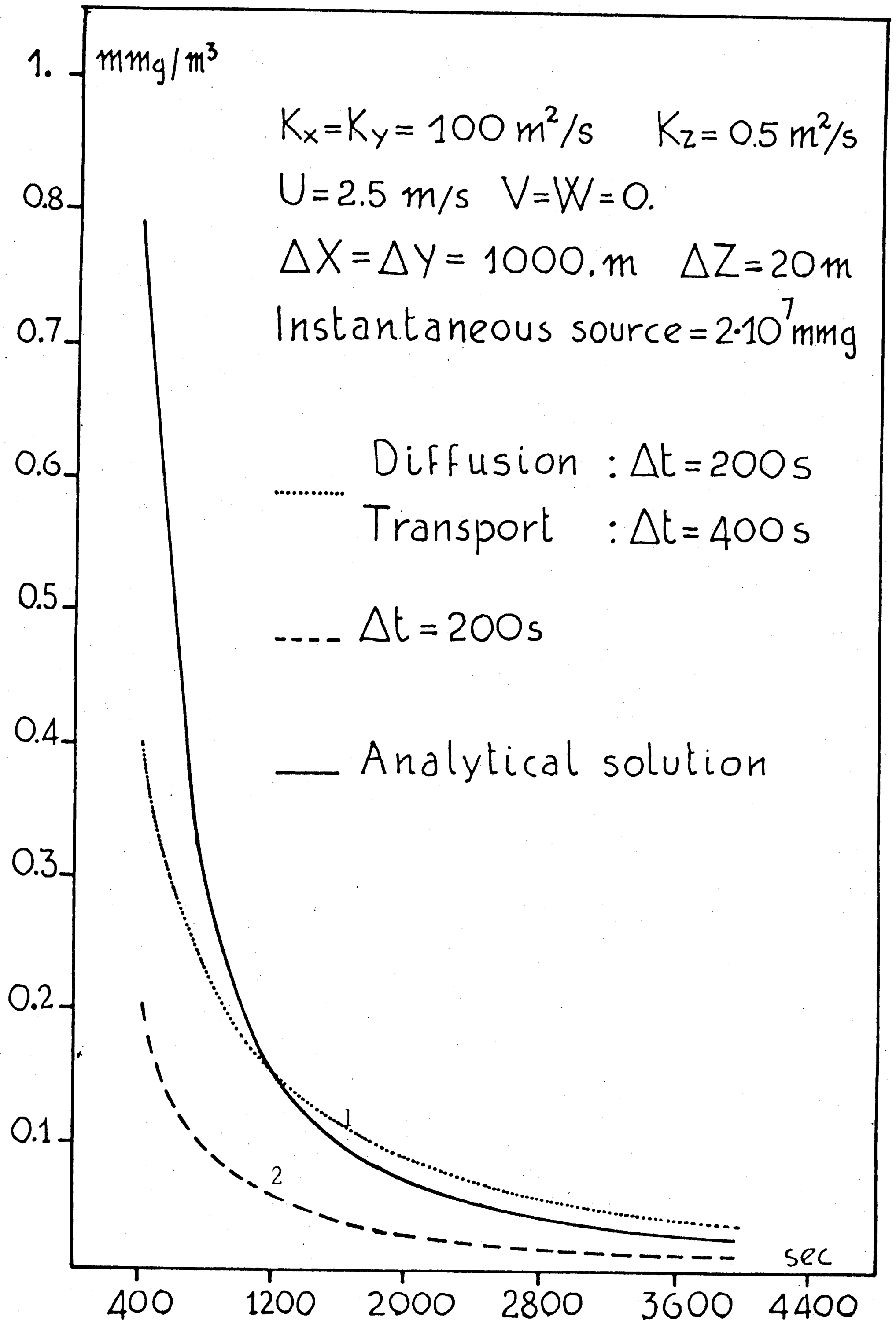

FIG. 12 Comparison of the analytical solution with the numerical ones:
1-diversified time step ; 2-uniform time step

SO_2-DAILY AVERAGE CONCENTRATION
JUL.73

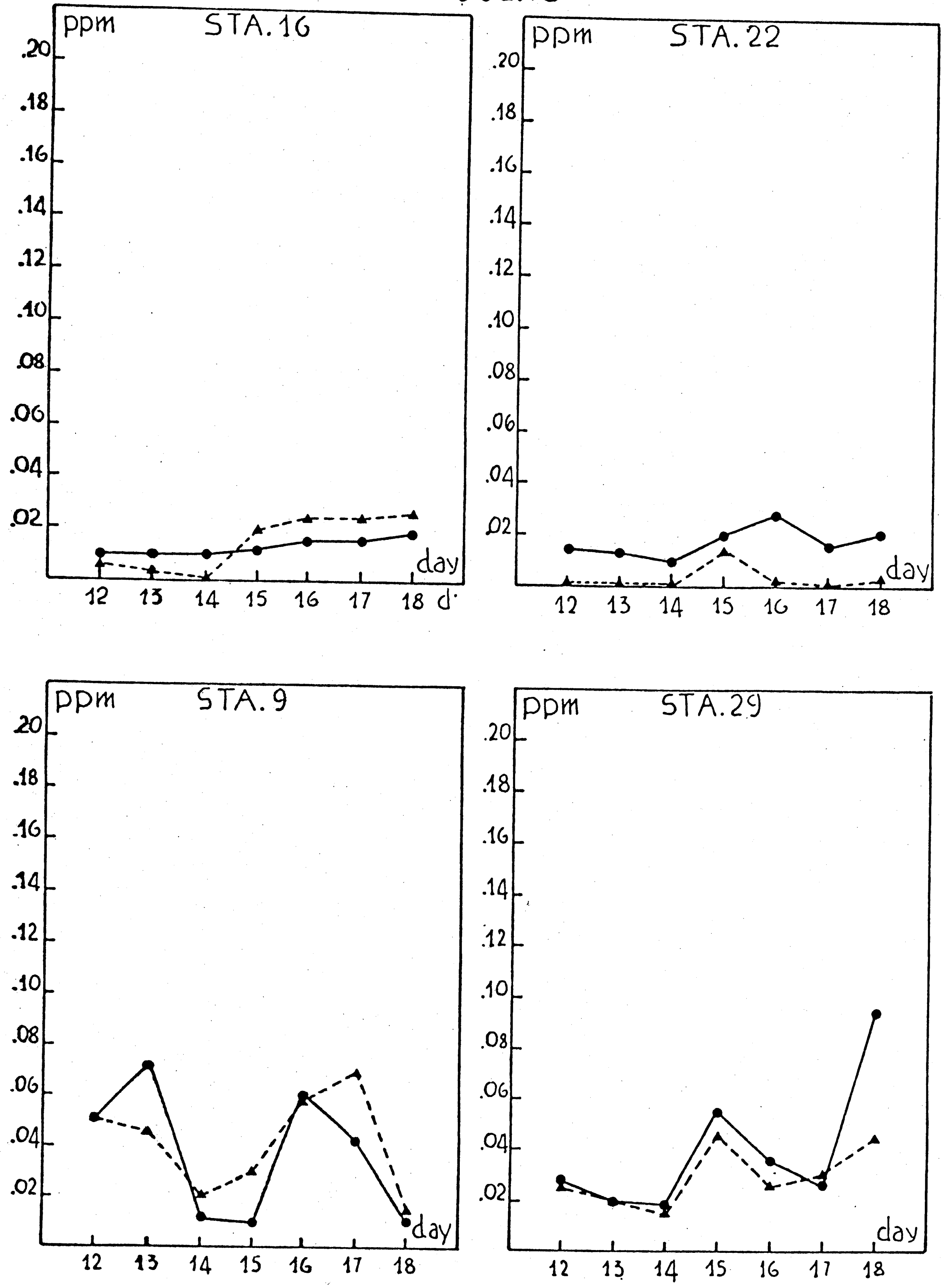

FIG.13 : ●——● OBSERVED ▲----▲ CALCULATED

SO_2-DAILY AVERAGE CONCENTRATION

DEC. 73

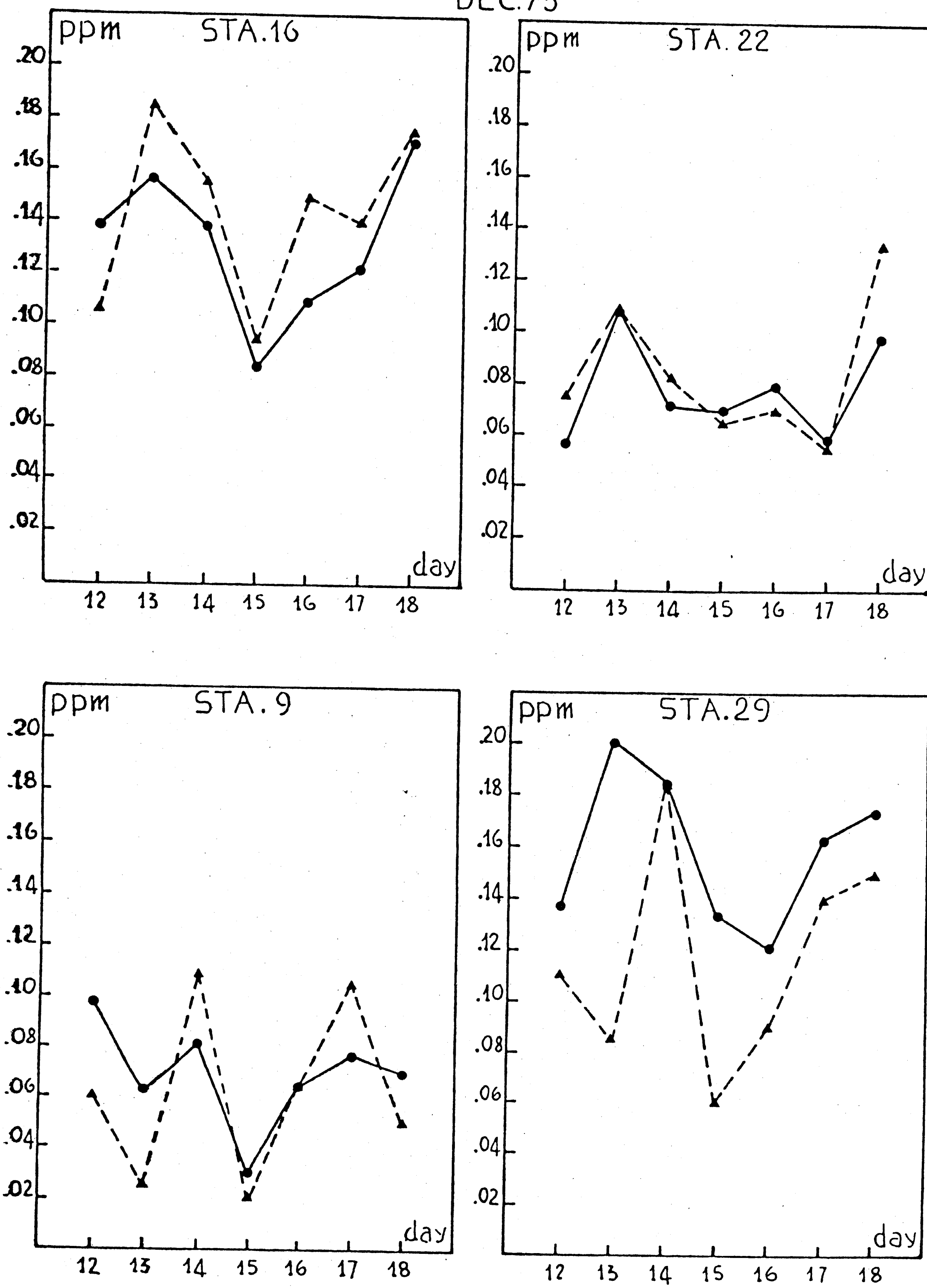

FIG. 14: ●—● OBSERVED ▲- - -▲ CALCULATED