Atmospheric Environment Vol. 11, pp. 605–616. Pergamon Press 1977. Printed in Great Britain.

J - 5

METEOROLOGICAL FACTORS AFFECTING SO_2 POLLUTION LEVELS IN VENICE

P. Zannetti, P. Melli and E. Runca
IBM Scientific Center, Venice, Italy

(*First received* 16 *August* 1976)

Abstract—Sulfur dioxide concentrations in the historical center of Venice and its surroundings are related to meteorological parameters using mean hourly SO_2 measurements. These were recorded over a two year period at ten automatic stations belonging to the air quality monitoring network installed by the Governmental Health Department. Meteorological data, including mean hourly values of wind direction and speed, temperature, cloudiness, pressure, humidity, rainfall, and visibility were provided by a meteorological station in the network. Effects of various meteorological parameters on measured SO_2 concentrations were examined individually and in combination. Analysis showed that the relationship between SO_2 concentration and a particular meteorological parameter can often be explained by the relationship between wind direction and that parameter. Additional results regarding the seasonal and diurnal cycles of pollution levels are also presented. Finally, a detailed study was carried out of the causes of high concentration pollution episodes in the historical center of Venice, whose artistic patrimony, unique in the world, is being seriously damaged by air pollution. Analysis showed that a limited number of such episodes occur only in winter, and mainly in conjunction with very light westerly winds.

1. INTRODUCTION

Air pollution is a common problem in many places around the world where widespread industrial and urban development has occurred. This is also the case in Venice, where during the last three decades a large industrial area has been developed jointly with two new urban centers. In this area, the pollution problem is heightened by the damage caused by atmospheric pollutants to the artistic patrimony of Venice, which is already threatened by the quite peculiar environmental conditions of high water, salinity, and high humidity.

Both the will to save this city, unique in the world, and the need to plan industrial developments, have led to public and private studies of the air pollution problem. To this end, a dense network of stations monitoring meteorological and SO_2 concentration data has been set up in the last three years. Two years of data from this network has made it possible to carry out the present analysis, the purpose of which is to relate the meteorological conditions and the pollution levels in the area. Similar analyses using only limited amounts of data, or limited in scope, have been carried out previously by several authors (Dechigi and Paccagnella, 1954; Sordelli and Grandi, 1972; Vendramini, 1973; Runca and Zannetti, 1973; Camuffo and Fassina, 1974; Zannetti *et al.*, 1975).

2. STUDY AREA

The area of investigation (Fig. 1) is a section of the Venetian Lagoon located in the northeastern part of Italy at the upper shore of the Adriatic Sea, from which the Lagoon is separated by two narrow strips of land: The Lido and Pellestrina. It includes the urban centers of Mestre, Marghera, and Venice, and the heavily industrialized area of Porto Marghera.

The urban centers of Mestre and Marghera are situated on the mainland and have a surface area of about 10 km^2. Close by is a large industrial area of about 20 km^2, whose main activities include oil-refining, petrochemical production, metallurgical processing of iron and other metals, and production of electric energy. Five km from the mainland, in the middle of the Lagoon, is the historical center of Venice, covering an area of 6 km^2 and standing on a cluster of small islands separated by a network of small canals and interconnected by many bridges. Due to its peculiar situation and history, the urban center has not undergone either significant modification or growth typical of other cities. The region is on the extreme end of the "Padana" plain and is essentially flat. Although there are few surface features affecting the local aerodynamics, the micrometeorology of the area is complicated due to the presence of the different types of surfaces.

3. REGIONAL CLIMATE

The Venetian area has a Mediterranean climate (Janeselli, 1959–74; Giordani Soika and Meneghini, 1970), in that it is generally mild with an average temperature of about 14°C. Only on a few days during the year does the temperature reach its extreme values, which are about 30°C and −5°C. A peculiarity of the area is its high average relative humidity (about 80%), which greatly reduces the typical mildness of the Mediterranean climate. The average yearly rainfall is about 780 mm, but in certain years it exceeds 1000 mm. Violent small scale convective

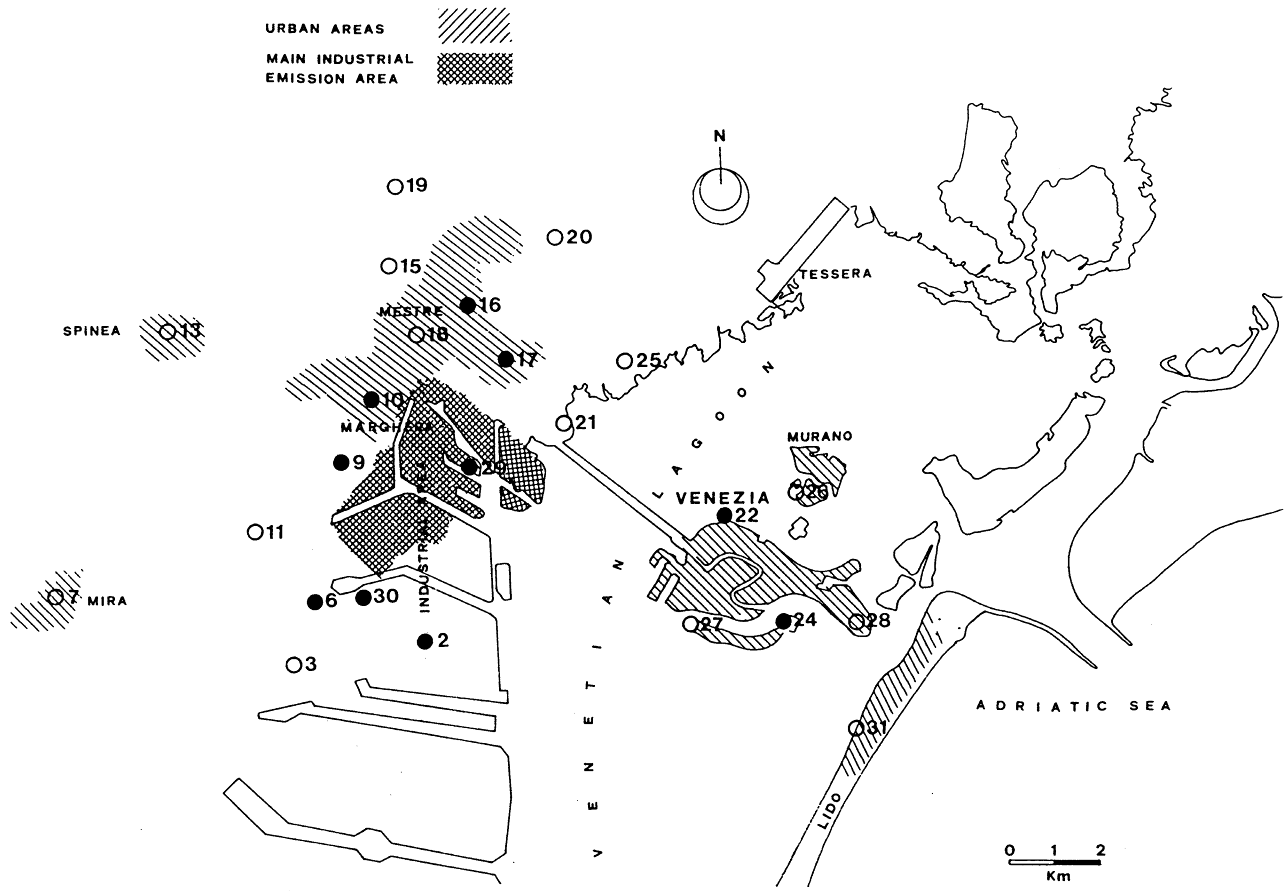

Fig. 1. Venetian area including the ISS-Tecneco SO_2 monitoring network. Black dots indicate the stations operating since February 1973, and whose data are used in the present study. White dots indicate stations put into operation one year later.

storms in summer caused by the high rate of evaporation from the lagoon are very frequent. However tornadoes only rarely occur, but the last one in September 1970 did cause serious damage.

The average pressure is about 1015 mb, but it is generally higher in the cold season. The prevailing wind direction is from the NE, however there are important seasonal variations. In particular, the frequency of winds blowing from the sea towards Venice and the mainland (i.e. from the SE and the S) is generally low, but becomes comparable to the frequency of NE winds during summer, while the frequency of wind blowing from the industrial area towards Venice (i.e. from the W and the NW) is also generally low although it increases in winter. Low speed ($\leqslant 3$ m/s) conditions predominate in the area, and speeds higher than 8 m/s are seldom measured.

A sea-breeze effect, characteristic of the area, has been detected by examining the evolution of the hourly winds roses obtained during periods with speeds lower than 3 m/s (Runca and Zannetti, 1973). Analysis of these roses showed a clockwise rotation of the prevailing wind direction during the day, characteristic of a sea-breeze effect. Atmospheric stability, defined according to Pasquill's criteria, on the average is neutral, however in winter the frequency of stable conditions increases. Such conditions are found mainly in connection with winds blowing from the mainland towards Venice. In summer, the frequency of unstable conditions increases mainly in association with winds blowing from the sea.

4. DATA

Data used for the present analysis have been provided by the network installed in the Venetian area for the Istituto Superiore di Sanità (Governmental Health Department) by Tecneco (several authors, 1973). At present the network (Fig. 1) consists of 24 stations for measuring ground level SO_2 concentration and one meteorological station located in the historical center 15 m above the ground. Although other meteorological stations belonging both to private and public organizations operate in the area, it was decided to use only the data supplied by the Tecneco station. Previous analysis (Runca and Zannetti, 1973) has shown, however, that there is substantial agreement among the data recorded by the different meteorological stations in the area.

Ten SO_2 sensors and the meteorological station have been operated continuously since February 1973, while the others started transmitting data during 1974. A small computer scans the sensors at each station every minute and computes hourly average values, as well as the highest thirty-minute average each day for each station. Moreover, any time that the thirty-minute legal standard of 0.30 ppm is exceeded, the computer prints a warning. The meteorological station records, on an hourly basis, wind speed and direction (eight sectors), pressure, relative humidity, temperature, rainfall, fog, and cloudiness.

The total SO_2 emission due to industrial activity has been estimated at about 160,000 tonnes per year for the period 1973–74. In the same period the emission due to domestic heating and other urban activities was about 10,000 tonnes per year. Data regarding the industrial emissions have been obtained from an inventory taken in 1972 as a consequence of a national law promulgated in 1971. Urban emissions were evaluated on the basis of data supplied by the National General Census of 1972 and were confirmed by estimates made by fuel wholesalers (personal communications).

Since emissions due to domestic heating are limited to 5–6 months a year, industrial emissions during the heating period are approximately 85% of the total SO_2 discharge in winter and 100% in summer. It must be pointed out, however, that no simple conclusions about the relative effects of the two types of emissions on pollution levels can be drawn from the above values, since the industrial emissions are characterized by a greater geometrical source height and a higher plume rise which cause a stronger dilution of the pollutants before they reach the ground.

As far as the urban sources are concerned a special law promulgated for the Venetian area requires that only nonpolluting fuels, such as natural gas, can be used in the historical center and surrounding islands. Transformation of the heating systems is presently being carried out and therefore the contribution of the historical center and surrounding islands to the SO_2 emissions is still around 3,000 tonnes/year.

5. CONCENTRATION LEVELS

Monthly averaged SO_2 values were computed for each station and some of the results are shown in Fig. 2. The substantial increase in pollution levels during winter (Dec.–Feb.) is due both to the presence of local domestic emissions and to a meteorological situation which is favourable to high pollution levels, as will be shown in the following sections. The effect is more pronounced for sites situated close to the urban centers, due to the low height at which domestic emissions are released.

Since industrial emissions are present throughout the entire year, very high values of SO_2 concentration also do occur in summer (Fig. 2) but they are confined to the area near the industrial region and are generally not persistent. Furthermore, from the same figure it can also be seen that sensors located in the urban

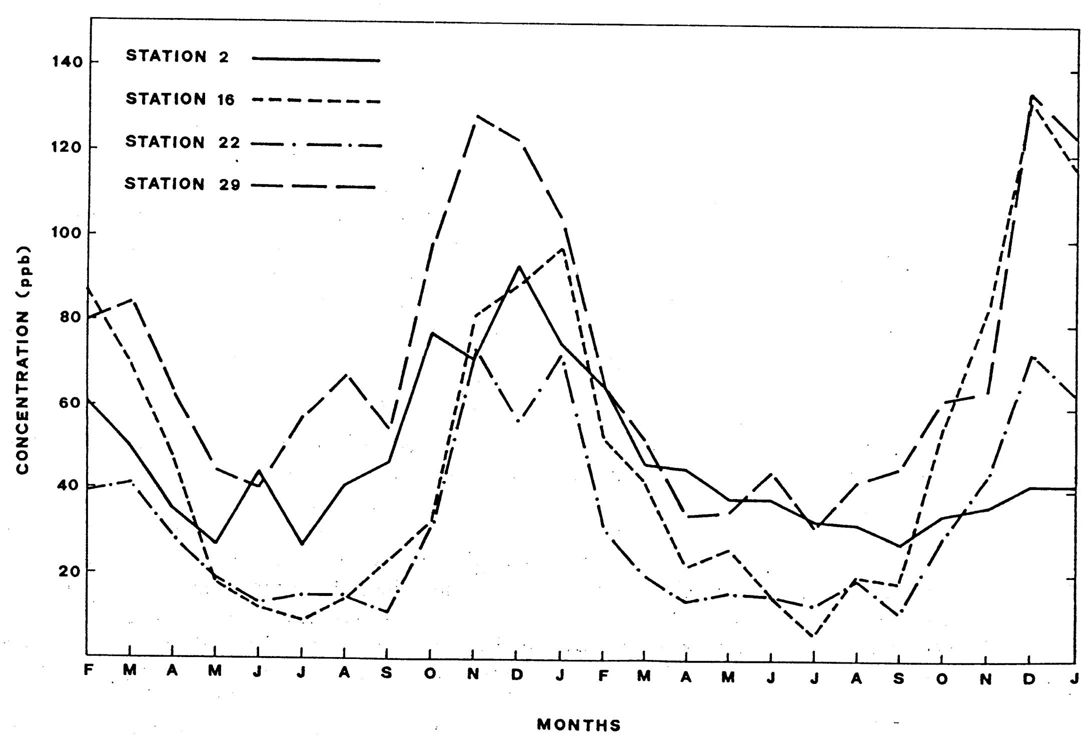

Fig. 2. Monthly average SO_2 concentrations measured at four stations during the period from February 1973 to January 1975.

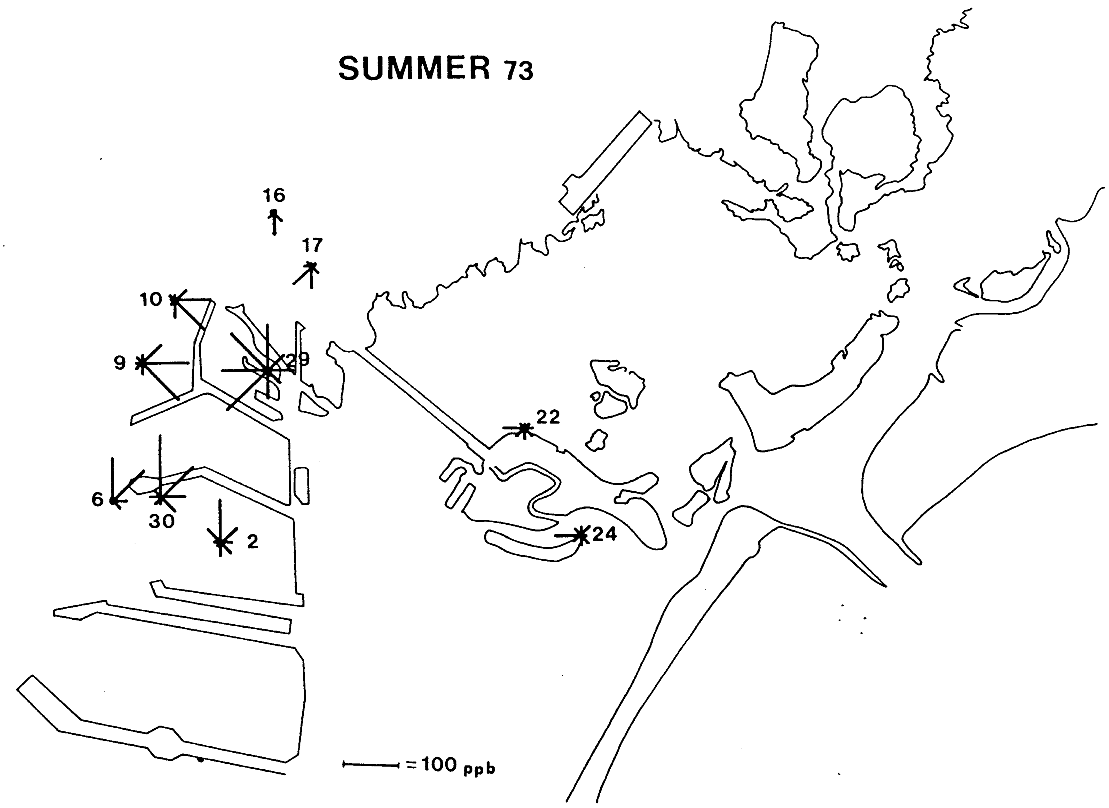

Fig. 3. Pollution roses: summer 1973.

area show winter pollution levels comparable with those located in the industrial area.

The above conclusions have been almost totally confirmed by the application of an air pollution climatological model developed by the authors (Runca *et al.*, 1975).

6. METEOROLOGY AND AIR POLLUTION LEVEL

One of the main problems concerning the pollution of the Venetian area is the evaluation of the effects of the different pollutant sources on concentration levels in the historical center. Therefore careful attention must be paid to wind direction and temperature. The correlation of wind direction and pollution concentration of each station can identify the sources mainly responsible for the pollution measured at the station, while temperature can relate the pollution level to the urban sources, as these emissions are almost totally due to domestic heating. In addition to the above analyses, which are of particular importance for concentrations in the historical center of Venice, additional analyses have been performed as described in the following sections.

A. Effects of wind direction

Pollution roses have been drawn for each station in order to show the mean seasonal SO_2 concentration values for eight wind direction sectors in summer (Fig. 3) and winter (Fig. 4). A general feature seen in the figures is that maximum average concentrations occur when the wind blows from the industrial area towards the station considered. In summer, winds blowing from the urban areas towards the stations are practically "clean winds". In winter, the distributions are more uniform at most of the stations, and of course all the values show a considerable increase in concentration, even for the above mentioned "clean directions", because of the presence of the urban emissions. For Station 29 in winter, any direction is strongly polluted as the station is surrounded by industrial and urban sources.

B. Effects of wind speed

Mean seasonal concentration values have been plotted versus wind speed for every station for two wind direction categories:

1. "polluted winds" from the industrial sources towards a particular monitoring station, and
2. "clean winds" from the remaining directions.

The analysis has been performed for the whole period (Feb. 1973–Jan. 1975) and separately for each winter and summer (Fig. 5). For the "clean winds", the (expected) conclusion is shown, i.e., that the concentration decreases as wind speed increases during the winter heating season reflecting the effects of transport. However, during the non-heating season

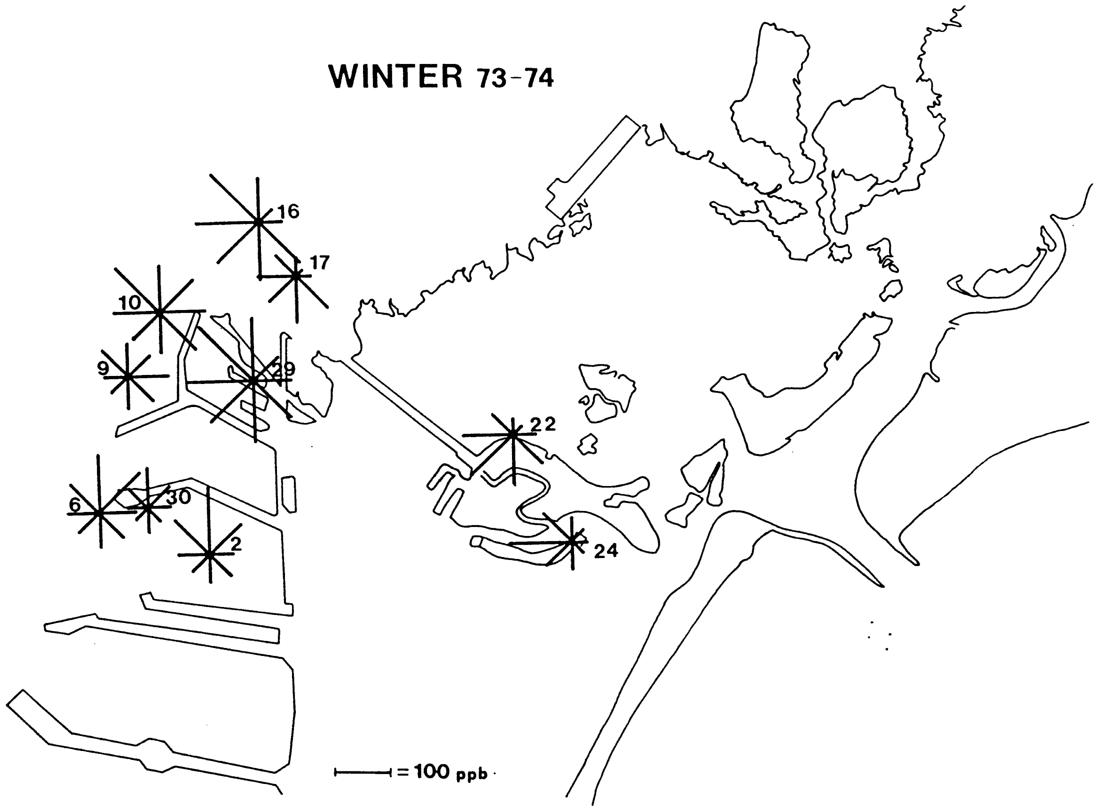

Fig. 4. Pollution roses: winter 1973–74.

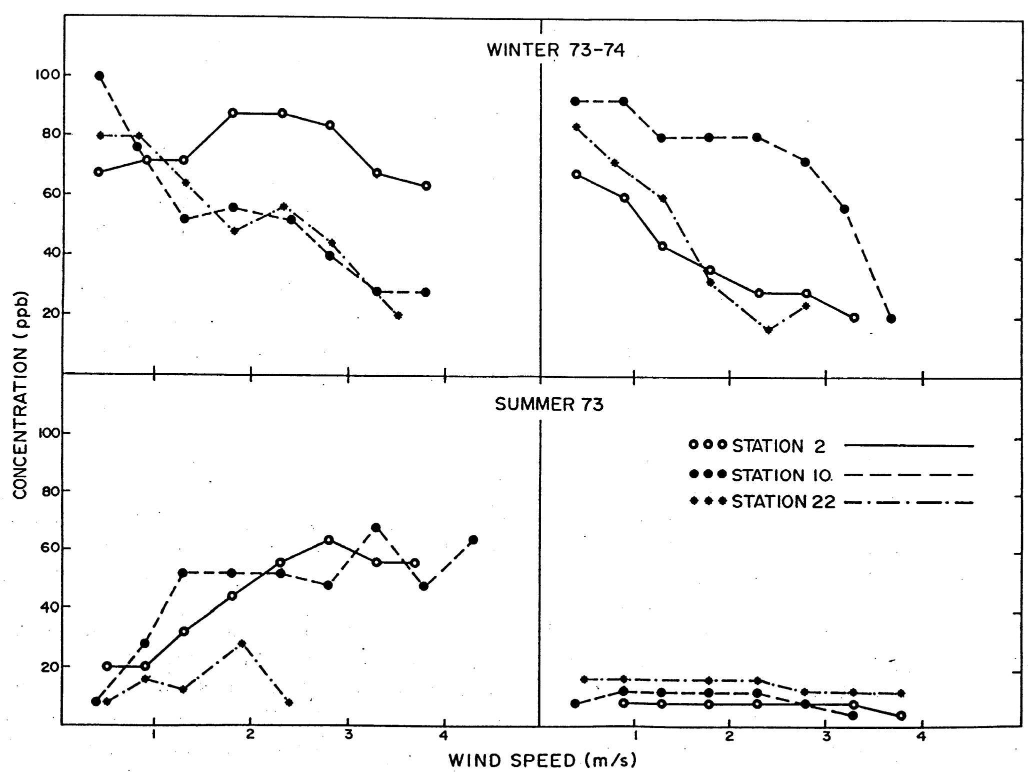

Fig. 5. Seasonal average SO_2 concentrations measured at three stations as a function of wind speed for "polluted" (left side) and "clean" winds (right side).

concentrations are independent of wind speed, and are at some "regional" background level.

The "polluted" winds show a more complicated pattern, in that stations located away from the industrial areas (i.e. 16 and 22) again generally shows a decrease in concentration as wind speed increases. For stations located close to the industrial area (i.e., Stations 9, 10, and 29), the concentration during the summer show a tendency to increase as the wind speed increases, or to remain almost constant in the range of speeds from 1–5 m/s. During the winter the concentration decreases as wind speed increases, except for Station 29 which shows an almost constant value. This is due to the particular location of Station 29 as mentioned before.

For the Stations 2, 6 and 30, the plots for both summer and winter show a maximum value when the wind speed is approximately 3 m/s. If we remember that the occurrence of wind speed higher than this value is rare, we can say that for these stations the concentration increases as wind speed increases. The concentrations at these stations, which are almost totally dominated by the industrial emissions, could be ascribed to a possible reduction in plume rise as the wind speed increases. In addition it must be pointed out that the annual wind rose shows that the strongest wind speeds occur for winds blowing from the "most polluted" directions for these stations.

C. Effects of temperature

By investigating the relationship between average SO_2 concentration and temperature during the whole period of analysis, it has been found that the concentration decreases both in winter and summer as temperature increases for every station but 9 and 10. Examples of this relationship are shown in Fig. 6 for winter and summer for four representative stations. However, in the non-heating season, the average values of the urban stations are independent of temperature.

To explain the behaviour of sensors 9 and 10, "temperature roses" for summer and winter were computed, in which a correlation is demonstrated between temperature class and wind direction. It can be concluded that the SE winds carrying pollutants from the industrial area towards Stations 9 and 10 are associated with higher average temperatures resulting from the unequal latitudinal distribution of solar energy. This explains the behaviour of the concentration in the summer. In the winter these stations show a different pattern due to the presence of urban emissions, whose effect is inversely proportional to temperature. This effect results in a decrease in the concentration as temperature increases up to 8°C. Then, as the effect of the "polluted" winds associated with the higher temperatures becomes important, the concentration increases as temperature increases. Such a phenomenon does not occur at the Stations 2, 6 and 30, since in general winds blowing from the industrial area towards them (i.e., from the N) are associated with lower average temperature and, moreover, such stations are less affected by the urban emissions.

D. Effects of rainfall

Analysis of seasonally average concentrations during rainfall and no rainfall conditions points out that stations located in the urban centers, or close to them, show a decrease of the pollution level during precipitation periods. The reductions are generally slight, but sometimes fall to half of those recorded without rainfall. Stations close to the industrial emissions, mainly Station 2, 6 and 30, seem not to be noticeably affected by the rainfall, especially when they are downwind of the industrial emissions. This might be explainable in terms of the very short travel distances from the industrial sources to these sites.

E. Effects of humidity

The effect of humidity on SO_2 concentration has been studied for each season and for the whole period of analysis. Results show that for Stations 2, 6 and 30 in any season there is an increase of concentration as humidity increases. Stations 9, 10 and 29 show a decrease in concentration in spring and summer as humidity increases, while in autumn and winter they measure an almost constant pollution level as the humidity changes. The above results can be mostly explained, once again, by analysing "humidity roses".

It can be shown that the winds blowing from N and NE have the maximum frequency of high humidity events, which explains the increase of concentration in Stations 2, 6 and 30 as the humidity increases. Thus, winds blowing from the mainland towards Venice are associated with a higher humidity than those blowing from the sea. This result was confirmed by an analysis carried out on data recorded at a meteorological station of the Italian Air Force, and can be explained by the marshy areas in the Padana Valley. Normally, continental air has lower absolute and relative humidities than maritime air. However, due to the marshy areas in the valley, the continental (or northwestern) flows have a lower absolute humidity, but a higher relative humidity, than do the maritime (or southerly) flows.

F. Effects of fog

Average pollution levels have been computed for the cases of no fog, slight fog and thick fog, and the results show that during fog conditions, which occur mainly in winter, monitoring stations located in the urban centers, i.e. Stations 16, 17, 22 and 24, record a high SO_2 concentration value. The increases are so strong that in several cases the concentrations are twice the values recorded during no fog situations. However, the other stations are not substantially affected by the occurrence of fog, and some of them even show a slight decrease of pollution when fog occurs.

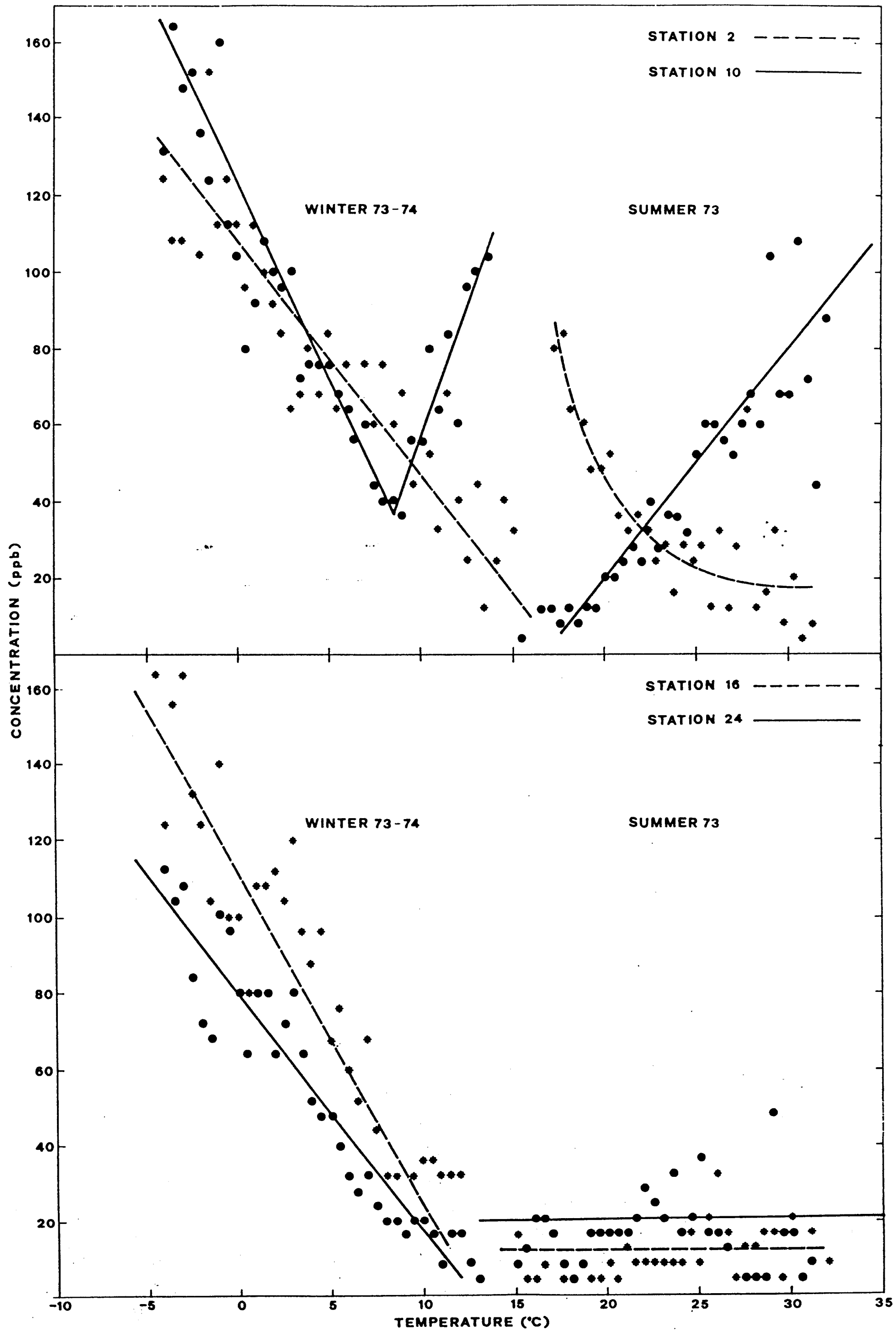

Fig. 6. Seasonal average SO_2 concentrations measured at four stations as a function of temperature.

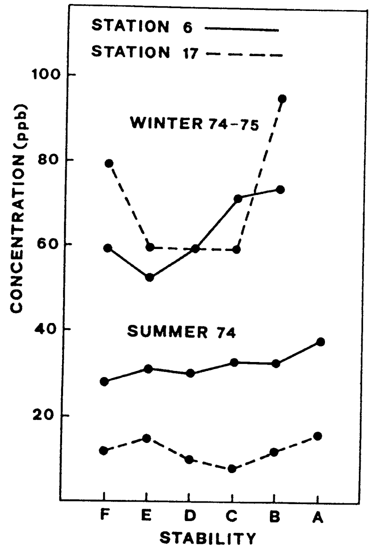

Fig. 7. Seasonal average SO_2 concentrations measured at two stations as a function of Pasquill's stability classes.

The increase of pollution recorded by the stations located in the urban areas can be explained by considering that the atmosphere tends to be near stagnant during evaporation-fog situations. The pattern shown by the other stations can be explained, as before, by considering "fog roses", and by taking into account the relative locations of the sensors and sources during fog and no fog conditions. From these roses it is apparent that fog occurs mainly when the wind is blowing from the mainland towards Venice, which explains the strong increase in concentration recorded by Stations 22 and 24 in fog situations.

G. Effects of stability classes

In the present analysis the stability classes of Pasquill have been used. Examination of histograms of concentration versus stability for every season, does not result in a general pattern for all of the stations. They show a different behaviour according to station location, as occurred for some of the other parameters. Stations 2, 6 and 30, located close to the industrial area and far from urban areas, in any season show higher concentration values as the instability increases (Fig. 7). This is expected, since they are affected almost only by the nearly industrial sources, whose plumes reach the surface more quickly during unstable conditions.

Stations 9, 10 and 29, located close to both urban and industrial sources, have a more complicated seasonal pattern since they do not show a well defined relationship between concentration and stability. This is probably because they are also influenced by domestic emissions. In fact, they behave like the stations located in the urban areas (Stations 16, 17, 22 and 24) which show higher values for unstable and stable situations and a minimum for neutral conditions, especially during winter. It is doubtlessly true that increased stability causes high pollution levels in the urban areas in winter due to the small effective stack heights associated with domestic heating, while the high values of concentration found with unstable conditions could be explained by considering that the few such conditions occurring in the winter are probably associated with cold northerly flows, which tend to warm from below and hence become more unstable. This cold flow causes an increase of the urban emissions.

7. DIURNAL CYCLE

The diurnal variation of SO_2 concentration was analyzed by computing seasonally averaged SO_2 concentration as function of time of day at every monitoring point. For the purpose of this investigation, a discussion of the results from the winters and summers of 1973–74 is sufficient to explain the features of the phenomenon. It has been observed that the pollution levels at sites in certain geographic areas do not show a great variation, and this made it possible to group the monitoring stations into classes having similar locations for the present analysis, as was done for the previous analyses.

Stations located to the south of the industrial area (2, 6 and 30) show a concentration peak in summer at 8–9 a.m. in association with the similar peak in the diurnal cycle of the frequency of "polluted winds" (i.e., N and NE winds). The same explanation, although the relationship between the peaks and the direction of flow is somewhat less evident, can be given for both the well marked peaks of concentration exhibited in winter by the same stations at about 10 a.m. and for the lower peak around midnight.

Stations 9 and 10 (Fig. 8) show a strong increase in summer in the mid afternoon, which is caused by a higher frequency in those hours of the "polluted winds", i.e., sea-breeze winds blowing from the SE. The peaks found in the winter at the same stations at 10 a.m. and 9 p.m. are, on the contrary, completely unrelated to wind direction, and must be ascribed to the diurnal cycle of domestic heating in the neighbouring urban areas. The influence of domestic heating is even more evident in the diurnal cycle found at sites 16 (Fig. 9) and 17. These curves show two marked peaks in the winter at 9 a.m. and 9 p.m. which are equally uncorrelated to wind direction frequency. In the summer, very low pollution levels are found in these stations, and their diurnal cycle can be correlated somewhat to polluted (southerly) winds.

Very low values with no definite trend are similarly found in summer at Stations 22 and 24, located in the historical center, while their behaviour in the winter is rather different from that of sites 16 and 17. The former sensors, in fact, show only one slight peak at 10–11 a.m., which cannot be related to the polluted winds and therefore might be ascribed to the pattern of the domestic heating. Such different behaviours in the urban stations can be explained by

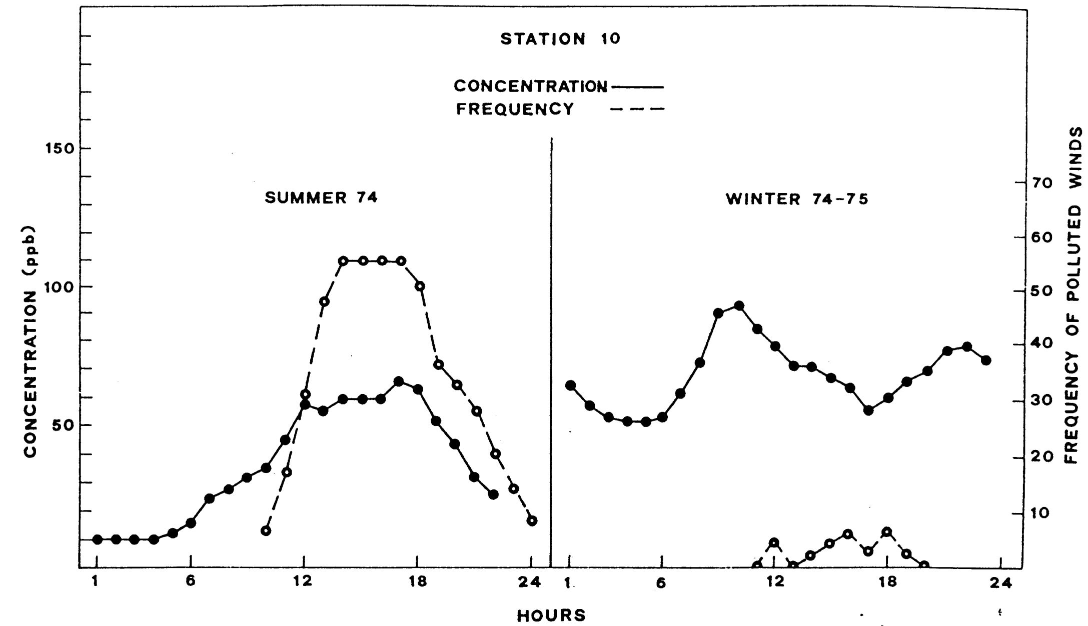

Fig. 8. Seasonal average SO_2 concentrations as a function of time of day compared with the seasonal frequency of "polluted" winds.

a difference in domestic heating systems and/or different local micrometeorological conditions.

At Station 29 two peaks at 10 a.m. and at midnight are clearly shown in its winter diurnal cycle. It is possible that they are related to the diurnal cycle of northerly wind frequency (like the behaviour at Stations 2, 6 and 30), although a definite conclusion cannot be drawn due to its location in the middle of the highly industrialized area. An important peculiarity of the diurnal cycle of Station 29 in summer is a minimum of concentration at 6 p.m. in conjunction with a maximum in the frequency of clean sea-breeze wind blowing from the SE.

In summary, in the winter, the combined effect of domestic heating and of polluted winds blowing from the industrial area causes a peak of concentration in all the stations between 9 and 11 a.m. Moreover, all of the stations, except those located in the historical

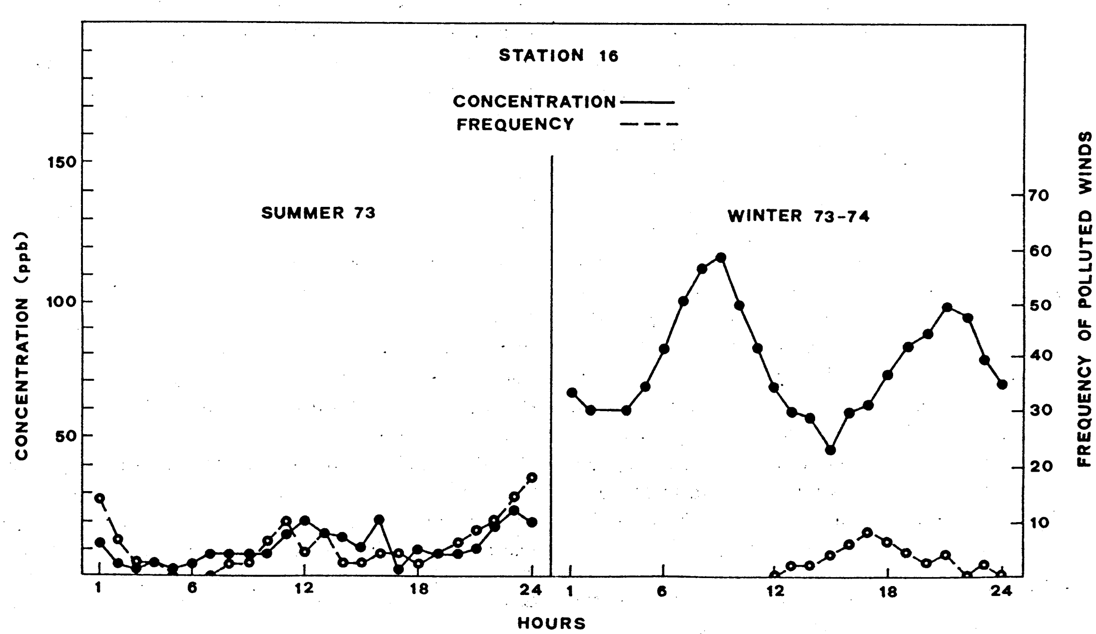

Fig. 9. Same as in Fig. 8 but for another station.

center of Venice, show another peak at night. In the summer the influence of the diurnal cycle of wind direction frequency is predominant and completely explains the patterns of the diurnal cycle at every station.

8. HIGH POLLUTION LEVELS

A. Hourly pollution levels higher than 200 ppb

An analysis of a high pollution event in which an hourly average concentration of 200 ppb, the legal hourly standard in Sweden and in the USA (Yanagisawa, 1973), was exceeded, was carried out for every station, and the results are reported in Table 1. The three figures given for each station in the first line of the table represent the total number of high pollution events recorded in two years (Feb. 1973–Jan. 1975), in the summer of 1974, and in the winter of 1974–75, respectively. In the following lines, the results of the above mentioned analysis are reported according to the classes into which the various meteorological parameters were subdivided. For every meteorological class M, and every monitoring station S, the three figures n_1, n_2 and n_3 refer respectively to the three above mentioned periods. These numbers represent the relative frequencies (multiplied by 1000) of the events of class M in which an hourly average SO_2 concentration higher than 200 ppb was measured at station S. The general conclusion that can be drawn from Table 1 is that the high pollution levels are related to the various meteorological parameters in the same manner shown in the previous chapter for the average pollution levels.

For wind direction in particular, it can be seen that the higher frequencies in the occurrence of high pollution levels are associated at every station with winds blowing from the industrial area towards the station, e.g., Station 30 shows its maximum values of n_1 (7%) for winds blowing from the N. At the historical center of Venice, the frequencies of the above events are generally low, particularly at Station 24. The particular influence of wind speed, already mentioned in the chapter on the analysis concerning this parameter, is even more evident in Table 1. Again, all of the stations except 2, 6 and 30 show the expected decrease of pollution episodes in conjunction with an increase in wind speed. Similar observations can be made for temperature, an increase of which causes a decrease of episode frequency in all the stations but 9 and 10, whose particular behaviour was explained by the "temperature roses". Finally, for rainfall, it can be concluded that for high pollution levels also, the general phenomenon of washout is not found in this data due to the very short travel distances between the SO_2 sources and the monitoring sites.

B. Pollution episodes recorded at the Venice stations

In addition to the previous study, an analysis of the concentration data from Stations 22 and 24 (both in the city of Venice) has been carried out during the occurrence of the following two situations:

1. A continuous increase in measured SO_2 concentrations for at least 6 h, with a final value greater than 100 ppb. The 6 h period was selected by trial and error.

2. A persistent occurrence for at least 6 h of SO_2 values greater than 100 ppb.

The seasonal frequency of occurrence of the above defined episodes is reported in Table 2. The main conclusion to be drawn from the table is that these episodes occur mainly during the heating season. Furthermore, those episodes during non-calm conditions only occur with a light wind blowing from the industrial area. Hence, taking into account the spatial distribution of emissions, and the results from the application of the climatological version of the Gaussian diffusion model of Runca *et al.* (1975), it can be concluded that domestic emissions produce a SO_2 background, while industrial emissions are required for the occurrence of the high-concentration episodes. Therefore, if the occurrence of episode could be predicted, and the emissions from the mainland temporarly reduced, it would be possible to keep pollution levels in the historical center under the legal standards.

Episodes of type 1 were found to occur under the following meteorological conditions: a wind speed less than 2 m/s, an absence of rainfall, and generally high pressure and relative humidity. As for type 2 episodes, analysis gave results which were slightly different from the previous ones. The differences concerned the wind speed, which was found to be around 1 m/s, and the occurrence of the phenomenon generally in conjunction with fog situations. Such differences between the characteristics of type 1 and 2 episodes are expected, since the former is probably related to a transport phenomenon, while the latter is probably related to stagnation situations associated with the presence of evaporation fog.

9. CONCLUSIONS

Sulfur dioxide concentrations measured over a two year period in the Venetian area were found to be caused both by industrial and urban sources, and were studied with respect to different meteorological conditions. A well marked difference in behaviour was detected between monitoring stations located in areas affected almost entirely by the industrial emissions and those influenced also by the local urban sources.

From the analysis of the effects of various meteorological parameters, wind direction was found to be the parameter best correlated with pollution concentration. However, only a cross analysis of direction with other meteorological parameters (e.g., temperature or relative humidity) could explain most of the trends in the level of concentration.

Table 1. Tabulation of SO_2 hourly average concentrations higher than 200 ppb. See text for the explanation of entries.

		Station 2			Station 6			Station 30			Station 9			Station 10			Station 29			Station 16			Station 17			Station 22			Station 24		
		267	8	40	381	14	25	452	17	36	464	38	27	348	11	36	698	9	214	402	2	147	140	3	22	141	2	32	76	0	3
Wind direction	West	1	0	0	2	0	0	1	0	0	1	0	4	11	0	21	78	41	121	60	0	126	10	0	0	40	20	39	41	0	4
	South–West	0	0	0	1	0	0	2	0	0	1	0	3	8	0	0	61	0	129	34	0	68	20	10	20	40	0	54	8	0	3
	South	1	0	0	0	0	0	8	0	0	13	0	0	13	0	0	16	0	38	44	9	48	43	9	29	5	0	0	1	0	0
	South–East	4	0	29	5	0	29	10	0	58	94	42	88	59	13	88	6	1	117	10	1	88	4	1	29	1	0	29	4	0	0
	East	3	0	38	8	4	0	10	4	0	65	19	12	30	14	51	20	0	0	3	0	12	1	0	0	2	4	0	0	0	0
	North–East	28	4	91	35	8	21	24	14	3	10	14	21	5	2	14	10	0	7	2	0	0	0	0	0	0	0	0	0	0	0
	North	33	16	15	51	21	22	70	24	54	8	8	11	8	0	15	47	8	109	17	0	54	1	0	4	0	0	2	0	0	0
	North–West	6	0	0	3	10	0	11	0	0	7	0	15	21	0	15	110	21	234	42	0	113	7	0	0	0	0	0	2	0	0
	Missing data	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Calm	1	0	0	3	0	8	11	0	12	13	4	8	17	0	14	40	4	89	41	0	87	7	0	18	11	0	8	3	0	2
	Variable	13	0	57	29	0	76	31	0	57	39	24	76	21	0	76	79	0	288	37	0	134	11	0	19	13	0	19	1	0	0
Wind speed (m/s)	0–1.5	4	1	4	8	0	8	13	3	12	19	18	14	19	1	19	47	3	115	37	2	88	10	0	14	15	0	18	6	0	2
	1.5–3	15	4	17	30	12	20	33	12	34	32	15	9	15	5	11	32	5	79	13	0	28	5	1	1	3	1	7	2	0	0
	>3	46	9	195	25	0	16	30	0	0	17	22	0	29	18	8	30	0	0	4	0	0	6	4	0	0	0	0	0	0	0
Tempera-ture (°C)	<5	23	0	9	27	0	12	37	0	25	13	0	13	32	0	18	111	0	134	83	0	108	17	0	14	28	0	21	9	0	0
	5–15	18	0	28	24	0	10	23	16	7	21	0	11	16	0	14	34	32	62	17	0	25	7	0	5	6	16	7	4	0	1
	15–25	7	4	0	16	8	0	24	8	0	26	6	0	13	0	0	15	4	0	1	0	0	3	1	0	0	0	0	0	0	0
	>25	7	1	0	5	3	0	10	4	0	65	46	0	31	16	0	7	1	0	6	3	0	4	1	0	0	0	0	4	0	0
Pressure (mm/Hg)	<752.5	10	0	0	17	0	0	12	0	0	27	0	0	17	0	0	44	0	0	1	0	0	8	0	0	5	0	0	3	0	0
	752.5–757.5	9	0	0	21	14	0	22	7	0	15	0	0	13	7	0	30	7	60	10	0	0	7	0	0	1	0	0	1	0	0
	757.5–762.5	9	6	5	20	6	0	27	5	5	19	2	16	11	1	0	30	5	108	11	0	54	4	2	5	4	2	5	4	0	0
	762.5–767.5	10	2	6	19	6	10	21	10	2	33	29	14	20	6	8	24	2	78	15	1	51	5	0	8	4	0	22	3	0	2
	>767.5	29	0	26	24	0	14	29	0	24	24	22	12	28	14	23	70	7	109	51	0	81	14	0	12	18	0	14	5	0	1
Relat. Humid. (%)	<60	23	0	92	14	3	13	15	1	4	52	32	17	33	3	21	30	1	61	11	0	17	6	1	4	2	0	0	5	0	4
	60–80	16	6	29	21	5	11	26	9	40	33	23	6	25	10	26	38	2	111	21	2	49	10	2	13	3	0	4	1	0	2
	>80	10	3	4	22	8	11	26	10	11	11	3	13	10	1	13	40	6	102	25	0	82	6	0	10	12	2	20	5	0	0
Rain	no rain	14	3	19	21	6	11	25	8	16	26	18	12	20	4	17	40	4	100	23	0	70	8	1	10	8	0	15	4	0	1
	light rain	17	0	0	23	0	0	17	0	50	8	0	0	5	34	0	20	0	100	0	0	0	0	0	0	0	0	0	0	0	0
	heavy rain	17	12	0	11	0	0	17	0	0	2	0	0	0	0	0	5	0	41	0	0	0	0	0	0	1	12	0	0	0	0
Fog	no fog	16	3	31	22	6	12	26	8	24	26	16	12	18	4	20	32	4	88	17	0	64	6	1	5	2	0	4	2	0	2
	slight fog	2	0	7	11	0	5	22	0	10	21	45	7	19	11	7	41	0	92	20	0	28	5	0	1	7	0	3	3	0	0
	thick fog	14	0	7	17	0	16	14	0	9	17	0	18	23	0	20	108	0	129	89	0	120	33	0	27	73	0	46	22	0	0
Cloudi-ness	no clouds	15	4	19	19	5	9	28	7	17	30	22	10	25	6	19	42	4	114	29	1	91	9	0	13	9	0	19	4	0	1
	light clouds	14	0	31	17	10	28	19	10	25	28	10	31	13	0	22	37	3	79	11	0	28	5	6	8	7	0	5	4	0	2
	overcast	12	2	2	27	7	2	18	7	5	8	2	2	5	4	0	26	4	62	6	0	14	2	2	0	2	2	5	3	0	0
Pasquill's Atmospheric stability	F	8	0	6	11	7	6	14	1	10	11	5	8	14	0	7	31	3	60	32	3	73	9	0	2	10	0	14	2	0	2
	E	21	0	28	15	0	28	18	0	8	8	0	16	8	0	8	35	0	36	17	0	20	9	0	0	5	0	4	5	0	0
	D	17	3	17	23	4	6	22	6	12	14	4	9	14	9	7	33	3	80	19	0	71	5	3	10	6	1	15	4	0	1
	C	17	3	56	31	10	12	40	6	38	46	34	17	37	17	43	63	13	219	13	0	25	4	0	0	7	3	17	5	0	0
	B	13	7	22	26	7	33	38	19	44	67	33	33	30	0	71	43	1	287	22	0	160	11	1	71	7	0	27	4	0	0
	A	9	9	0	16	0	0	42	0	0	48	45	0	16	0	0	9	0	0	0	0	0	3	0	0	3	0	0	3	0	0

Table 2. Seasonal frequency of episodes recorded at the Venice stations of both "a continuous increase" and "a persistent situation" of high pollution levels

		Spring 73	Summer 73	Autumn 73	Winter 73–74	Spring 74	Summer 74	Autumn 74	Winter 74–75
Station 22	Continuous increase	2	0	5	4	0	0	7	9
	Persistent situation	1	0	6	12	0	0	1	20
Station 24	Continuous increase	1	0	3	4	0	0	2	7
	Persistent situation	0	0	8	13	1	0	1	3

The pollution level in the city of Venice was found to be considerably lower than on the mainland. Nevertheless, particular meteorological conditions occurring in winter, as well as the influence of both urban and industrial sources, produced a limited number of episodes in which pollution levels were reached which were comparable to those in the industrial area. These situations most frequently occurred in conjunction with very light westerly winds, i.e., winds blowing from the industrial area towards Venice.

As a last comment on the unfavourable situation confronting Venice in the winter, it must be emphasized that with strong winds blowing from SE, i.e., in low pollution conditions, the meteorological situation is favourable for the other peril threatening Venice, i.e., "high water".

In the future, these data will be used in conjunction with various pollution and boundary layer models in an attempt to further define the complex relationship existing in the Venice area between meteorological parameters and the contributions of the local and industrial sources to the observed SO_2 pattern.

Acknowledgement—The authors are indebted to Tecneco and Istituto Superiore di Sanità for providing the data for this study. Sincere appreciation is expressed to Dr. S. Boscolo for his help in the analysis of the data and in carrying out some of the required computer programming. Appreciation is also extended to Prof. R. Bornstein of the Department of Meteorology at San José State University for his careful review of the final manuscript.

REFERENCES

Camuffo D. and Fassina V. (1974) Metodi d'analisi ed interpretazione fisica delle misure di SO_2 effettuate in Venezia nel 1972. *Inquinamento*, Vol. XVI N.5, Etas Kompass, Milano.

Dechigi M. and Paccagnella B. (1954) Inquinamento atmosferico da prodotti della combustione e dell'attività industriale. Proceedings of the 17th National Congress of the "Associazione Italiana per l'Igiene", Venice, October.

Giordani Soika A. and Meneghini D. (1970) Di alcune modificazioni del clima di Venzia nell'ultimo trentennio: ripercussioni sul fenomeno dell'acqua alta. *Bollettino del Museo Civico di Storia Naturale, Venice*. Vol XX–XXI.

Janeselli R. (1959–1974) Osservazioni eseguite nell'osservatorio meteorologico dell'Istituto Cavanis di Venezia. *Atti dell'Istituto Veneto di Scienze, Lettere ed Arti, Venice* (published yearly).

Raynor G. S., Smith M. E. and Singer I. A. (1974) Meteorological effects on sulfur dioxide concentrations on suburban Long Island, New York. *Atmospheric Environment* **8**, 1305–1320.

Raynor G. S., Smith M. E. and Singer I. A. (1974) Temporal and spatial variation in sulfur dioxide concentrations on suburban Long Island, New York. *J. Air Pollut. Control Ass.*, **24**, 586–590.

Runca E. and Zannetti P. (1973) A preliminary investigation of the air pollution problem in the Venetian area. Technical Report, Venice IBM Scientific Center.

Runca E., Melli P. and Zannetti P. (1976) Computation of long-term average SO_2 concentration in the Venetian area—*Appl. Math. Mod.* **1**, 9–15.

Several Authors (1973) Sistema di rilevamento dell'inquinamento atmosferico nella zona di Venezia. Technical Report PROT/AGA N.60, Tecneco, Fano, Italy.

Sordelli D., Zilio Grandi F. *et al.* (1972) Ricerche sull'inquinamento atmosferico della zona di Porto Marghera, Mestre, Venezia. Proceedings of the "Convegno Internazionale di Studi: Antinquinamento 1972", Milano, November.

Stern A. C. (1968) editor. *Air Pollution*. Academic Press, Vol. 1.

Vendramini R. (1960) Relazione sui risultati delle rilevazioni sistematiche eseguite dal 1956 al 1959 sull'inquinamento dell'aria nella zona di Mestre e Marghera. Technical Report, Istituto di Igiene, University of Padua.

Vendramini R. (1973) Inquinamento atmosferico e sue proposte per combatterlo. Technical Report, Istituto di Igiene, University of Padua.

Yanagisawa S. (1973) Air quality standards national and international. *J. Air. Pollut. Control Ass.*, **23**, 945–948.

Zannetti P., Melli P. and Runca E. (1976) SO_2 in Venezia: analisi e prospettive. Proceedings of the 3rd Meeting "Ambiente e Risorse", University of Padua, Bressanone, September 1975.

Zilio Grandi F. (1975) Ricerche sulla qualità dell'aria nella zona di Porto Marghera, Mestre e Venezia. Proceedings of the 2nd Meeting "Ambiente e Risorse", University of Padua, Bressanone, September 1974.