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SULPHUR-DIOXIDE CONCENTRATION IN THE NORTHERN ADRIATIC HEALTH RESORT AREA

Koncentracije sumpornoga dioksida na rekreacijskom području sjevernog Jadrana

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Abstract – The series of 1226 samples of 24-hours SO_2 concentration data in Veli Lošinj during the period 1986–1989 have been analysed together with basic meteorological variables measured on Mali Lošinj at 3 climatological terms. The day-to-day synoptic weather types are examined in order to relate synoptic scale flow patterns to the SO_2 concentration data. The pollution level in Lošinj area was found to be considerably lower than the minimum legal value of SO_2 based on public health criteria which is 60 μgm^{-3} for 24 hours. Nevertheless, particular meteorological conditions such as anticyclonic situations with slight winds from SW–NW direction in winter and bora favourable conditions in spring produced the limited number of situations with 24-hour SO_2 concentration level greater than 40 μgm^{-3}. From the analysis of the effects of various meteorological elements wind speed and directions were found to be best correlated with the pollution concentration. It is shown that the worst cased air pollution situations in areas of low emission rates are not necessarily stagnation periods but my be periods with good ventilation.

Key word index: SO_2 concentration, Northern Adriatic, weather types.

Sažetak – U radu je analiziran niz od 1226 dnevnih uzoraka koncentracije SO_2 u Velom Lošinju u razdoblju 1986–1989 te osnovni meteorološki elementi izmjereni u Malom Lošinju u tri klimatološka termina. Kako bi se utvrdio odnos strujanja na sinoptičkoj skali s izmjerenim koncentracijama sumpornoga dioksida analizirani su svakodnevni tipovi vremena na sjevernom Jadranu. Pokazalo se da je nivo onečišćenja u Lošinju znatno manji od minimalnih vrijednosti 24-satne koncentracije SO_2 zasnivane na zakonskom kriteriju (60 μgm^{-3}). Ipak, specifične meteorološke prilike kao što su anticiklonalne situacije sa slabim strujanjem SW-NW smjera zimi i situacije s burom u proljeće doprinose pojavi ograničenoga broja slučajeva s dnevnim vrijednostima koncentracije SO_2 koje prelaze 40 μgm^{-3}. Analiza temperature zraka, insolacije te smjera i brzine vjetra pokazala je da je vjetar najbolje koreliran s iznosom 24-satne koncentracije sumpornoga dioksida.

Ključne riječi: koncentracije SO_2, sjeverni Jadran, tipovi vremena.

1. INTRODUCTION

Air pollution is a common problem in many places around the world where a widespread industrial and urban development has occurred. This is also the case in the Rijeka region on the northern Adriatic coast where during the last decades a large industrial area has been developed. A variety of pollutants, continuously emitted into the atmosphere, associated with characteristic meteorological conditions and orographically induced processes have created serious air pollution problems in the Kvarner Bay area.

The Kvarner Bay includes the island of Lošinj which represents an "oasis of health" for chronic diseases like bronchial asthma or chronic bronchitis. It is very important to save this health resort area from air pollution and its devastating effects. The wish to save the area and the need to plan industrial development have led to this study of the air pollution problem. For this purpose, a station monitoring SO_2 concentration data has been set up in the last few years on the islands of Lošinj. Five-year data from this station have made it possible to carry out the present analysis, the purpose of which is to show the air pollution condition in the

area and to relate the air pollution levels to meteorological parameters. Attention will be particularly paid to the cases of high SO_2 concentration and the interaction of synoptic-scale through local-scale flow patterns as related to the effective transport of air pollutants to the subject area.

2. AREA OF STUDY

The island of Lošinj is part of the greatest island group in the northern Adriatic region (the Cres–Lošinj archipelago). A great variety of landscapes, vegetation and soil together with their extremely attractive coastline make these islands an important tourist area. A map of Lošinj and its surrounding area (presented in Figure 1) gives the location of the various landmarks and measurement sites referred to in this paper. The greatest number of pollution sources (an oil refinery and petroleum industry, a cokery, a thermal power plant, local industrial sources, heavy traffic and household heating) is sited in the urban area of Rijeka, as indicated on the map. Since there are no significant sources of air pollution on the island of Lošinj, the consequences and possible implications on air quality have to be discussed with regard to Rijeka as the main source of pollution.

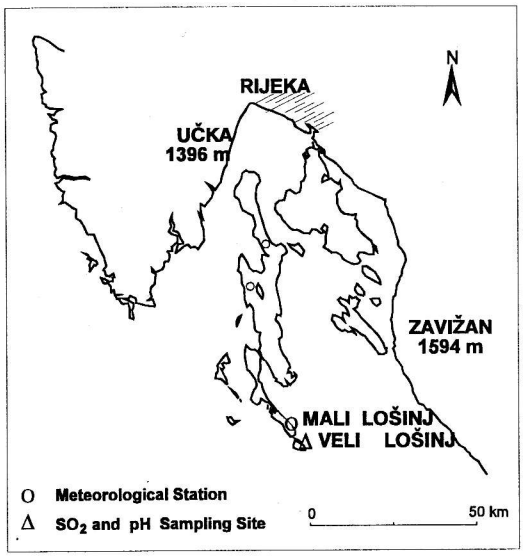

Figure 1. The Northern Adriatic area with the meteorological and air quality measurement sites referred to in the paper.

Slika 1. Područje sjevernoga Jadrana s lokacijama meteoroloških mjerenja i mjerenja kvalitete zraka koje se spominju u članku.

3. DATA

The sampling of 24-hour SO_2 concentration data (the bubbler technique with pre-filter and H_2O_2 solution) has been organised in Veli Lošinj on the initiative of The Children's Hospital for Allergic Diseases. The program of the measurements is provided by The Public Health Institute in Rijeka. In the vicinity of sampling site there is no pollution sources.

A series of 1226 samples during the period 1986–1989 has been analysed together with the leading meteorological variables measured in Mali Lošinj on 3 climatological terms. In order to relate the synoptic scale flow patterns to the SO_2 concentration data the day-to-day synoptic weather types have been exam-

Table 1. Statistical parameters of SO_2 concentration (μgm^{-3}) in Veli Lošinj (1986–1989).

Tablica 1. Statistički parametri koncentracije SO_2 (μgm^{-3}) u Velom Lošinju (1986–1989).

	N	NM	Avg	Med	Std	20p	50p	70p	90p	95p	98p	99p	Max	N HCD
Year	1226	236	14.7	10.0	15.0	3	10	18	34	42	56	67	103	79
Win.	227	134	25.7	24.0	13.9	13	24	33	44	61	67	63	77	35
Spr.	274	94	17.0	14.0	14.4	4	14	22	34	43	64	73	82	18
Sum.	361	7	6.2	4.0	7.5	3	4	6	12	16	22	39	76	3
Aut.	364	0	14.5	11.0	16.6	3	11	16	28	43	65	79	103	23

Legend:
N – number of samples
NM – number of missing days
Avg – average value
Med – median
Std – standard deviation
p – percentiles
N HCD – number of days with SO_2 concentration $>40\,\mu gm^{-3}$

Legenda:
N – broj uzoraka
NM – broj nedostajućih šodataka
Avg – srednja vrijednost
Med – medijan
Std – standardna devijacija
p – percentili
N HCD – broj dana s koncentracijom SO_2 $>40\,\mu gm^{-3}$

ined. This analysis has been performed for the whole period and separately for each season.

4. SO_2 CONCENTRATIONS

When sets of air quality data exist, their statistical characteristics can be determined and assigned to the pollution concentrations. Such treatment provides a simple and compact representation of the data.

The fact that there are no significant sources of pollutants on the island of Lošinj is easily visible from the SO_2 statistical parameters given in Table 1.

Concentration levels generally show very low values in both seasonal and yearly data, with some differences between seasons. The mean concentrations in winter are more than four times greater than in summer. A substantial increase in pollution levels during winter is due both to the presence of local domestic emission and to a meteorological situation which is favourable to high pollution levels, as will be shown in the following sections. Fifty percent of the data have values less than 10 μgm^{-3}. Except for one single sample, the observed maximum concentrations do not exceed 100 μgm^{-3}. Only 5% of the data are greater than 40 μgm^{-3} which is almost three times greater than the average value. In contrast to these data, the average yearly SO_2 concentrations for the same period in the urban area of Rijeka at some specific locations exceed 100 μgm^{-3}

Although much below the permissible 24-hour concentration value, concentrations > 40 μgm^{-3} in Lošinj should not be ignored since they are related to some specific meteorological conditions and enhanced transport of pollutants from other regions (the Rijeka Bay, Northern Italy, Central Europe). In an attempt to identify those meteorological conditions associated with high concentrations of sulphur dioxide in the considered area, all the days in which concentration exceeded 40 μgm^{-3} were selected for a further analysis and will henceforth be defined as high SO_2 concentration data (HCD) in that particular area.

5. SYNOPTIC WEATHER PATTERNS IN DAYS WITH HIGH SO_2 CONCENTRATION

Weather is considered to be the ultimate forcing function for many, if not most, environmental processes. There are several classification schemes that organise the atmospheric circulation patterns and the resultant weather into categories of types. The most famous classification systems are particularly associated with the European studies of the Northern Atlantic Ocean and Europe (Hess and Brezowsky, 1969 and Lamb, 1972). These classic studies focused a geographical organisation of weather patterns over large regions and even an entire hemisphere. Poje (1965) developed a classification of weather types for smaller regions such as the Northern Adriatic area (Table 2). His classification is based on the patterns of pressure systems on daily weather maps and the associated weather characteristics.

Environmental systems respond to such day-to-day synoptic weather types and to their succession (especially to persistent runs of types for a period of days). The synoptic calendars of modified Poje's weather types for the period of 1986-1989 have been used in this paper in order to analyse the meso-scale synoptic situations in the days with high SO_2 concentrations.

The relative frequency of HCD days in the different weather type categories is presented in Figure 2, along with the frequency of weather categories, determined through a 5 year period. The most common weather types in the Northern Adriatic during winter are anticyclones and bridges of high pressure, while a zero pressure gradient field dominates in other seasons. The strengthening of cyclonic activity in the spring over the Genoa Bay results in specific flow patterns on the front side of such cyclone (Northern Adriatic) which contribute to temperature inversion conditions and a greater frequency of weather type 2. It was found that more than 50 % of HCD days fall into one of 3 categories: anticyclone, bridge of high pressure and cyclone. Anticyclonic weather types are generally related to the highest level of concentration, especially in winter and autumn, which are the seasons with a greater number of HCD days. SO_2 concentration is greater than 40 μgm^{-3} in more than 50 % of the days with an anticyclone over the Northern Adriatic. The variation of the meteorological parameters associated with this type shapes the characteristic image of the weather in the considered area.

6. METEOROLOGICAL CONDITIONS DURING DAYS WITH HIGH SO_2 CONCENTRATION

Although synoptic pattern classifications are very useful to form an overall picture, each individual weather system has its own unique characteristics and may greatly influence the transport of pollutants and the concentration levels over a region. Therefore, the behaviour of wind, temperature and insolation in describing the observed pollutant concentrations was outlined. for the whole period and separately for winter, spring and autumn. The summer data were not considered because of only 3 HCD days.

Wind speed and direction

Seasonal winds are characteristic for the Northern Adriatic coast and its islands: the Bora (a relatively cold, strong and gusty wind blowing from the north-eastern quadrant), the Sirocco (a relatively warm and steady wind from the south-eastern quadrant) and the so called coastal circulation. The wind direction distribution for the separate seasons and the year shows that the prevailing wind direction in Mali Lošinj is from NNE (Figure 3). However, there are important seasonal variations. In particular, the frequency of winds blowing from S–SE is generally low but becomes comparable to the frequency of NNE winds in spring as a consequence of the strong cyclonic activity in that part of the year.

Table 2. Brief description of the six weather types used.

Tablica 2. Kratki opis šest upotrebljenih tipova vremena.

weather type	description
type 1	An anticyclone over the Northern Adriatic or larger area (Mediterranean)
type 2	A bridge or ridge of high pressure over the Northern Adriatic. A bridge of high pressure, between two depressions, has generally an W-E oriented axes in winter and SW-NE in summer. A ridge is mostly coupled with an anticyclone in Western Europe or the Azores
type 3	A cyclogenesis in the Genoa Bay or a depression in the Bay of Trieste which (with their isobaric systems) cover the Northern Adriatic
type 4	A low pressure trough over the Northern Adriatic, usually with a N-S or NW-SE axis and depression dominated over Northern Europe
type 5	A zero pressure gradient field over the Northern Adriatic
type 6	Transitional types, mostly with a southeasterly, easterly, westerly or northeasterly flow over the Northern Adriatic

When grouped by wind direction, the percentage of HCD cases with NNE wind was very high and ranged from 25% in winter to 39% in autumn. It is obvious that high concentrations with NNE winds occur more often than it would be expected from the distribution directions. This is in accordance with the more frequent occurrence of 1 and 2 weather types in HCD days. A cold air supply from the north, associated with a huge continental anticyclone or deep high pressure ridge, exists in such bora favourable situations (Jurčec, 1989). A bridge of high pressure with a W–E oriented axis coupled with an anticyclone in the Azores is the reason for more frequent W winds in HCD days in winter compared with their frequency determined by using all days. The persistence of cyclonic circulation in the Genoa Bay enables air pollution from Northern Italy to reach the Lošinj area in a south-westerly flow. Consequently, the frequency of SW directions is greater in HCD days than in all days. Wind speed in such situations is often very low, even calms can be observed (8.6% in HCD days). The concentration increases as wind speed decreases during the winter heating season reflecting the effects of insufficient air mixing and low dispersion. Opposite conditions dominate during spring in days with SO_2 concentration $>40\ \mu gm^{-3}$. Up to 80% of HCD days in that season are observed in March, a month with very strong cyclonic activity and frequent front passages over the Northern Adriatic accompanied by a strong bora wind (Bajić, 1989).

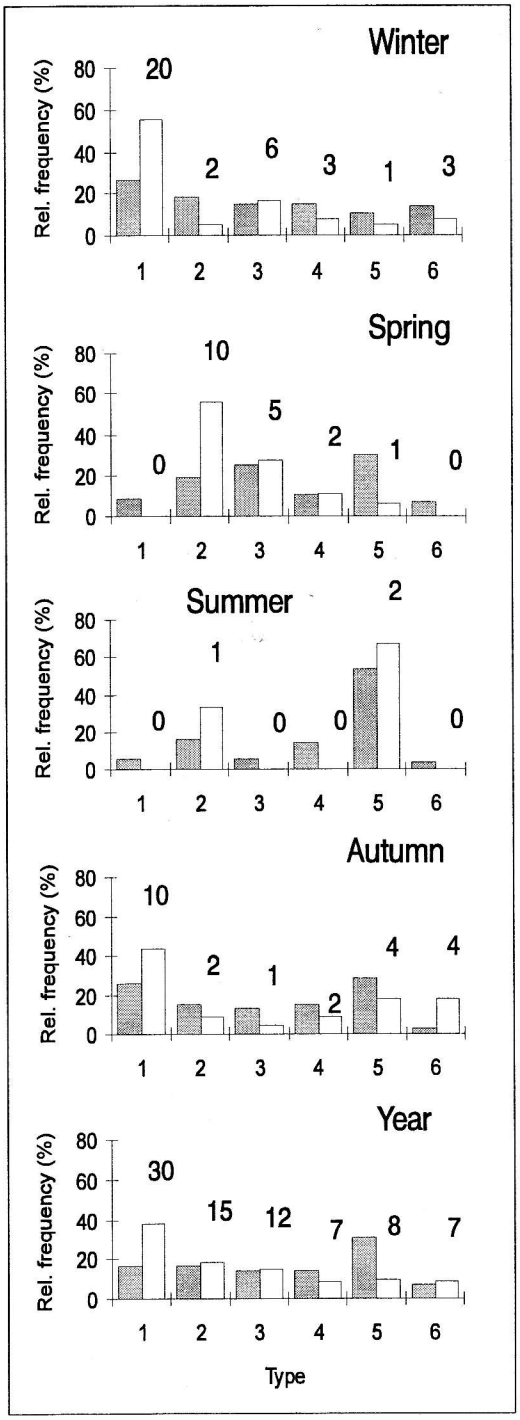

Figure 2. The relative frequency of the Northern Adriatic weather types occurrence in all (dashed bars) and HCD (white bars) days for 1986–1989. The number of days with high SO_2 concentrations are indicated above the bars.

Slika 2. Relativne učestalosti tipova vremena na sjevernom Jadranu u svim danima (osjenčeni stupci) i HCD-danima (bijeli stupci) za 1986–1989. Broj dana s visokim koncentracijama SO_2 označen je iznad stupaca.

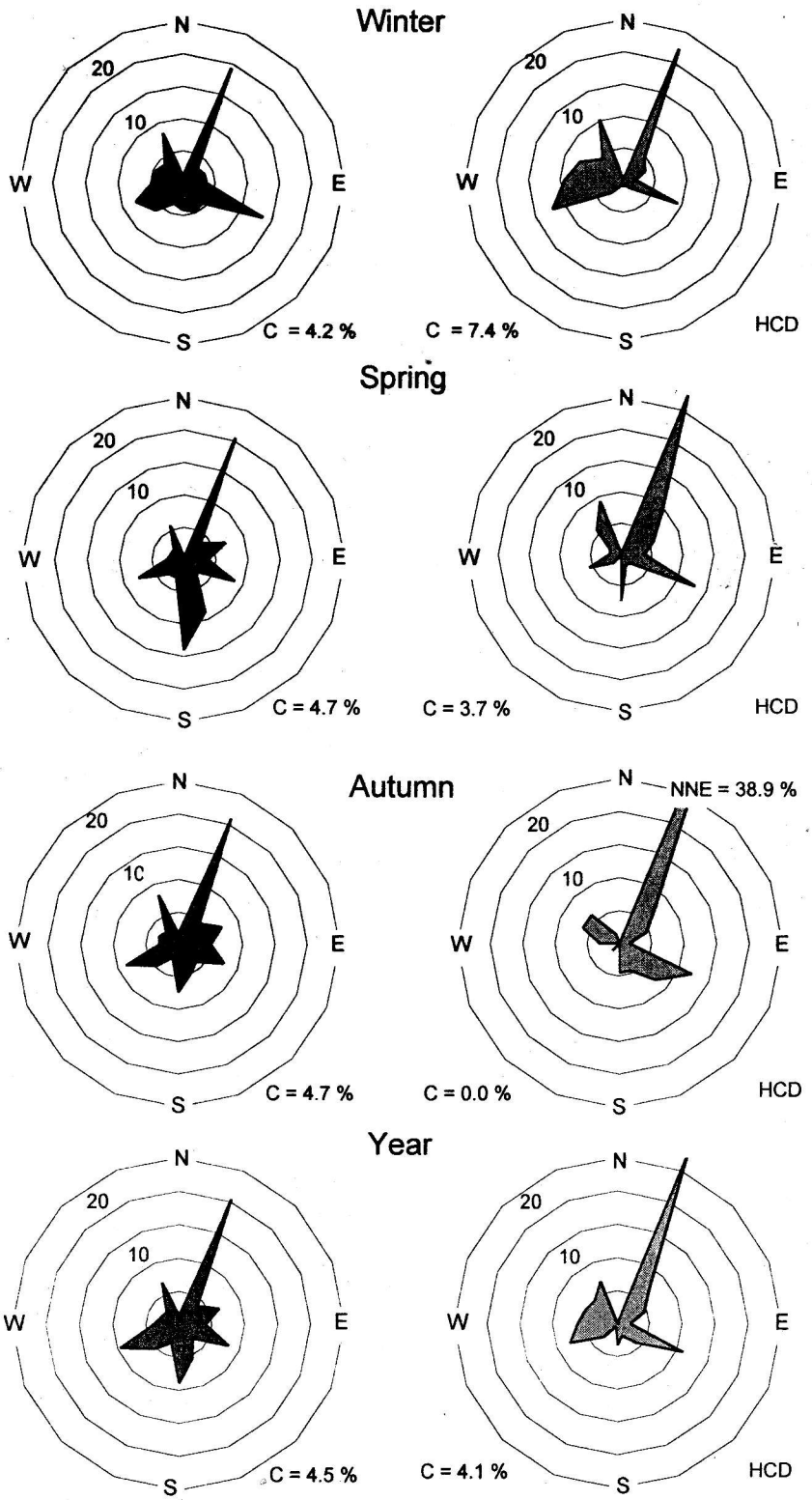

Figure 3. Wind roses for Veli Lošinj (19861–989). Left – all days, right – HCD days
Slika 3. Ruže vjetra za Veli Lošinj (1986–1989). Lijevo – svi dani, desno – HCD-dani.

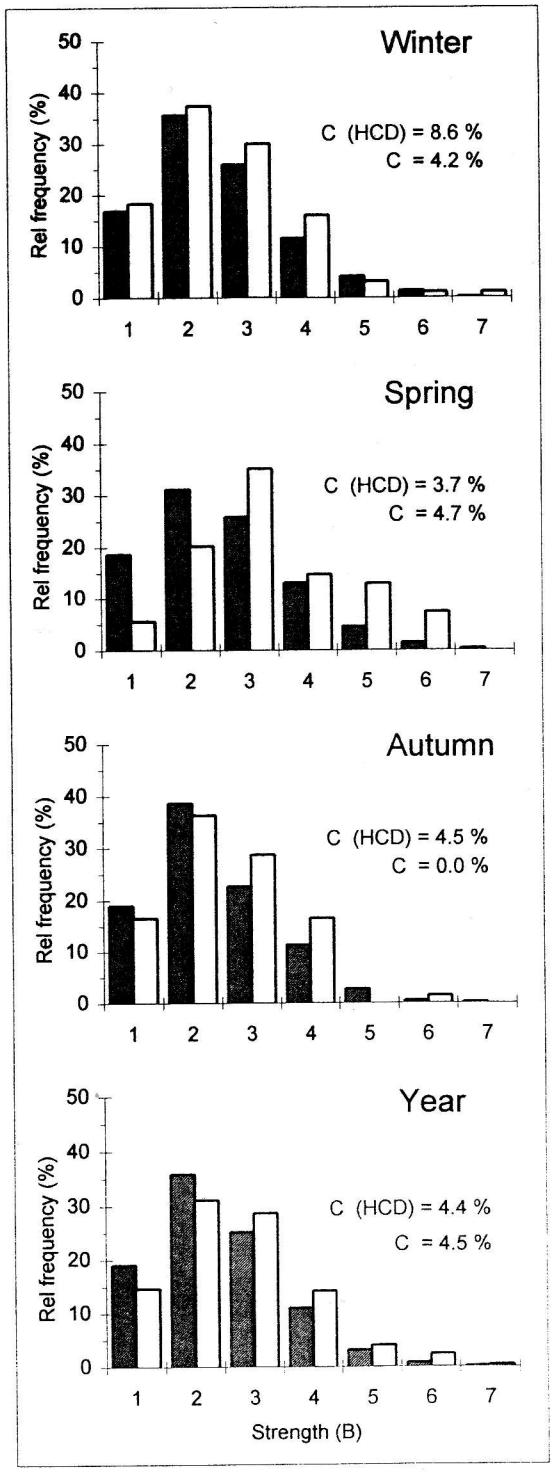

Figure 4. The relative frequency of wind strength for the whole period 1986–1989 (shaded bars) and for HCD days (white bars) in Veli Lošinj

Slika 4. Relativna učestalost jačine vjetra za čitavo razdoblje 1986–1989 (osjenčani stupci) i za HCD-dane (bijeli stupci) u Velom Lošinju.

Air temperature and insolation

By investigating the relationship between temperature and air pollution levels during the period considered it has been found that there is no significant correlation between those two parameters. However, higher values of SO_2 concentration seemed to be more often in connection with lower mean temperatures in all seasons, particularly in spring (Table 2 and Figure 5). This is in accordance with the given results of weather type and wind data analysis. During typical anticyclonic bora conditions in spring a strong NNE wind is accompanied by low temperatures and a great number of insolation hours (Table 4 and Figure 6). It is interesting to notice the distribution of insolation hours in autumn. During HCD days the sky was either clear (anticyclones) or very cloudy (fronts and cyclones). This insolation characteristic is more pronounced in situations with SO_2 concentration 40 μgm^{-3}.

The analysis of the given meteorological parameters showed some weather situations to be specific with respect to the persistence of higher SO_2 concentration in period of several days. One of them is described in the following section.

7. WEATHER SITUATION 20 OCTOBER – 11 NOVEMBER 1987

In autumn 1987, up to 19 HCD days were observed during the period 20 October – 11 November. The time series of temperature, wind, pressure and cloudiness together with SO_2 concentration course are given in Figure 7. During the whole period some intervals of identical weather features can be noticed. The first few days (until 26 October) are characterised by a ridge of high pressure directed NNW–SSE (Figure 8). The flow at 850 hPa suggests an air mass transport from the Mediterranean at the front side of an upper-level trough. By 3 November the centre of this system had drifted eastwards and on 6 November a new anticyclone had become established over Central Europe producing light winds and clear sky over much of Europe and maintaining a northerly flow. Such situations allow the transport of polluted air from Western Europe to reach the Northern Adriatic. The best relationship between concentration and meteorological parameters is expressed in the case of wind speed and wind direction during the same weather type. The greatest 24-hour amount of SO_2 in the air was found to occure on 8 November under the following meteorological conditions: wind speed less than 2 ms^{-1}, changeable wind direction, clear sky and high pressure.

8. CONCLUDING REMARKS

Pollution level in the Lošinj area was found to be considerably lower than the legislative value. Nevertheless, particular meteorological conditions occurring mainly in the cold part of the year produced a limited number of episodes when the 24-hour SO_2 concentration levels reached values greater than 40. From the analysis of the effects of various meteorological parameters wind speed and direction were found to be the

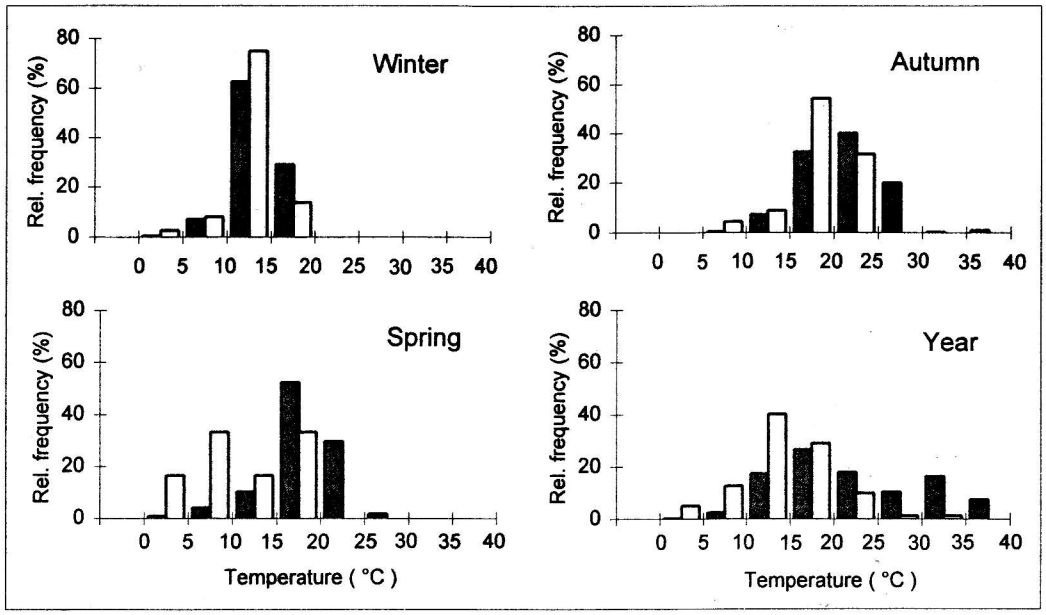

Figure 5. The relative frequency of mean daily temperatures for the whole period 1986–1989 (shaded bars) and for HCD days (white bars) in Mali Lošinj.

Slika 5. Relativna učestalost srednjih dnevnih temperatura zraka za čitavo razdoblje 1986–1989 (osjenčani stupci) i za HCD-dane (bijeli stupci) u Malom Lošinju.

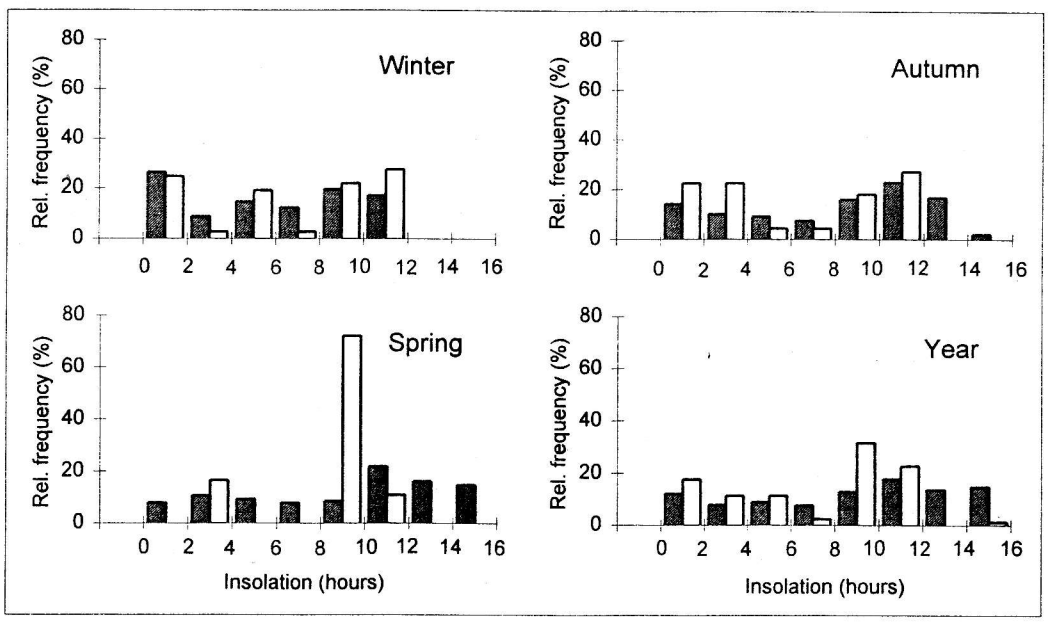

Figure 6. The relative frequency of insolation hours for the whole period 1986–1989 (shaded bars) and for HCD days (white bars) in Mali Lošinj.

Slika 6. Relativna učestalost sati osunčavanja za čitavo razdoblje 1986–1989 (osjenčani stupci) i za HCD-dane (bijeli stupci) u Malom Lošinju.

Table 3. Basic temperature characteristics for all and HCD days in Mali Lošinj (1986–1989).

Tablica 3. Osnovne temperaturne karakteristike za sve dane i za HCD dane u Malom Lošinju (1986–1989).

		MAX		MIN		MEAN		STD	
Temperature (°C)		ALL	HCD	ALL	HCD	ALL	HCD	ALL	HCD
Winter	TAVG	13.8	13.1	–1.1	–0.8	8.7	7.9	2.52	2.65
	TMAX	17.0	17.0	2.2	2.2	11.1	10.5	2.46	3.29
	TMIN	13.0	9.7	–2.3	–2.3	6.6	5.9	2.70	2.85
Spring	TAVG	21.7	14.3	–0.4	–1.2	13.1	5.9	2.52	5.43
	TMAX	25.5	17.1	0.9	-0.9	16.4	8.5	4.44	6.07
	TMIN	17.5	11.5	–3.2	–3.2	10.4	4.0	3.86	5.37
Summer	TAVG	31.5	26.4	13.7	16.1	22.9	22.4	2.79	5.50
	TMAX	33.5	30.5	16.7	19.5	27.0	26.2	3.16	5.88
	TMIN	25.3	23.0	11.0	14.0	19.6	19.6	2.76	4.91
Autumn	TAVG	25.4	19.5	3.8	3.8	16.3	13.5	4.37	3.67
	TMAX	31.3	21.3	6.0	6.0	19.6	16.1	5.02	3.49
	TMIN	22.5	17.1	2.2	2.5	14.1	11.9	4.09	3.43
Year	TAVG	31.5	26.4	–1.1	–1.2	17.4	9.5	6.75	5.40
	TMAX	33.5	30.5	0.9	-0.9	19.3	12.2	6.97	5.38
	TMIN	25.3	23.0	–3.2	–3.2	13.3	7.6	5.88	5.78

Legend:
TAVG – average daily temperature
TMAX – maximum daily temperature
TMIN – minimum daily temperature
MAX – maximum value
MIN – minimum value
MEAN – mean value
STD – standard deviation

Legenda:
TAVG – srednja dnevna temperatura
TMAX – maksimalna dnevna temperatura
TMIN – minimalna dnevna temperatura
MAX – apsolutni maksimum
MIN – apsolutni minimum
MEAN – srednja vrijednost
STD – standardna devijacija

parameter best correlated with pol-lution concentration. Concentrations above 40 μgm^{-3} occurred under a wide range of meteorological conditions but principally in two types of situations: a) anticyclonic situations with slight winds from SW–NW directions in winter and b) bora favourable situations in spring and autumn with NNE winds.

While these results refer to a very specific geographical area in which very specific meteorological conditions occur, they are illustrative of the general problem of interpreting local air quality survey data in areas where mesoscale circulation as modulated by synoptic-scale events is the major determinant of regional air pollution transport and dispersion. In other words, "the worst cased" air pollution situations in areas of low emission rates are not necessarily stagnation periods but may be periods with good ventilation.

Since it appears that the Lošinj area is sensitive to pollution originated from NW–NNE and SW, a great number of higher pollution events could be avoided by taking appropriate control measures and by lowering emission levels in the Kvarner Bay and Northern Italy areas.

Table 4. Basic insolation characteristics for all and HCD days in Mali Lošinj (1986-1989).

Tablica 4. Osnovne karakteristike osunčavanja za sve dane i za HCD-dane u Malom Lošinju (1986-1989).

	MEAN		STD	
Insolation (hours)	ALL	HCD	ALL	HCD
Winter	4.2	4.8	3.46	3.54
Spring	7.7	8.2	4.44	3.45
Summer	10.8	10.5	3.84	5.88
Autumn	6.1	4.3	4.03	3.73
Year	7.5	5.6	4.64	4.02

MEAN - mean daily amount of insolation hours
STD - standard deviation

MEAN - srednja dnevni broj sati insolacije
STD - standardna devijacija

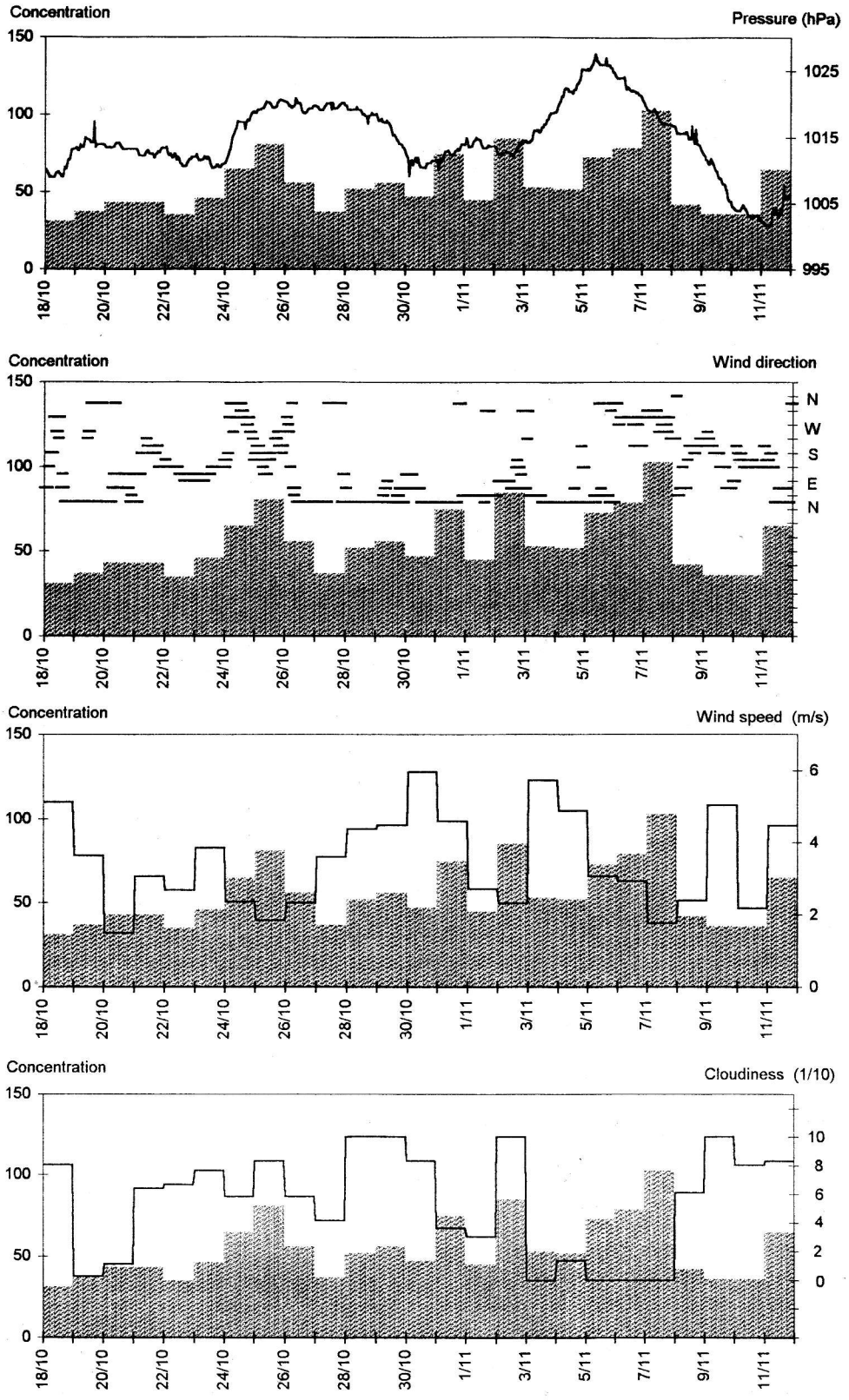

Figure 7. The time series of meteorological elements in Mali Lošinj and SO_2 concentration in Veli Lošinj for 20 October – 11 November 1987.

Slika 7. Vremenski nizovi meteoroloških elemenata u Malom Lošinju i koncentracija SO_2 u Velom Lošinju za razdoblje od 20. listopada do 11. studenoga 1987.

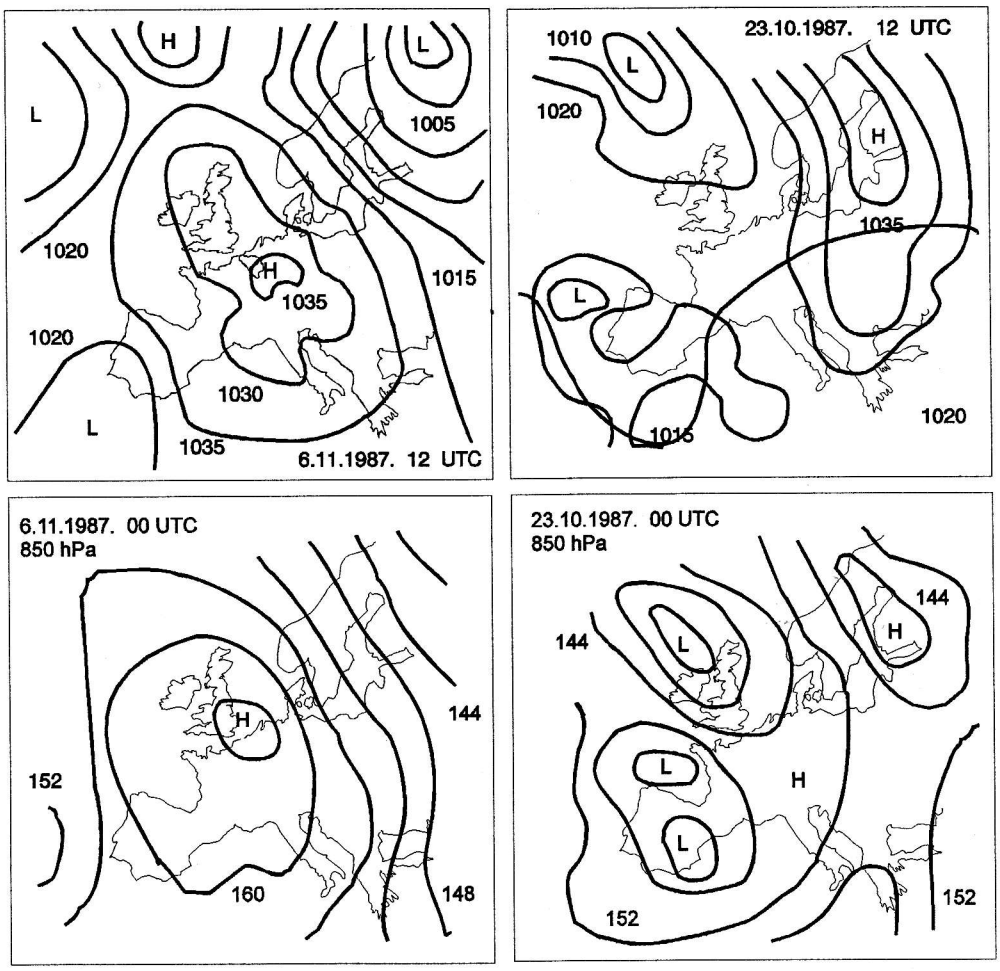

Figure 8. The synoptic situations on 23 October 1987 and 11 November 1987 on the surface (above) and at 850 hPa (below).
Slika 8. Sinoptička situacija za 23. listopada 1987. i 11. studenoga 1987., pri tlu (gore) i na 850 hPa (dolje).

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