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Further measurements of atmospheric carbon dioxide at Mt. Cimone, Italy: 1979–1985

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ABSTRACT

This paper presents atmospheric CO_2 concentration data continuously analyzed in the period March 1979–June 1985. A graphic computer selection method has been used in order to reject highly variable hourly data affected by local sources and malfunctions of the analyzer.

The increasing trend during the time interval considered is 1.7 ppm per year; the seasonal oscillation of monthly values, whose amplitude is 13 ppm, has been fitted by a linear term (trend) and two Fourier harmonic terms. Each annual set of daily mean values has been interpolated by a least square cubic spline using 1 node every 30 days. A relation between the behaviour of selected CO_2 data and prevailing winds, "SW" (180°–290°) and "NE" (0°–90°), appears quite evident; this behaviour is also demonstrated during Sahara-dust transport episodes. During winter, "NE" winds continue the high CO_2 concentrations measured on site, while "SW" winds are characterized by lower concentrations. In summer the situation is reversed. Therefore, we can assume the presence of a meridional gradient changing sign according to the season.

1. Introduction

Mt. Cimone observatory, a station of the Italian Meteorological Service, has been participating in the WMO-BAPMoN program since 1978. Measurements have been carried out on a regular basis by a continuously operating infrared analyzer; the record obtained represents the longest observation available at present in the Mediterranean area. Full details on the morphology and the geographical position of the observation site (Fig. 1) have already been given (Ciattaglia, 1983; Cundari and Colombo, 1986).

The observatory is located at the summit of Mt. Cimone (2,165 m.s.l.), which is the highest peak of the Northern Apennines, where a Meteorological station is also situated. Wind records classify the site as the most windy among all the Italian Meteorological Stations. The location of the site, exposed to undisturbed air inflow from all directions, enables us to state that measurements are performed in high quality background conditions for a large part of the year. Measurement procedures and experimental apparatus (NDIR URAS 2T) have been described earlier (Ciattaglia, 1983); the methodology basically follows that fixed at the WMO/UNEPU/ICSU Meeting (WMO, 1981).

A set of 6 CO_2/N_2 mixtures provided by the Scripps Institution of Oceanography, La Jolla-California, stored in chrome-molybdenum tanks, is used to perform periodic calibrations of the working standards. At present, the carrier gas influence has only been investigated in a preliminary form. We made an attempt to correct our CO_2 values for carrier gas: measurements show that our CO_2 data, expressed in WMO CO_2 in air scale, must be increased by about +4 ppm. In this paper, data are referred to the WMO—80 Scale without correction for the carrier gas influence.

2. Data selection

Continuous CO_2 values are both registered on a chart recorder and integrated to obtain hourly CO_2 concentrations, which are stored in com-

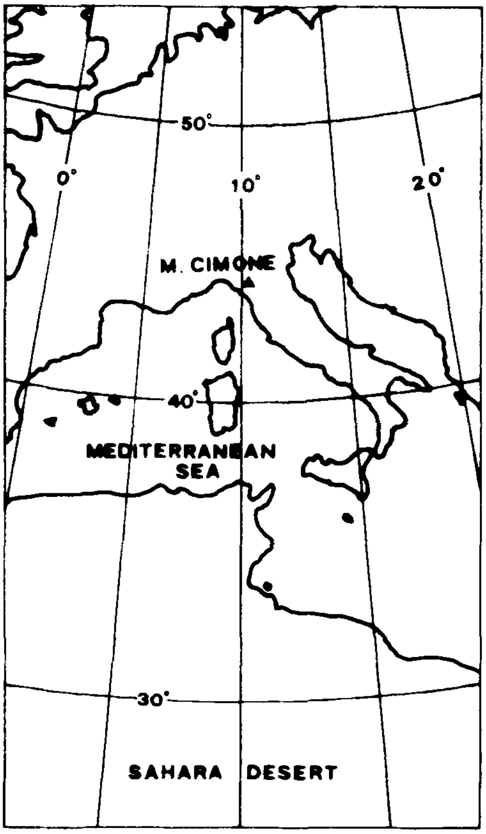

Fig. 1. Location of the observation site: Mt. Cimone, Italy, 44°11′N, 10°42′E 2,165 m.s.l.

puter files, together with hourly wind data, in order to be used as a data bank for any kind of analysis. Obviously, CO_2 values affected by failure of the apparatus or by occasional local sources are not included in the files. Removed values represent a small portion (11.2%) of recorded data and are usually singled out with the help of the stripchart-recorder. All filed hourly CO_2 values are plotted together with related wind data by a routine computer program. The diagram obtained (see example in Fig. 2 concerning 3 different periods of the year) allows both a quick location of incidental anomalous variations as well as an estimate of within-day and day-to-day recurrent yearly variations on a qualitative basis. Objective statistical methods, based on "steady conditions" have been adopted in other measurement sites, in order to eliminate those values affected by local sources, with the purpose of obtaining the representative long-term and seasonal CO_2 behaviours. These selection methods are based on the assumption that only small variations in instantaneous concentration occur in an air mass free of local contamination, so that intervals of measurement with high CO_2 variations have to be rejected. In our case, statistical criteria do not seem suitable because such data selections do not always have coherent verifications from a physical point of view: in fact, our experience suggests, and the results of the present study show, that short-time variations at Mt. Cimone can be correlated with regional or even wider scale air-mass changes.

3. Time scale data analysis

The Mt. Cimone time series of hourly CO_2 data shows variations classifiable into 4 different scales: hour-to-hour and day-to-day changes of a few ppm, seasonal and long-term behaviours. Indeed, some precautions concerning the interpretation of such variations have to be taken, as they can be related to numerous and often superposed causes.

Hour-to-hour changes are more evident during summer time. In this period the standard deviation (SD) of hourly data within a day reaches about 2 ppm as a monthly mean. The SD decreases during the rest of the year, coming down to the minimum value of about 1 ppm during the days between the end of April and the end of May (Fig. 2b). A minimum variability of hourly data, around May, is also present in Barrow's records (Peterson et al., 1982). All the main features of hour-to-hour variations, found during the year at Mt. Cimone can be summarized in 3 examples (Fig. 2a, 2b, 2c). The largest within-day changes of CO_2 concentration can be found during the hot period (Fig. 2c); these changes are systematic: the CO_2 concentration decreases by some ppm at sunrise, reaches a minimum in the afternoon and increases at sunset. This oscillation takes place from the end of May until September and is more evident in July and August. The diurnal decrease of atmospheric CO_2 is explained by the photosynthetic intake of the vegetation growing in the valleys below.

The observatory is above the timberline as the forests grow only up to 1,600 m. Therefore the effect of vegetation can be considered to be more

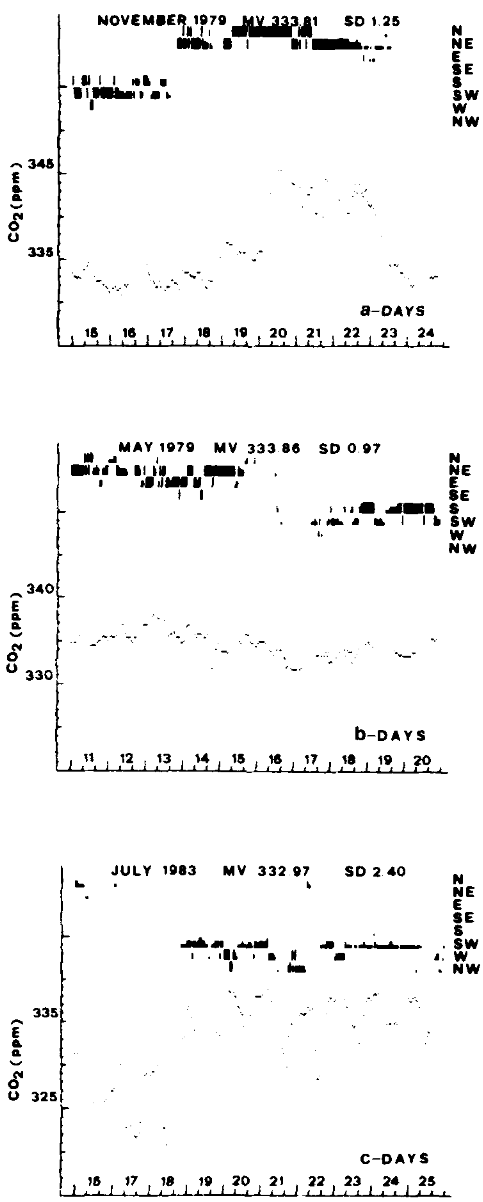

Fig. 2. Behaviour of hourly CO_2 values (WMO 80 scale) during 3 different periods of the year. The upper section of the figure illustrates hourly wind intensity using the following scale:

>3, <5 ms^{-1}

>5, <10 ms^{-1}

>10 ms^{-1}

Calm is represented by blank intervals. Wind direction is divided into 8 sectors.
MW = Monthly Average.
SD = Standard Deviation.

than a simple regional influence and typical of a site located a few hundred metres above mid-latitude continental areas. The influence of vegetation cannot be separated out from the measurements because of its persistence; anyway the disturbance is not so noticeable so as to obscure, during summer months, the CO_2 annual trend obtained from all data. Evident hour-to-hour variations in winter time are substantially related to transient meteorological conditions.

A CO_2 relation has been observed with local wind directions: higher CO_2 concentrations together with a greater scattering in the records appears quite evident in air coming from the North more than in air coming from the South of Mt. Cimone during the cold season. For example, the crossing of a front between November 17 and 18 1979, over Mt. Cimone is marked by a change in wind direction, first blowing from the "SW" sector and then from the "NE" sector. Hourly CO_2 values are more scattered in coincidence with a change in wind direction and these reach a maximum between 20 and 22 of November (Fig. 2a). Fig. 2b shows a typical distribution of hourly values in May.

The flat behaviour of the values shows, in contrast, no relation between CO_2 data and wind direction blowing for several days southward and then northward. In order to quantify these features, a CO_2 analysis depending on wind direction is presented later in this paper.

Daily CO_2 concentrations based on hourly data are plotted in Figs. 3a–f from 1979 to 1984. The daily values (obtained as a mean of hourly data) are fitted, for each year, by least square cubic spline functions (continuous lines) using one node every 30 days. This interval between 2 adjacent nodes has been chosen in order to describe the annual CO_2 cycle. At the bottom of each diagram are drawn, using the same scale unit of the *y*-axis, the daily absolute values of the deviation from the spline. A qualitative analysis of those deviations shows larger daily variations during summer, partly due to the influence of vegetative intake. The scattering of daily values during fall and winter is due instead to the cyclonic activity which favours the inflow of air masses of different origin and with different CO_2 values. From the end of April to the end of May, day-to-day CO_2 concentrations appear more steady.

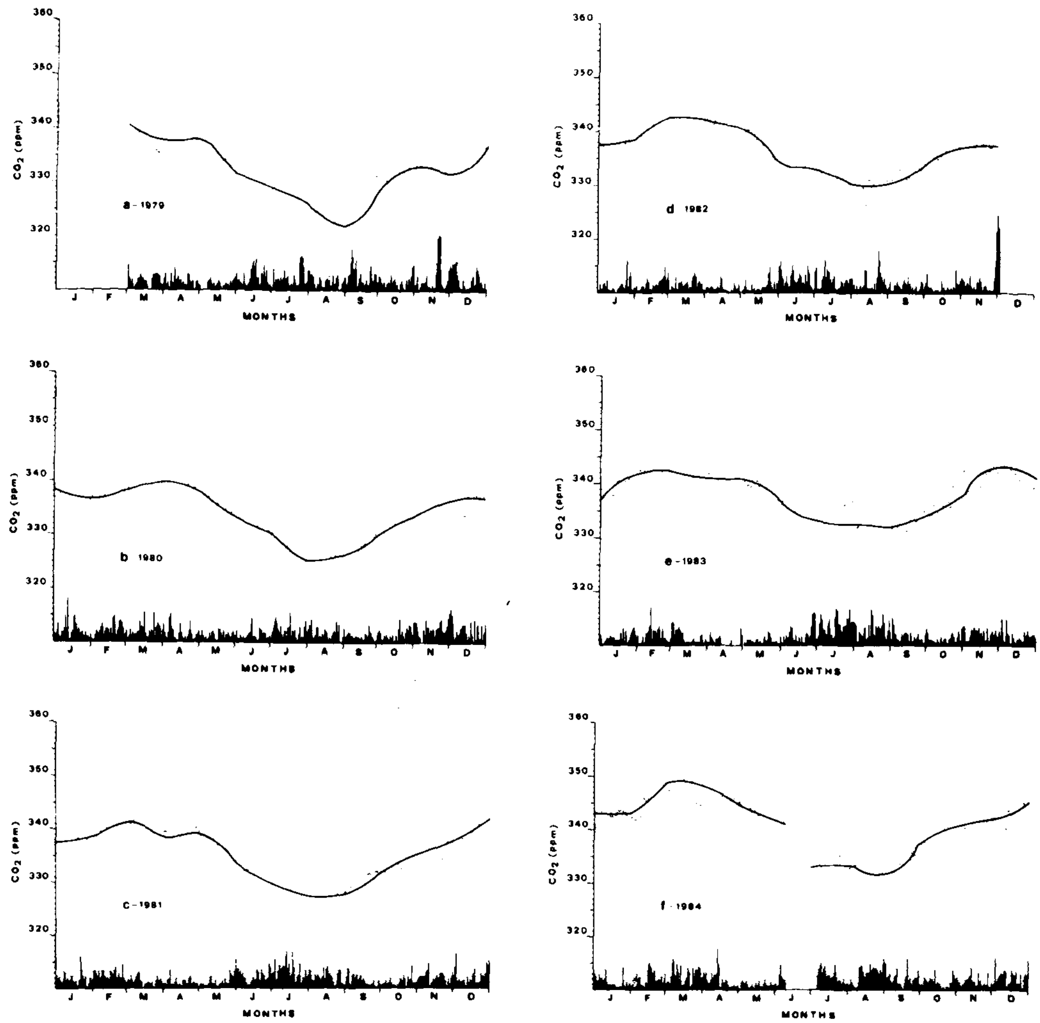

Fig. 3. Daily average CO_2 concentration (dots) at Mt. Cimone (WMO 80 scale) from 1979 to 1984; the carrier gas correction, needed to convert the data from this relative scale to mole fractions, has not been applied. Continuous lines are least square cubic spline functions showing yearly mean CO_2 behaviour. The segments in the lower section of the graphs indicate, using the same scale as the *y*-axis, the absolute deviation of the daily means from the curves. In Fig. 3f, the curve is discontinuous because of a prolonged interruption in the operation of the apparatus.

Seasonal and long-term behaviour of CO_2 at Mt. Cimone is expressed by monthly and annual average concentrations (Table 1) for the period March 1979–June 1985.

Monthly values, calculated from daily averages, are plotted in Fig. 4 and fitted with an analytic function consisting of a linear term plus 2 Fourier harmonic terms. The behaviour of such values follows an annual cycle with a minimum in August and a maximum between the end of winter and the beginning of spring. The average cycle amplitude deduced from the analytic function is 13 ppm. The largest deviations above and below the amplitude of the values occur in 1983 and 1984 and are about 11 ppm and 16 ppm, respectively. Cycle amplitude, phase and asymmetry related to biosphere CO_2 intake and release processes in the boreal hemisphere are globally concordant with the feature obtained in other mid- and high-northern latitude stations

Table 1. *Monthly and annual average CO_2 values in the WMO 80 scale; the carrier gas corrections needed to convert the data from this relative scale to mole fractions have not been applied. The 1979 mean has been calculated using Jan. and Feb., 1980 detrended values. Differences between monthly and annual means sent to WMO (WMO, 1984) from 1979 to 1984 and those in the table are due to the fact that some of them have been recalculated after rejecting, in a graphical analysis, those affected by local sources.*

	1979	1980	1981	1982	1983	1984	1985
J		337.73	338.33	338.56	339.22	343.10	346.64
F		336.89	339.94	341.18	342.95	346.08	344.92
M	338.29	339.11	339.23	342.46	341.80	348.01	347.36
A	338.78	339.34	339.34	342.49	341.04	347.29	347.21
M	333.85	335.17	336.40	337.66	339.12	343.21	342.72
J	330.81	332.46	332.23	333.60	335.24	341.15	338.28
J	326.69	327.17	327.79	331.61	332.97	333.23	
A	324.23	325.86	327.32	329.40	331.96	332.14	
S	325.58	328.19	330.54	332.10	333.50	334.50	
O	331.24	332.00	333.73	336.15	336.75	339.10	
N	333.76	335.93	336.29	338.06	340.79	341.69	
D	334.43	337.30	340.01	341.96	342.39	343.67	
ANNUAL MEAN	332.44	333.93	335.09	337.10	338.14	341.09	

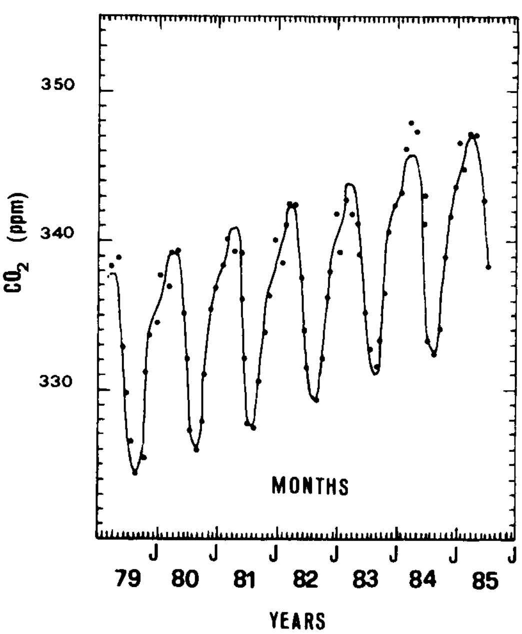

Fig. 4. Monthly CO_2 average in WMO 80 scale (the carrier gas corrections needed to convert the data from this relative scale to mole fractions have not been applied) at Mt. Cimone (crosses) fitted using a function consisting of a linear term plus 2 Fourier harmonic terms. The function behaviour is represented by the discrete sequence of points (one point every 10 days).

(Peterson et al., 1982; Bolin and Bischof, 1970; Wong et al., 1984). The mean long-term increase of CO_2 concentration, over the whole period of measurement is 1.7 ppm per year. This trend has been calculated by averaging the differences between each yearly value and the adjacent one and is concordant with other long-term records. The high monthly values in the first 6 months of 1984 with respect to 1983 are responsible for the higher year-to-year increase of 2.96 ppm, recorded from 1983 to 1984.

4. CO_2—wind analysis

The main purpose of this analysis is to deduce some relationships between hourly CO_2 data and hourly wind data, by classifying the CO_2 values according to the local wind direction at the time of the measurements. The investigations have been carried out using standard hourly wind observations, taken at Mt. Cimone Meteorological Station. The prevailing winds come from the SW, but northerly winds, particularly those blowing from the NE are evident too, except during summer. A CO_2 dependence has been observed on local wind directions. All hourly CO_2 data with wind blowing with intensities greater than 3 ms^{-1} and lasting for more than 4 h from the "SW" sector (from 180° to 290°) and from the "NE" sector (from 0° to 90°) have been selected. Persistent and strong wind from the "SW" sector usually causes a sea air inflow, while winds blowing from the "NE" sector are characterized by a continental air inflow. For the "SW" and the "NE" sectors, hourly CO_2 data have been compared with the corresponding average CO_2 values of the cubic spline curves (Fig. 3). We have not included the first 4 hourly CO_2 values at the beginning of each "blowing episode" in order to avoid some local influences. Our method allows us to examine air travelling some tens of kilometres (50 km is the distance between the Mediterranean coast and Mt. Cimone).

Monthly frequencies of values, above the spline curve concentration value, have been computed (Fig. 5) in order to illustrate CO_2 behaviour in both sectors: in the November–March period, the "SW" sector shows a low % of CO_2 values above the "average"; in the May–August period,

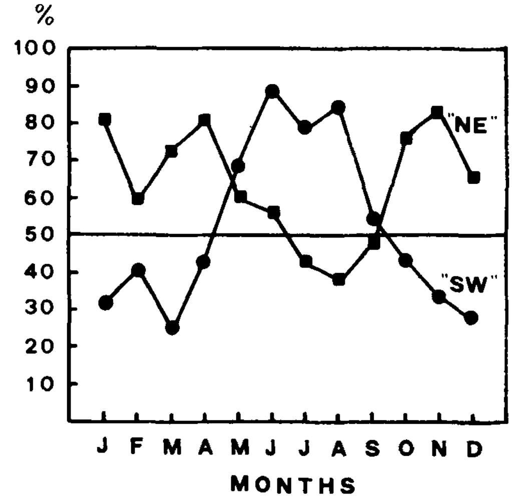

Fig. 5. Monthly frequencies of hourly CO_2 data with positive shift related to the average behaviour from 1979 to 1984 (cubic spline curves of Fig. 3). Wind direction has been considered in accordance with the following sectors: "SW" (from 180° to 90°) and "NE" (from 0° to 90°).

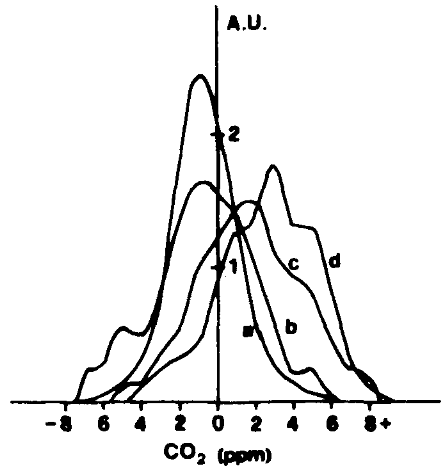

Fig. 6. Continuous normalized distributions of selected hourly CO_2 values around the average behaviour ($x = 0$) in 4 periods:
(a) Jan., Feb., Mar. and Nov., Dec. "SW" sector.
(b) Jul., Aug. "NE" sector.
(c) Jan., Feb., Mar., Apr. and Oct., Nov., Dec. "NE" sector.
(d) May, Jun., Jul., Aug. "SW" sector.

on the other hand, 70% to 90% of the values exceed the spline functions. April, September and October hourly CO_2 values are almost equally distributed around the average. Each point of the "SW" curve is determined by processing between 500 to 1,500 data values. The "NE" sector exhibits almost the opposite behaviour with most values exceeding the spline function, except during July and August when they tend to lie below. Each dot of the "NE" curve is determined by processing an average of about 200 data values for summer months and 500–600 for the rest of the year. In order to obtain the mean deviation in ppm of both CO_2 sector values from the "average", the dispersion around the spline functions has been computed. Normalized curves "a" and "d" (Fig. 6) represent continuous frequency distributions of the "SW" sector values from November to March and from May to August, respectively. Curves "b" and "c" are the July to August and October to April "NE" sectors, respectively. The x-axis represents the difference between each CO_2 hourly value and the corresponding spline value.

These periods group together the months in which hourly CO_2 data have the same tendency to lie above or below the spline in Fig. 3a–f. Fig. 6 shows the tendency of CO_2 values to lie above or below spline curves. The dispersion and the asymmetry are lower in the "a" curve than in curves "c" and "d". Two possible explanations of the results can be considered: (a) anthropogenic CO_2 release; (b) natural CO_2 surface/atmosphere exchanges.

Firstly, anthropogenic CO_2 release alone is not likely to explain all the meaningful features. Anthropogenic sources are mostly located in the industrial regions of Central Europe and during the whole year, we should expect air with higher CO_2 concentrations to come from the "NE" sector rather than from the "SW" sector. That is not the case in warm periods, when lower concentrations in air come from the "NE" sector rather than from the "SW" sector.

Secondly, in middle and high northern latitude, where the annual vegetative cycle presents a well-defined behaviour, continents are "sources" of atmospheric CO_2 in winter and "sinks" in summer. Continental air is expected to come from the "NE" sector to the observation site (Fig. 1).

This might explain the generally high CO_2 values in cold periods and the low values in July and August (Fig. 5), though during these months, the local vegetation intake reduces the daily mean concentrations at Mt. Cimone. Sea air from the "SW" may have Mediterranean or Atlantic origin. CO_2 exchanges across the sea surface are complex and not completely investigated. The curve of the "SW" sector (Fig. 5) shows low concentrations in cold months and high concentrations in summer. This curve is opposite in phase with respect to the "NE" curve, because of the inertia of sea air in following the CO_2 seasonal variations induced by the biosphere.

CO_2 anthropogenic advection from the "NE" sector, coincident with the increase of CO_2 values in cold periods, cannot be disregarded, although in July and August, this influence, when present, appears to be dominated by a vegetative influence. We must also consider the fact that the CO_2 production "cycle" caused by combustion reaches a maximum during winter (when industrial production and domestic heating reach their peak).

The results of the discussion show the presence of a mean meridional CO_2 gradient, of 2–3 ppm, in the lower troposphere between the Mediterranean Sea and central northeastern Europe, changing sign with the season. This is in agreement with temporal and spatial global CO_2 distributions presented by Komhyr et al. (1985).

The flat behaviour of hour-to-hour values found in May (Fig. 2b), being less sensitive to wind direction, can be interpreted using the results of the present analysis, as follows. The restarting of the photosynthetic activity at mid and high northern latitudes during May, provokes an impoverishment of the CO_2 content in the European continental air, that reaches a value similar to that of the southerly air, the CO_2 content of which is maintained lower until the beginning of Spring (cf. Fig. 8 by Komhyr et al. (1985)). The opposite mechanism of release by the biosphere, in the global balance of CO_2, should again show a similar behaviour in hour-to-hour variations approaching September, but this is not clear, principally because this record period is still disturbed by diurnal vegetative activity.

This analysis does not consider wind directions from 100° to 170° because of their very low frequency. On the other hand, CO_2 concentration values do not behave uniquivocally in relation to northwestern winds, probably because of the mixed air origin, continental or atlantic.

5. Sahara dust transport

Episodes of Sahara dust transport at Mt. Cimone are not infrequent.

A few times in a year, air with dust coming from the Sahara Desert is transported to Mt. Cimone after having travelled in the lower atmospheric strata from northern Africa through the Mediterranean Sea. Those episodes, averaging 10 times per year, and sometimes lasting a few days, may happen anytime during the year, but usually in coincidence with southern winds blowing at 2.5–10 ms^{-1}. These transports have been detected locally since 1983 by means of filters used for routine sampling of suspended particulate matter (SPM). In these conditions, we expect to analyze CO_2 concentration in air coming from North Africa or at least mixed with air of the Mediterranean sea. During the hot period, CO_2 concentrations show values above average (see example in Fig. 2c). On 19 July 1983, a transport phenomenon begins and continues until the 25th. Hourly values increase rapidly from early on the 19th, although preserving an oscillating diurnal cycle. The net behaviour of hour-to-hour values, in this period, can be regarded as the result of a superposition of 2 different causes: a synoptic scale transport of high CO_2 content originating very far from Mt. Cimone (about 1000 km at least), and a diurnal influence of the local vegetation. Daily means in 1983 (Fig. 3e) clearly show high CO_2 values relating to the period examined. A similar event happens on 27 and 29 June when another dust transport occurs.

During the cold season, Saharan transports are characterized by low CO_2 and by small record variability. A typical example is illustrated in

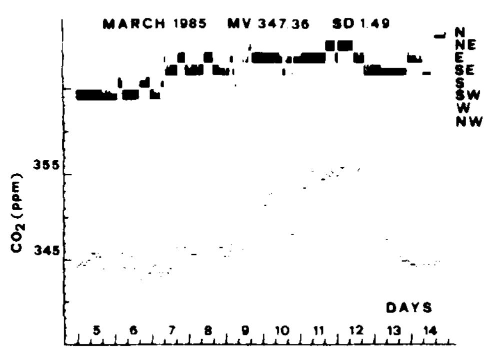

Fig. 7. Hourly CO_2 values for the period 5th–14th March 1985. Winds are represented as in Fig. 2.

Fig. 7; on 5, 6 and 14 March 1985, low values of hourly concentration are related to Sahara desert dust transport phenomena. This seasonal behaviour of hourly CO_2 concentrations, usually high during summertime and low in winter, is in accordance with the results of the preceeding analysis concerning air coming from the "SW" sector.

6. Conclusions

In the light of the results achieved, the use of "steady condition" statistical methods, besides being difficult to implement, appears to be unsuitable for the records of Mt. Cimone. As a matter of fact, hour-to-hour and day-to-day variations often occur in relation to events beyond a local scale evolution. This is probably the result of the altitude of the measurement site, being exposed to winds of different origin, as well as of its geographical position surrounded by large areas having non-homogeneous features related to the CO_2 cycle.

In order to prove unequivocally the northern European origin of the air coming from the "NE" sector, a measuring apparatus of air samples is undergoing tests. The future research program will implement air sampling in flasks and will be carried out on an alpine peak similar to Mt. Cimone. This experiment should allow us to study the contribution of the Po River Basin (a polluted industrial area) to the increase of CO_2 values during winter in relation to winds blowing from the "NE" sector.

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