CORRELATION BETWEEN SOLAR RADIATION AND TOTAL SUSPENDED PARTICULATE MATTER IN SANTIAGO, CHILE—PRELIMINARY RESULTS

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Abstract—This is a first-approach study tending to correlate solar radiation and temperature with total particulate matter in Santiago, Chile, a city heavily polluted by this contaminant.

Experimental data for monthly average total radiation, $\bar{G}$, were provided by the Chilean Meteorological Bureau. Diffuse monthly average radiation, $\bar{D}$, was calculated. The concentrations of TSP were provided from the monitoring system of the Chilean Environment Health Service.

Results show that there exists a relationship between TSP and solar radiation and temperature for urban sites, but not for suburban sites, even considering the monthly average values. Further and more detailed studies are necessary in this field.

Key word index: Total solar radiation, diffuse solar radiation, temperature, suspended partiulate matter, Santiago, Chile.

INTRODUCTION

Santiago, the capital of the country, located under subtropical latitudes in the Southern Hemisphere is recording for more than 12 years high amounts of air pollution, especially of suspended particulate matter, due to the combination of natural and socio-economic conditions. The urban metropolis, settling more than four million people, 60% of the national industries and above 600,000 vehicles is located in a basin surrounded by up to 5000 m summits and slopes of Andean and Coastal ranges, deforested due to the scarce winter rainfall (less than 300 mm as annual average) and under permanent anticyclonic thermal inversion layers and high amounts of solar radiation.

As in many latinoamerican cities, Santiago is suffering a very rapid and extensive geographical expansion, changing the land cover from agricultural and forested floodplain to urban land uses, remaining everywhere several kilometers of unpaved roads and streets.

The effect of particulate matter over solar radiation is an increase in the quantities of radiation absorbed, diffused into space and subject to some other optical effects (Kondratiev, 1969).

Short wave radiation is considerably modified when it crosses a polluted atmosphere, being reduced by 10–20% in industrialized cities and by 2–10% in cities where atmospheric photochemical pollution is principally due to automobile emisions. The reduction depends on seasonal variation of pollutant concentrations and on Sun inclination (Oke, 1987). Spectral composition and directionality of short wave radiation is changed. Pollutants filter preferably shorter waves. In the UV, 40–90% is lost by absorption and diffusion in the atmosphere, reducing plant photosynthesis, tannic acid, and production of vitamin D (Oke, 1987; Zardecki and Gerstl, 1981).

This study is the first approach to find a correlation between solar radiation (global, measured on a horizontal surface and calculated diffused radiation) and concentrations of total suspended particulate matter (TSP) measured in Santiago, Chile, a highly polluted city.

METHODOLOGY

Total daily average solar irradiance incident on a horizontal surface at the top of the atmosphere, G_0, undergoes an important sequence of phenomena on its way through the

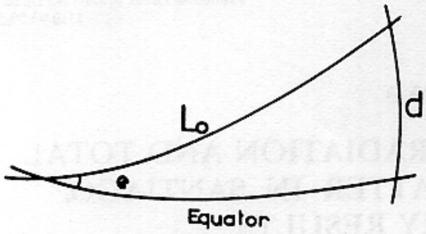

Fig. 1. Curve triangle showing the position of the Sun, the distance L_0, and the Aries point.

atmosphere. A fraction of this radiation is received on the surface of the Earth as total radiation, *G*, and can be considered as the sum of direct radiation, *I*, and diffuse radiation, *D*. For the purpose of this study, albedo and absorption are not explicitly considered.

For this study experimental data for monthly average total radiation, $\bar{G}$, was taken from Seco *et al.* (1993). Diffuse monthly average radiation, $\bar{D}$, was calculated by developing a computerized method using the experimental data, $\bar{G}$, and the calculated G_0, according to Liu and Jordan (1960):

$$\bar{D} = \bar{G} \sum_{i=0}^{i=6} a_i \, (K_T)$$

where K_T is the mean coefficient of atmospheric transparency which is equal to $\bar{G}/G_0$. The values for the polynomial coefficients, a_i, are given as follows:

$$a_0 = -1.678, \quad a_1 = 35.3493,$$
$$a_2 = -230.4057, \quad a_3 = -709.0082,$$
$$a_4 = -1152.0511, \quad a_5 = 954.2366, \quad a_6 = -318.0824.$$

G_0 was calculated from the total solar irradiance incident on a horizontal surface at the top of the atmosphere according to Liu and Jordan (1960):

$$G_0 = \frac{24}{\pi} \, r \, I_{SC} \, (\cos f \cos d \text{ sen } w_S + w_S \text{ sen } f \text{ sen } d)$$

where *r* is the radiovector Sun–Earth ($= 1 + 0.033 (360N/365)$) (List, 1958); G_0 the radiation (in ly d^{-1}) on the top of the atmosphere; I_{SC} the solar constant ($= 116.4$ MJ $m^{-2} d^{-1}$); *f* the latitude (in rad) of the site; *d* the Earth's declination (in rad); *N* the day of the year; w_S the hour angle

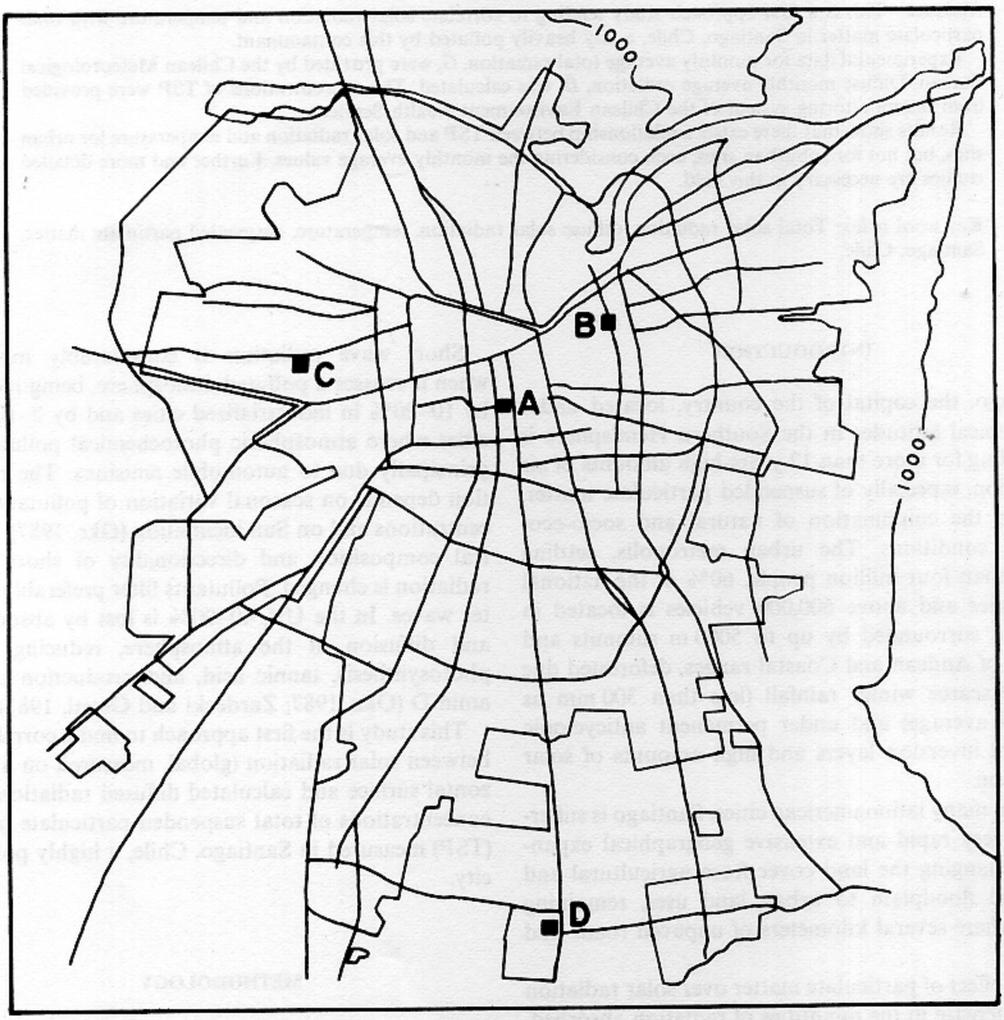

Fig. 2. Schematic map of Santiago including the 1000 m contour line of the basin, the principal avenues and streets of the city and the location of the sampling sites.

(in rad) at sunset, given by $w_S = \text{arc cos}(-\text{tg} f \text{tg} d)$ with d calculated from sen d = sen e sen L_0, L_0 being the curved distance from the point where the Sun is situated and the ARIES point and finally, e the angle between L_0 and the equator (Fig. 1).

The values for $\bar{G}_0$ were calculated using another computerized method developed by our group considering the latitude and longitude of Santiago, Chile: 33°26′ lat. S and 70°40′ long. W. $\bar{G}_0$ was obtained by integrating instantaneous irradiance from sunrise to sunset. The Earth's declination was calculated for a nonbissextile year (List, 1958).

TSP concentrations, gravimetrically determined, were obtained using high volume samplers, belonging to the monitoring system of the Chilean Environment Health Service. The four sites with the longest and more complete number of samples were selected for this study including two urban sites and two suburban sites in Santiago city. Figure 2 shows a schematic map of Santiago including the 1000 m contour line of the basin, the principal avenues and streets of the city and the location of the sampling sites. Site A is about 1 km south of downtown and Site B is about 2 km east of downtown. The suburban sites are located 14 km (site C) and 26 km (site D) from downtown. Sampling ran from 1978 to 1988, excluding February (summer) every year.

Table 1 shows the monthly frequence of the sampling, the percentual variability coefficient and the extreme values of concentration (maximum and minimum) for the different sampling sites. Greatest concentrations are observed during autumn–winter periods with a maximum value of 1142 $\mu g\ m^{-3}$ for 24 h, in the urban site B, during June 1988.

Considering the maximum values of TSP during the critical periods it has been observed that they occur either with dry and clear days or with humid and cloudy days (Ara-Seebla-Consecol, 1990).

RESULTS AND DISCUSSION

The most favorable condition for Santiago's high level of atmospheric pollution seems to be an increase of anticyclonal influence and atmospheric high pressures associated to the development of a relative prelittoral low pressure along the coast of Central Chile and the development of high pressures above the East side of the Andes Range (Argentina). Figure 3 shows the ideal representation of the atmospheric circulation for critical pollution events in Santiago. In these conditions, which appear in autumn and winter, the air goes down the mountain valleys to the closed basin of Santiago.

The air coming down from the high atmosphere as well as from the mountain valleys explains the maximum levels of subsidence and consequently, the development of high thermal inversion on the surface (Fig. 4).

The inversion increment occurs preferably during sunrise on clear days or when the sky is partially covered, that is, when seasonal and daily temperatures are relatively low. It has been observed that the typical meteorological conditions coinciding with the critical events registered between 1979 and 1986 correspond to the minimum daily temperature between − 0.5 and 10°C, in absence of rain and accompanied by weak winds (Romero *et al.*, 1989). The moisture content of the atmosphere shows a clear daily and annual regime. Values are higher in the morning than

Table 1. Monthly frequence of the sampling (MF), percentual variability coefficient (VC) and extreme values of concentration (maximum and minimum) for the different sites

	Site A				Site B				Site C				Site D			
AA'o	MF*	VC†	Max‡	Min§	MF	VC	Max	Min	MF	VC	Max	Min	MF	VC	Max	Min
1979	4,6	16	568	110	6,0	13	455	47	4,9	24	850	56	2,8	12	397	46
1980	7,0	16	608	87	5,7	17	486	87	4,9	15	585	114	6,0	29	461	44
1981	7,0	21	753	30	6,4	19	498	6	6,1	36	989	44	7,9	20	493	35
1982	3,3	26	418	106	2,4	26	315	53	3,4	18	726	133	5,6	17	283	24
1983	6,6	14	508	99	6,6	22	388	58	6,4	15	658	55	6,6	41	650	39
1984	5,3	40	855	101	6,8	12	312	86	7,0	36	411	107	6,3	12	332	43
1985	7,4	15	610	87	6,3	12	351	61	5,5	15	545	134	6,2	24	417	30
1986	7,1	14	447	92	6,8	14	330	50	4,4	15	475	112	5,3	26	504	40
1987	5,9	16	538	125	5,3	21	417	45	4,8	18	613	51	4,6	12	334	24
1988	6,0	20	665	123	6,3	50	1142	58	5,1	23	975	84	5,2	19	434	73

*Annual monthly frequence of sampling.
†Percentual variability coefficient.
‡Maximum 24 h concentration for the year ($\mu g\ m^{-3}$).
§Minimum 24 h concentration for the year ($\mu g\ m^{-3}$).

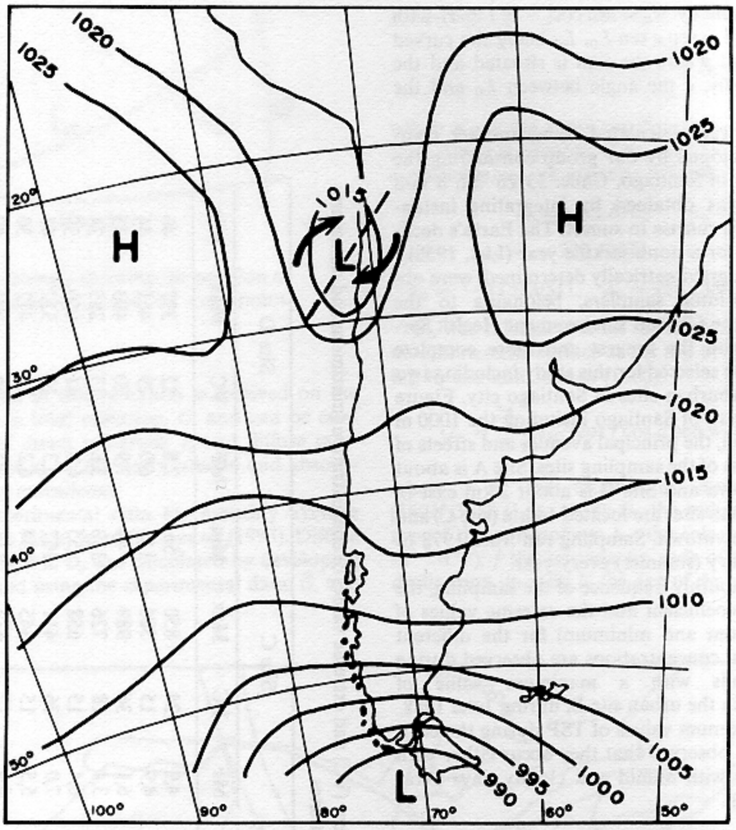

Fig. 3. Ideal representation of the atmospheric circulation for critical pollution events in Santiago (source: Ulriksen, 1993).

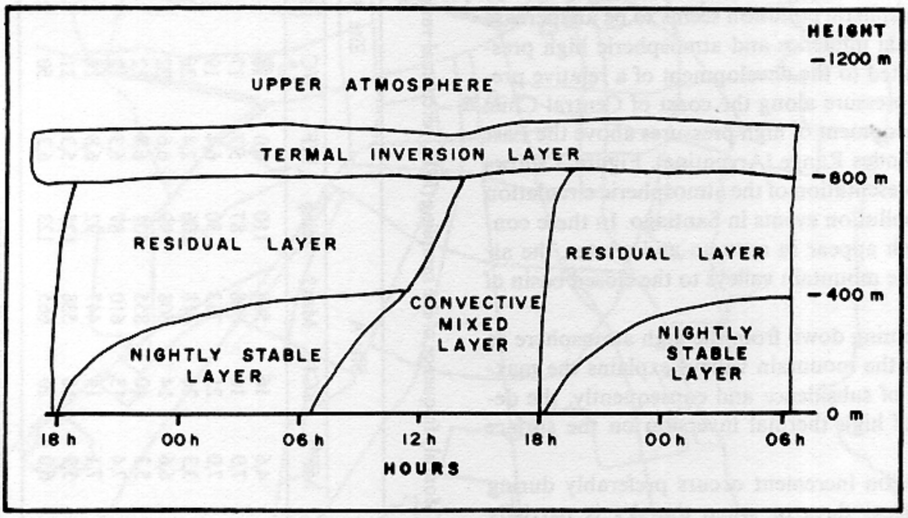

Fig. 4. Ideal scheme of the daily variation of the atmospheric boundary layer (source: Ulriksen, 1993).

in the afternoon, when the values reach 40–50%. The morning values vary from 60 to 70% during the summer periods, reaching up to 90% during the winter periods.

Figure 5 shows the correlation curve, throughout the whole year, for an 11 yr period, significant to 99.99% between the experimental monthly average concentrations of total suspended particulate matter (TSP) and the log of the monthly average of total solar radiation, at site A. Figure 6 shows the correlation curve, throughout the whole year, for an 11 yr period, significant to 99.99%, between the monthly average

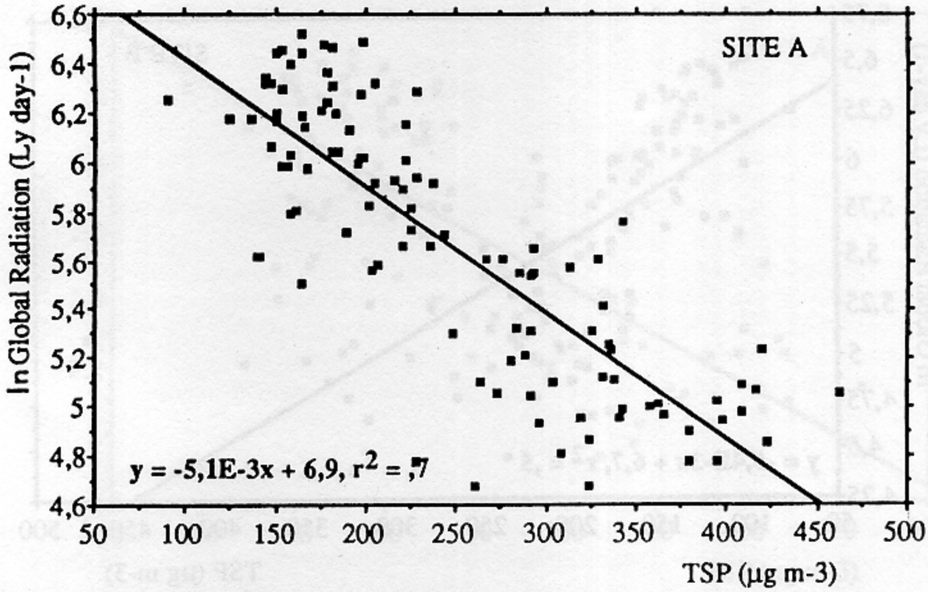

Fig. 5. Correlation curve, throughout the whole year, for an 11 yr period, between the monthly average concentrations of total suspended matter (TSP) and the log of monthly average of global solar radiation, at site A.

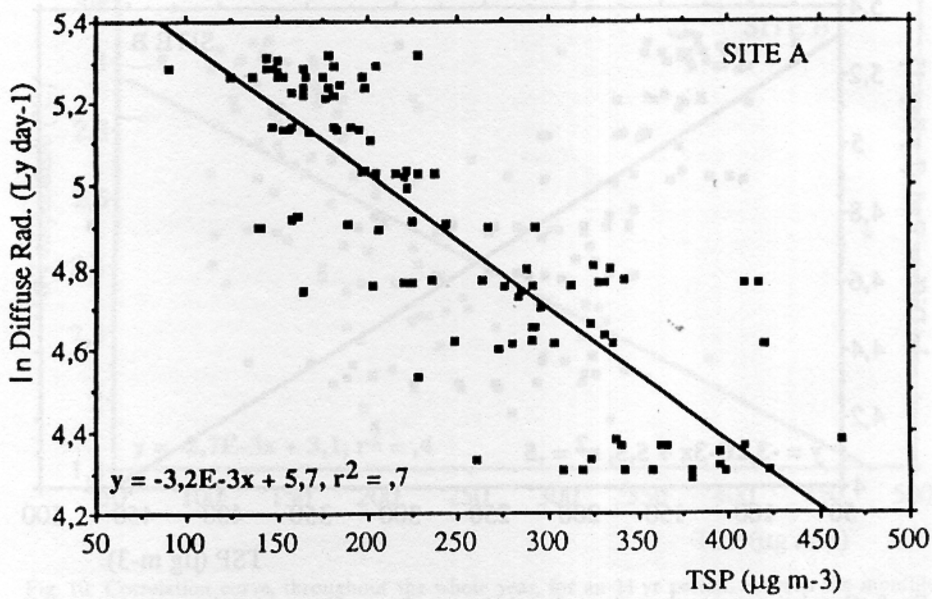

Fig. 6. Correlation curve, throughout the whole year, for an 11 yr period, between the monthly average concentrations of total suspended matter (TSP) and the log of monthly average diffuse radiation, at site A.

concentrations of TSP and the log of the monthly average of calculated diffuse solar radiation, at site A. Some data on radiation have been eliminated because there are no data on TSP. The obtained correlation coefficients were 0.837 for 107 data items for Figs 5 and 6.

Figure 7 shows the correlation curve, throughout the whole year, for an 11 yr period, significant to 99.99%, between the monthly average of the concentrations of TSP and the log of the monthly average of experimental total solar radiation, at site B. Figure 8 shows the correlation curve, throughout the whole year, for an 11 yr period, significant to 99.99%, between the monthly average concentrations of TSP and the log of the calculated monthly average of diffuse solar radiation, at site B. Some data on radi-

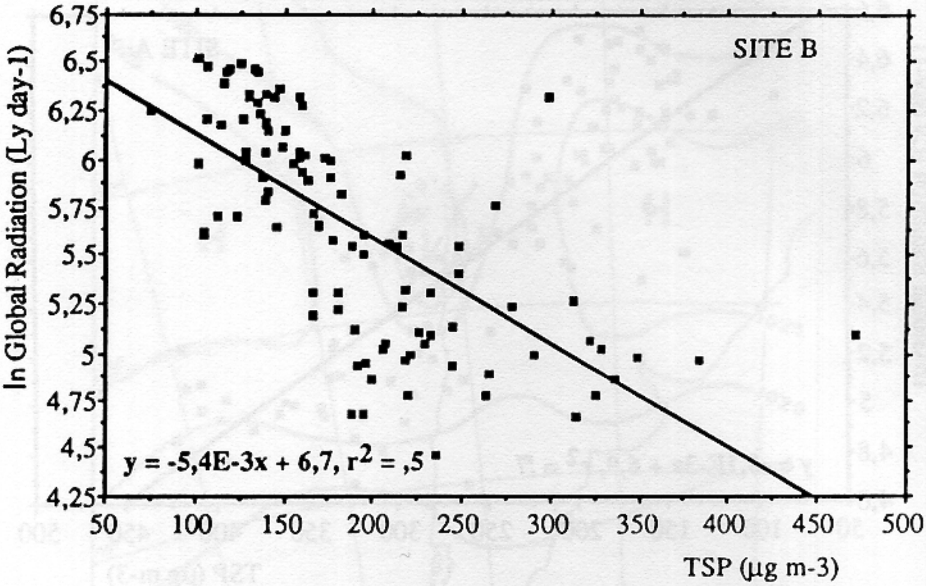

Fig. 7. Correlation curve, throughout the whole year, for an 11 yr period, between the monthly average of concentrations of total suspended matter (TSP) and the log of monthly average of global solar radiation, at site B.

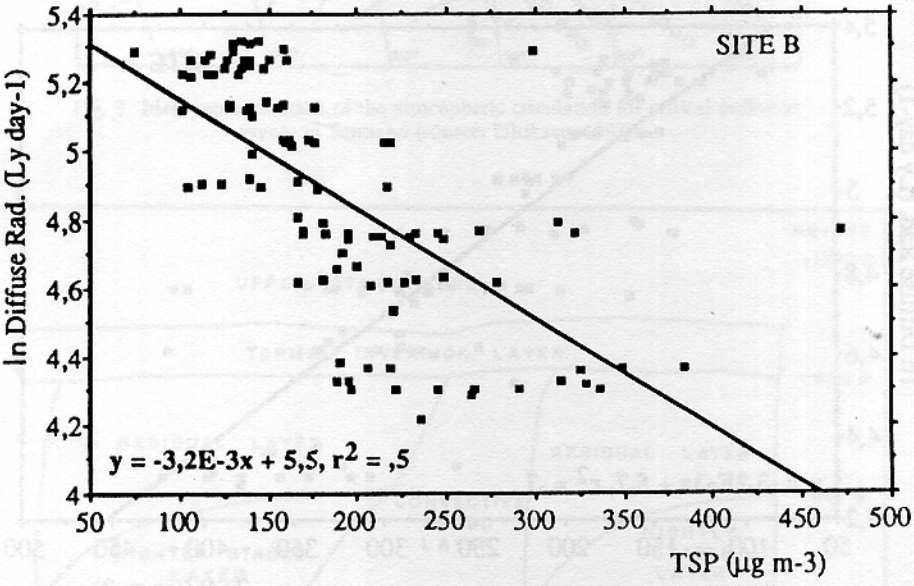

Fig. 8. Correlation curve, throughout the whole year, for an 11 yr period, between the monthly average of concentrations of total suspended matter (TSP) and the log of monthly average of diffuse radiation, at site B.

ation have been eliminated because there are no data on TSP. The obtained correlation coefficients were 0.707 for 101 data items for Figs 7 and 8.

In the urban cases (sites A and B) solar radiation decreases when TSP increases. The calculations for the two suburban sites (C and D) do not show any correlation.

Other authors have reported that good agreement is obtained for a comparison between predicted and observed solar radiation in an urban area for clear days between aerosol and global solar and UV flux. For hazy days the mass-size distribution of aerosol becomes important (Bergstrom and Peterson, 1977). A positive dependence has also been observed between the diffuse component and optical thickness (Peterson, 1977).

Figures 9 and 10 show the correlation curves, throughout the whole year, for an 11 yr period, signifi-

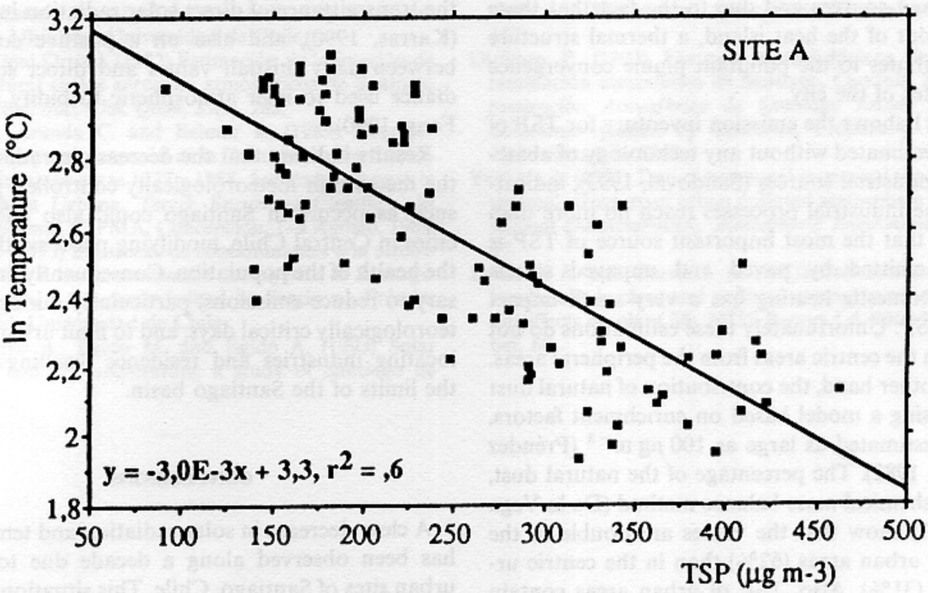

Fig. 9. Correlation curve, throughout the whole year, for an 11 yr period, between the monthly average of concentrations of total suspended matter (TSP) and the log of the temperature at site A.

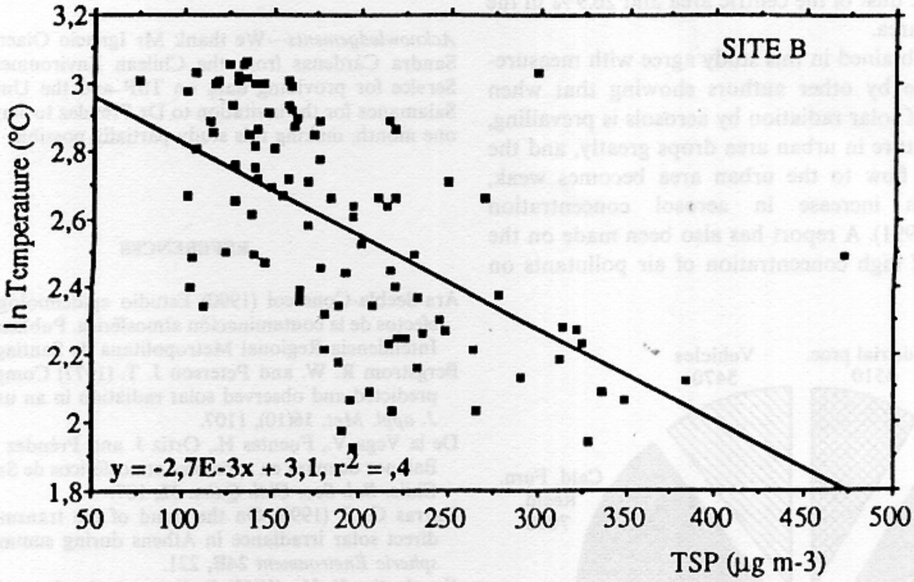

Fig. 10. Correlation curve, throughout the whole year, for an 11 yr period, between the monthly average of concentrations of total suspended matter (TSP) and the log of temperature at site B.

cant to 99.99%, between the monthly average of TSP and the log of the monthly average temperature at both sites, respectively. The obtained correlation coefficients were 0.775 for 107 data items, and 0.632 for 101 data items, at sites A and B, respectively. These results are consistent with the relationship between solar radiation and temperature shown by Seco *et al.* (1993).

Our results show that there exists a relationship between TSP and solar radiation and temperature for urban sites, even if the values considered were the monthly average, but not for suburban sites.

The radiation decrease and the pollution increase account for the extension and altitude attained by the dust dome over the areas of great urban density, buildings and motor vehicles which characterize the historic center of Santiago city, where the sampling sites (A and B) are located. This relation disappears towards the peripheral urban areas as a consequence of the small quantity of pollutants coming from moving and fixed sources and due to the fact that these areas are out of the heat island, a thermal structure that contributes to the pollutant plume convergence to the center of the city.

Figure 11 shows the emission inventory for TSP of Santiago, estimated without any technology of abatement for industrial sources (Sandoval, 1993), indicating that the industrial processes reach no more than 8.8% and that the most important source of TSP is the dust emitted by paved and unpaved streets (66.1%). Domestic heating has a very small impact over the TSP. Unfortunately these estimations do not distinguish the centric areas from the peripheral areas.

On the other hand, the contribution of natural dust to TSP, using a model based on enrichment factors, has been estimated as large as 100 $\mu g\, m^{-3}$ (Préndez and Ortiz, 1982). The percentage of the natural dust, using the chemical mass balance method (De la Vega *et al.*, 1987) show that the values are double in the peripheral urban areas (62%) than in the centric urban areas (31%). Also, TSP of urban areas contain more pollutant chemical inorganic and organic species such as lead and other trace elements or PAHs, respectively, than the TSP of peripheral urban areas (Préndez, 1993). Sulfates represent 22.5% of the anthropogenic dust of the centric area and 26.9% in the peripheral area.

Results obtained in this study agree with measurements made by other authors showing that when scattering of solar radiation by aerosols is prevailing, air temperature in urban area drops greatly, and the convergent flow to the urban area becomes weak, causing an increase in aerosol concentration (Yoshida, 1991). A report has also been made on the influence of high concentration of air pollutants on the transmittance of direct solar radiation in summer (Karras, 1990), and also on a positive correlation between daily dustfall values and direct solar irradiance used to infer atmospheric turbidity (Liu and Feng, 1990).

Results indicate that the decrease in radiation and the increase in meteorologically controlled pollution such as occurs in Santiago could also affect other cities in Central Chile, modifying photosynthesis and the health of the population. Consequently, it is necessary to reduce emissions, particularly during the meteorologically critical days, and to limit urban growth, locating industries and residence dwellings beyond the limits of the Santiago basin.

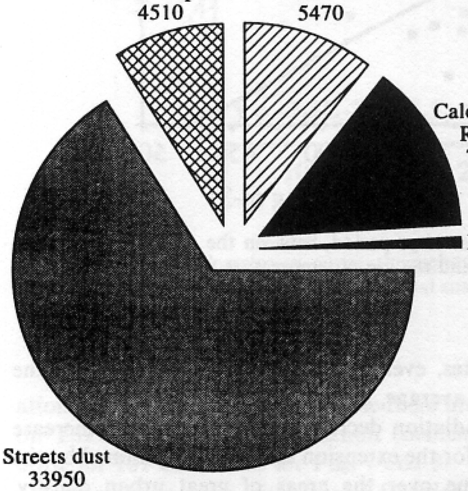

Fig. 11. Emission inventory for TSP of Santiago in 1990, estimated without any technology of abatement for industrial sources (adapted from Sandoval, 1993).

CONCLUSIONS

A clear decrease in solar radiation and temperature has been observed along a decade due to TSP at urban sites of Santiago, Chile. This situation seems to be controlled by meteorological conditions.

Further and more detailed studies are necessary in this field in order to evaluate the possible impact over the population.

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