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GLOBAL RADIATION ATTENUATION BY AIR POLLUTION AND ITS EFFECTS ON THE THERMAL CLIMATE IN MEXICO CITY

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ABSTRACT

Solar radiation attenuation in Mexico City is estimated by comparing global radiation intensity observed at a station in the downtown area, relative to that observed in a cleaner rural air at a site 8 km northeast of the airport. On average, the city receives on clear days during the dry season 21.6% less solar energy than the rural surroundings. Similar values of attenuation are observed during the rainy season when aerosol concentration is abated by a wash-out effect. As expected, solar dimming shows an inverse relation to wind and temperature. Attenuation reaches its maximum (25–35%) with prevailing weak winds (1–2 m/s) and high noon relative humidity. In the city, variation of global radiation by the day of week, shows that solar attenuation is highest on Tuesdays, while on Saturdays solar dimming by smog was less. Since a similar weekly variation (with lower values) was observed at the rural site, the conclusion was that the smog layer affects the solar radiation climate in rural areas beyond the immediate city limits. The declining annual mean of maximum temperatures observed near the limits of the Mexico City basin, suggests that the smog layer is affecting the radiation and thermal climate of a vast region downwind of the capital city.

An attempt is made to show that while in the industrial and downtown areas the day time heat island effect dominates over the cooling effect of aerosols, in other suburban and rural sites downwind and away from the warm air mass, the reflecting properties of the smog layer seem to prevail resulting in an observed decreasing trend in maximum temperatures. From the above it may be concluded that maximum temperatures continue to rise in downtown Mexico City in spite of the attenuation due to absorption and reflection of incoming solar energy by the smog layer. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: Mexico City; air pollution; solar radiation; climate change; urban–rural climate; temperature; annual, mean, maximum; heat island

1. INTRODUCTION

In developing countries, urban growth has been concentrated in an increasing number of large conurbations. In 1990, 45 out of 69 cities (65%) with more than 3 million inhabitants were in developing countries (United Nations, 1989). One of the environmentally-related problems of large cities is the deterioration of air quality. As a result of the accelerated growth, resource shortages are exacerbated by ever increasing demands for services. Air pollution and the consequential health impact on the population are some of the problems faced by these megacities.

Mexico City is well known for being one of the largest conurbations in the world (estimated population in 1995: 17.5 million), as well as for its highly polluted atmosphere. Meteorological aspects of this problem have been examined by Jáuregui (1988), Klaus *et al.* (1988), Nickerson *et al.* (1992), Miller *et al.* (1994), and more recently by Bossert (1997), who has used a regional model (RAMS) to investigate the detailed meso-scale flow structure over the Mexico City region. Recent measurements of the columnar

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aerosol concentration have been reported by Vasiliev (1995). While air pollution is still a serious problem with regard to some pollutants like ozone and its precursors (see Jáuregui, 1993a), dust and CO_2, the levels of other airborne contaminants (e.g. lead, SO_2) have been substantially abated to below the standard level by the improvement of gasoline and diesel fuels introduced in 1991 (see Jáuregui, 1995; Rosas *et al.*, 1995).

Even though many large cities in the developing world are presently plagued by high levels of atmospheric pollution, to our knowledge the topic of the long-term effects of the urban aerosol layer on the thermal climate has received little attention.

This paper attempts to estimate the depletion of all-wave global radiation ($K\downarrow$) observed in the city, compared to that received at a rural site during clear days of the dry and rainy season. Also, cross correlations are calculated to determine the link between depletion of $K\downarrow$ with wind speed, relative humidity, air quality index and maximum temperature. Depletion of $K\downarrow$ is also determined by the day of week in order to detect the effect of traffic.

2. THE GEOGRAPHICAL SETTING

Local topographic and climatic features often contribute to worsen the air pollution situation in Mexico City: the surrounding mountains reduce ventilation and favour the formation of surface inversions especially during the dry season when an anticyclonic type of weather prevails (e.g. clear skies and weak pressure gradient). During the rainy season the turbulent moist trade winds reduce the frequency of stable air conditions providing dilution of pollutants by convection, and washout by precipitation.

3. THE DATA AND INSTRUMENTATION

An urban automatic climatological station (School of Mines) located in the centre of town and one in a rural area (Plan Texcoco, 8 km NE and upwind from the airport), both including global radiation were set up in 1994 (see Figure 1 for location). Additionally, global radiation data from the Tacubaya observatory, located on the western suburbs, was also used for comparison. The accuracy of the three sensors corresponds to the second class according to the WMO classification (WMO, 1990). Details of the radiation instruments are shown in Table I. The pyranometers have been compared with a reference instrument kept at the solar radiation laboratory of the Geophysics Department on the grounds of the University.

4. METHODS

It is well established that urban air pollution leads to dimming of the incoming solar radiation in comparison to that observed in rural surroundings. Many studies have provided evidence for this effect, especially since the 1970s when air pollution began to gain relevance (for a review on this topic see Oke, 1979). While some large midlatitude cities in the industrialized world have gradually improved their air (e.g. the Ruhr urban conglomerations, London, Pittsburg, Los Angeles, Tokyo), the large conurbations in tropical countries have seen an important increase in the air pollution problem, as their populations have increased, adversely affecting their health.

4.1. Long-term solar radiation trend

Since high aerosol concentrations at an urban site reduce the total incident solar energy, one approach to estimate the amount of reduction of the solar beam has been to investigate the aerosol's radiative effects using various turbidity parameters, e.g. the Linke factor (Linke, 1922) and the Angstrom turbidity coefficient (Angstrom, 1961). This approach requires a long-term time series of an elaborate direct beam component of solar irradiance at specified hours, and whenever there are no clouds in the sight of path. Based on this method, Galindo and Muhlia (1970) have shown that aerosol concentration in the atmosphere in Mexico City has increased considerably, so much so that according to the Angstrom classification (Angstrom, 1961) it corresponds in recent years to a very turbid one, as shown in Table II.

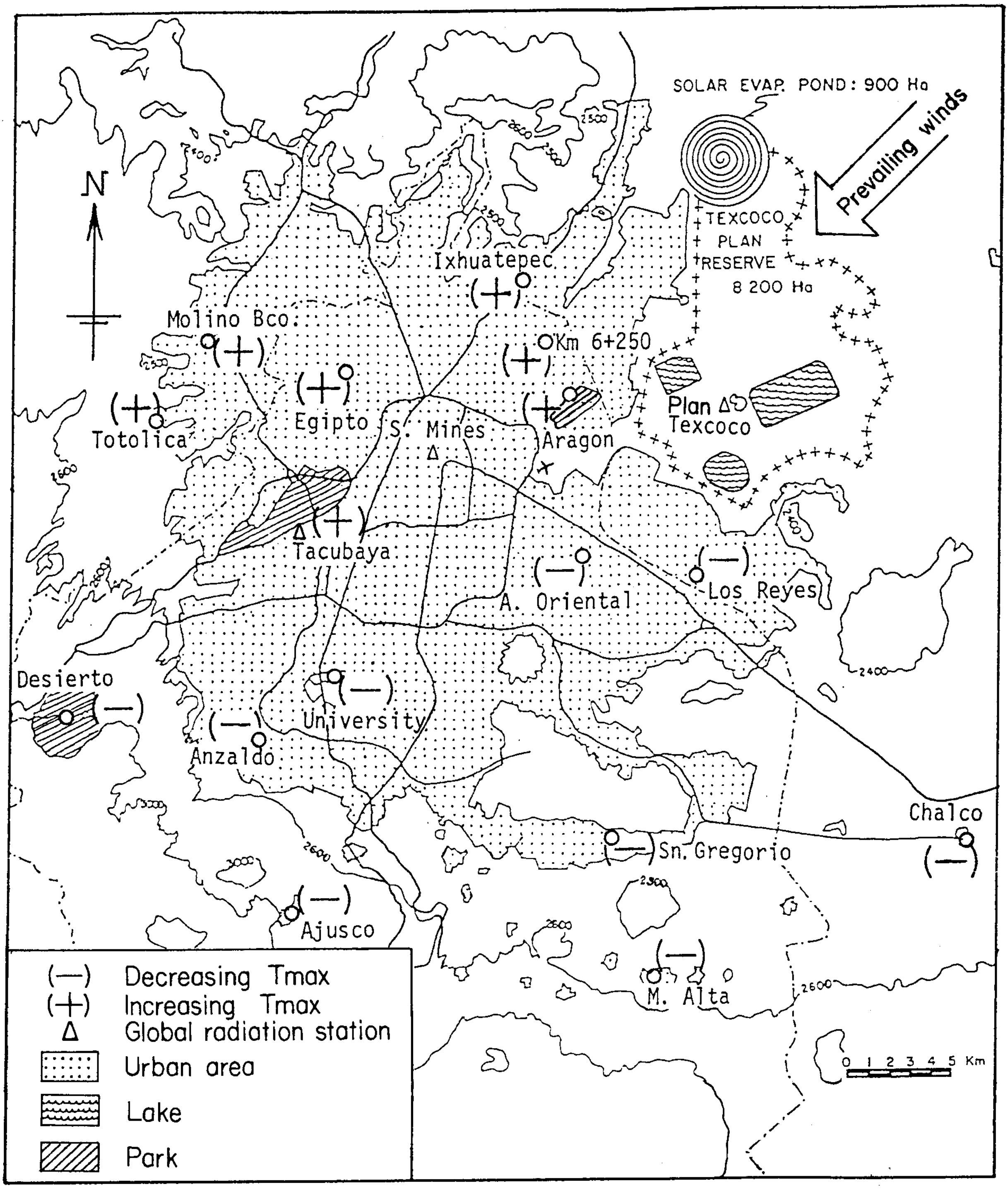


Figure 1. Location of climatological stations

Table I. Instrument characteristics

Site	P. Texcoco	School of Mines	Tacubaya Obs.
Pyranometer	Eppley	Vaisala	Kipp/Zonen
Model	100848	HMP 31 Ut	CM 11
Range	0.285–2.8 μm	0.285–2.8 μm	0.305–2.8 μm
Accuracy	±1%	±1% from 0–1400 w/m^2	±1%

Table II. Turbidity parameters of Mexico City's atmosphere for various periods (Galindo and Muhlia, 1970; Vasiliev, 1995)

Period	τ	β	$N * 10^{-9}$
1911–1928	0.084	0.071	0.63
1957–1962	0.173	0.147	1.30
1967–1991	0.286	0.246	12.5

β, Angstrom's turbidity coefficient; τ, optical depth; $N * 10^{-9}$ aerosol columnar concentration.

Using the trend approach, Stanhill and Kalma (1995) have detected a substantial decrease in global radiation over a period of 35 years in Hong Kong. During this time solar irradiation measured at Kowloon decreased annually by an average of 57 MJ/m^2 (or a decline of 1%/year), which seems to be a very steep decrease for an insular city of 6 million inhabitants.

4.2. Urban/rural solar radiation comparisons

The effects of air pollution on solar radiation have been estimated by Peterson and Flowers (1974) by comparing attenuation of urban K↓ relative to that observed in cleaner rural air near the city. This is, as noted by Oke (1979), difficult to achieve because of the transport of pollutants downwind of the city; besides, even though the control has been carefully selected upwind of the prevailing wind direction (as in the present case prevailing wind direction being from the NE), dispersion of pollutants takes place in all directions, especially in a city located in a closed basin.

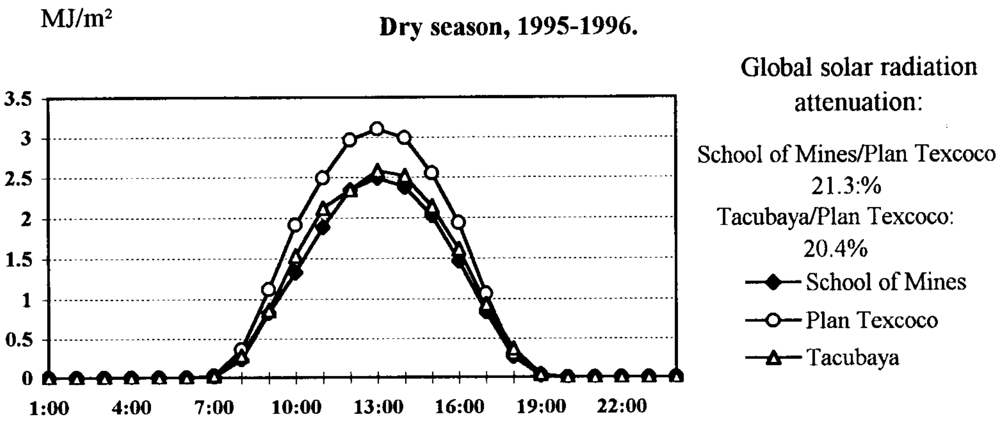


Figure 2. Mean global solar radiation for clear days (2, 6, 10, 11, 19 December 1995; 1 January, 5, 11 April, 9, 12, 23, 26 December 1996) at three sites in Mexico City during the dry season

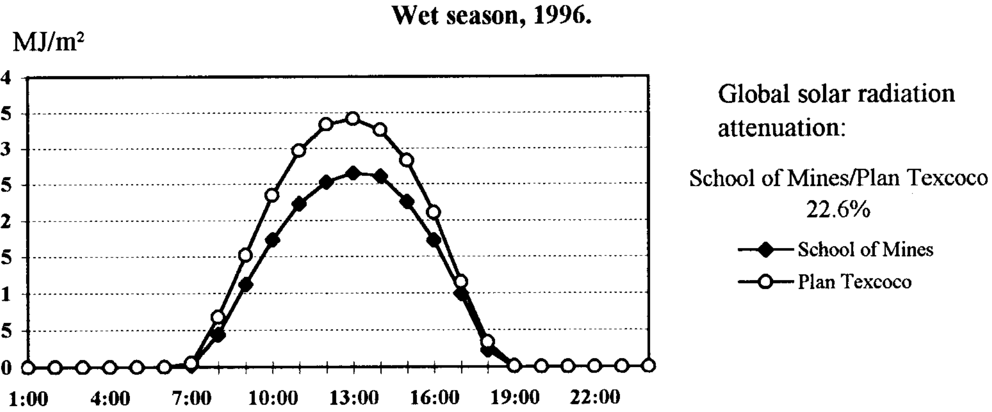


Figure 3. Mean global solar radiation for clear days (11, 16, 17, 18, 30 October 1996) at an urban (School of Mines) and a rural (Plan Texcoco) site in Mexico City during the rainy season

5. RESULTS

5.1. Mean daily solar radiation attenuation

Figure 2 shows the mean global radiation for nine clear days (2, 6, 10, 11, 19 December 1995; 1 January, 5, 11 April, 9, 12, 23, 26 December 1996) in the dry season (November–April) at the three sites in Mexico City. A larger number of days was not possible since it was difficult to select days with clear sky conditions simultaneously at the three sites. As would be anticipated, values at the suburban station (Tacubaya) lie close, but above those corresponding to the urban site (School of Mines) located in the densest portion of the pollution layer and recording the lowest levels of radiation. On average, the city receives on clear days 21.6% less solar energy than the rural surroundings to the northeast. The mean percentage of solar attenuation at the suburban Tacubaya observatory was practically the same (1% less) as that observed in downtown. Although these values are characteristic of clear days in the dry season when surface inversions (and air pollution episodes) are more frequent, the reduction varied with the averaging period. During the rainy season (May–October) global radiation in the capital city on five clear days in October 1996, as compared with that observed at the rural site was reduced to 22.6%; a figure practically equal to the value observed during the dry season (Figure 3). The above results suggest that while particulate pollutant levels tend to be lower during the rainy season (due to the removal from the atmosphere of a considerable amount of aerosols by the rainout and wash-out effect), the higher prevailing humidity favours an increase in turbidity.

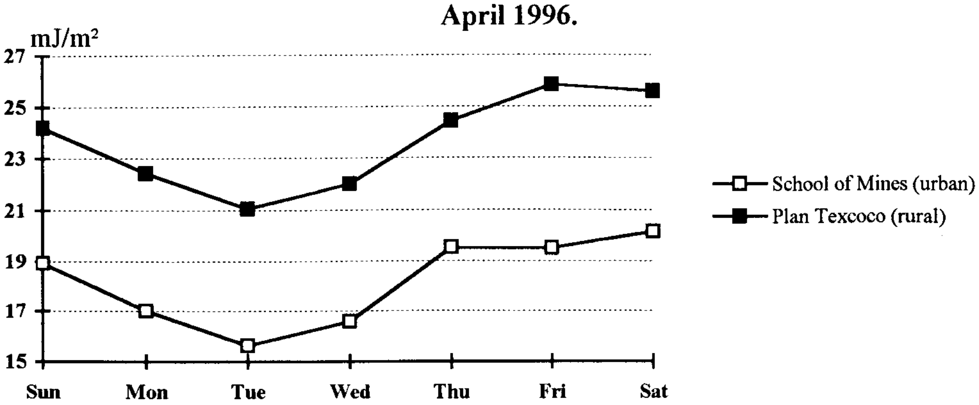


Figure 4. Mean global radiation at School of Mines (urban) and Plan Texcoco (rural) by day of week

5.2. Solar radiation attenuation by day-of-week

Since air pollutant concentrations are mainly linked to emissions from vehicular (and industrial) activity, urban/rural comparisons of global radiation by day-of-week were made for clear days for a month in the dry season. As may be seen in Figure 4 a weekly variation of solar dimming at both sites is clearly evident for the month of April 1996. The solar dimming variation at the rural site is almost identical (although at much higher values) to the urban curve implying that the rural site is still affected by the presence of the smog cloud. For this particular month, solar attenuation was most marked on Tuesdays (35%) while on Saturdays solar dimming by smog was least in the week but still quite high (25%). As would be expected, the patterns of weekly variation of solar dimming varied considerably from week to week differing sometimes markedly from the one presented in Figure 4.

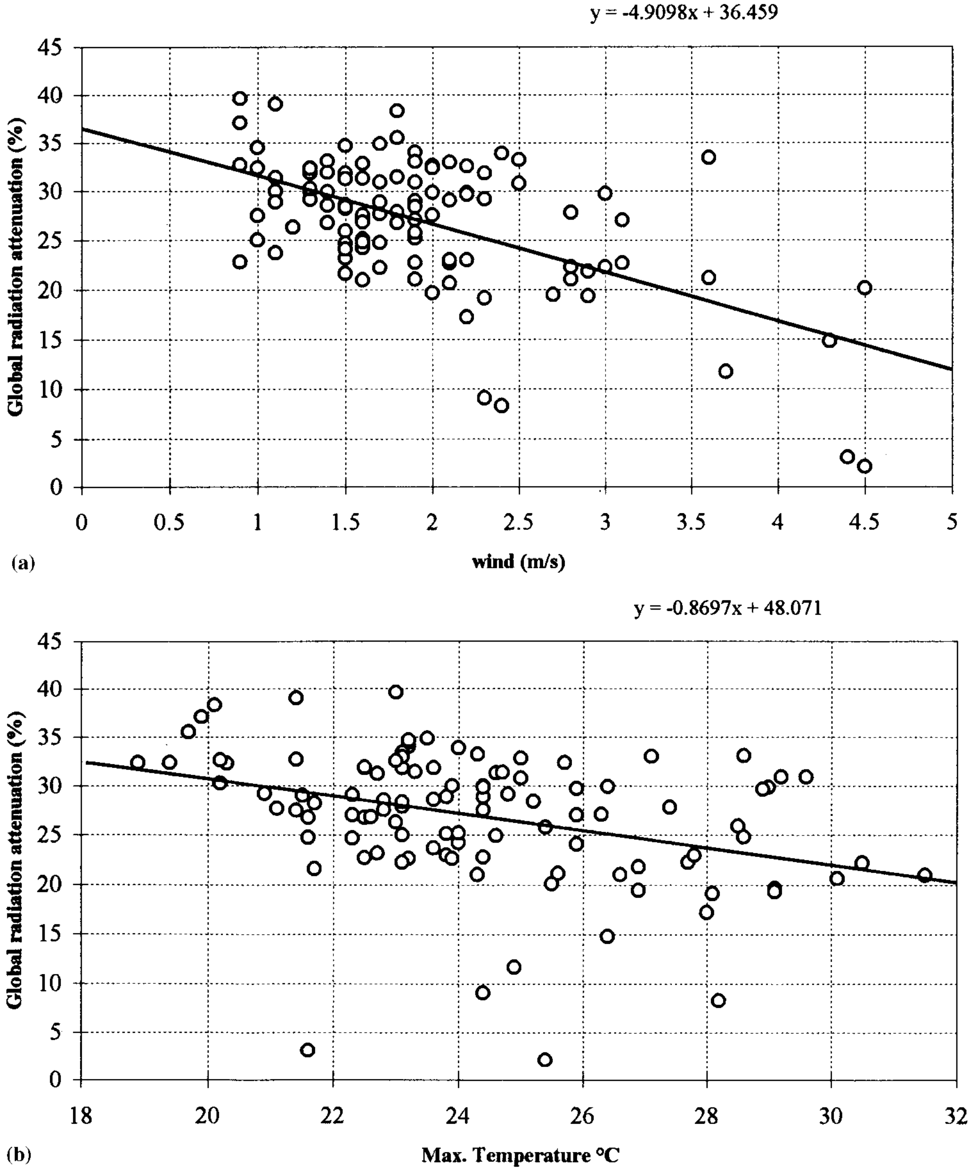


Figure 5. (a) Linear regression of wind speed (m/s) at 15:00 h at urban site versus urban/rural global radiation attenuation (%) between 8:00 and 18:00 h. Period: December 1994, January, March and April 1995. Total number of days: 107. (b) Linear regression of maximum temperature (°C) at urban site versus urban/rural radiation attenuation (%) between 8:00 and 18:00 h. Period: December 1994, January, March and April 1995. Total number of days: 107

5.3. Global radiation attenuation and its relation to air quality and some meteorological variables

As anticipated, global radiation attenuation shows an inverse dependence on wind speed and temperature, and is directly related to air pollution concentration and relative humidity. Winds in the city are usually weak (1–2 m/s) when attenuation reaches its maximum values of 25–35% (Figure 5a). Solar dimming tends to be weak with higher values of maximum temperatures that may enhance active mixing in the urban layer (Figure 5b). During the dry season air pollution levels (mainly determined by ozone but also by total suspended particles from dust storms and PM10 by vehicular traffic (Jáuregui, 1993a)) usually reach above the standard (0.11 ppm or 100 air quality standard units). On those occasions, the reduction of the solar beam is in the order of 24–35% (Figure 6a). Attenuation tends to be higher when

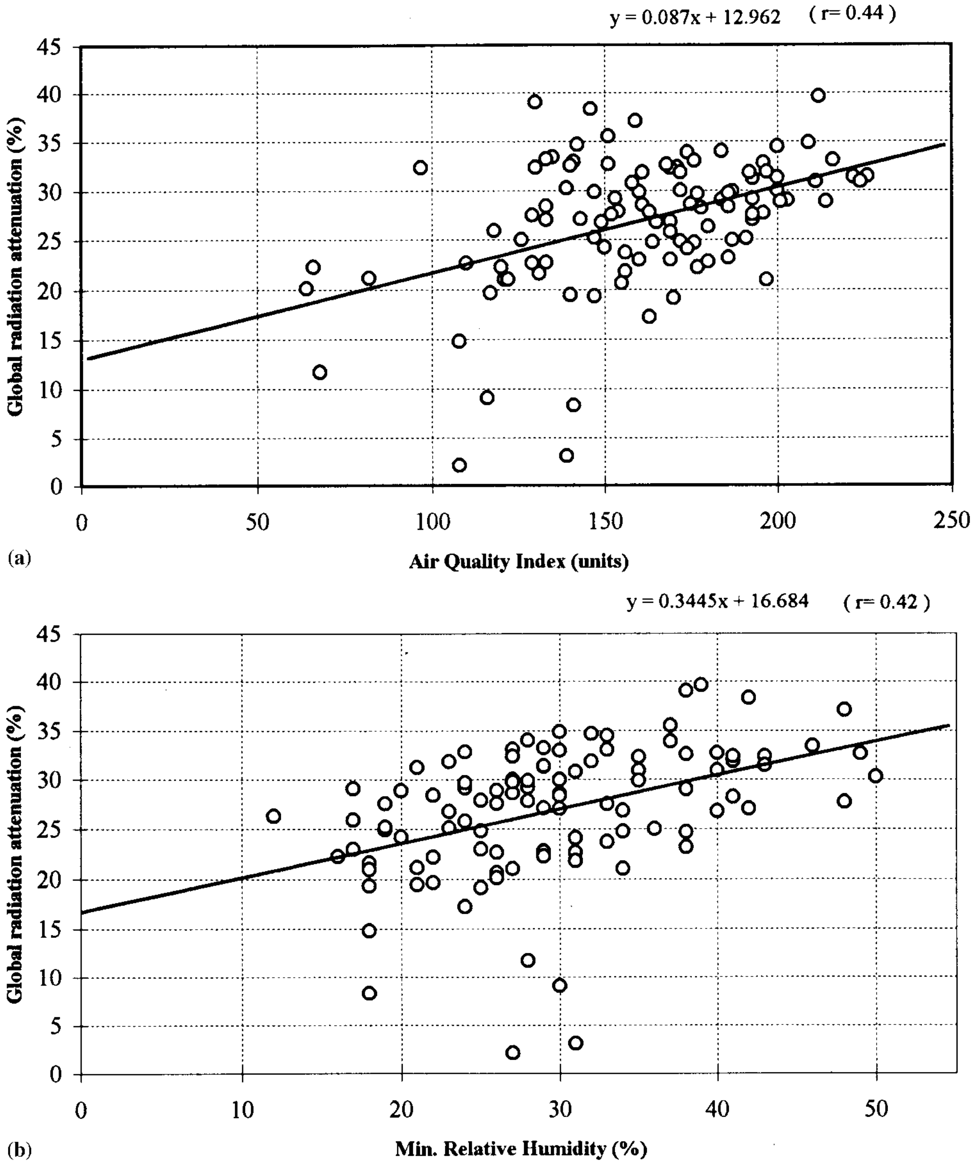


Figure 6. (a) Linear regression of air quality index (50–250) as observed in downtown at noon versus urban/rural global radiation attenuation (%) between 8:00 and 18:00 h. Period: December 1994, January, March and April 1995. Total number of days: 107. (b) Linear regression of relative humidity at about noon (urban site) versus urban/rural global radiation attenuation (%) between 8:00 and 18:00 h. Period: December 1994, January, March and April 1995. Total number of days: 107

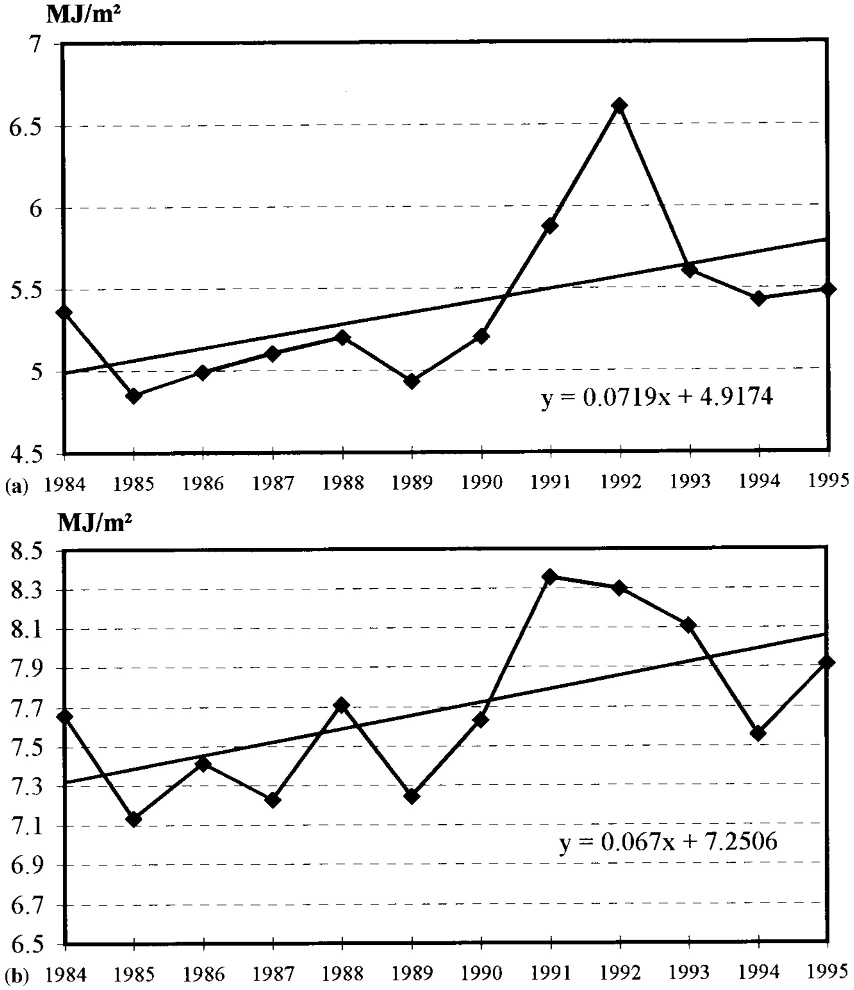


Figure 7. (a) Mean diffuse radiation (MJ/m^2) for dry season (January–April, November–December) at the University. Period: 1984–1995. (b) Mean diffuse radiation (MJ/m^2) for wet season (May–October) at the University. Period: 1984–1995

relative humidities at about noon are somewhat higher than normal (Figure 6b), suggesting that part of the aerosols are hygroscopic, increasing their size in a more humid environment.

5.4. Solar radiation trend

Figure 7 shows the annual totals of diffuse radiation (MJ/m^2) for the dry (Figure 7a) and rainy (Figure 7b) seasons as observed at the solar radiation observatory located at the University grounds (see Figure 1), and for the period 1984–1995. While an increasing trend is apparent during both the dry and rainy seasons for the diffuse component, no appreciable trend is evident for the global radiation curve (not shown). This result suggests that the diffuse/direct ratio of global radiation has been gradually altered during the period due to an increase of aerosol particles generated by a corresponding increase in combustion processes (traffic, industry) that took place as the city increased its population.

Although the climatic role of tropospheric aerosols is not yet well established, it is hypothesised that the observed increase in diffuse radiation would tend to induce cooling of the urban layer by an increase in reflected visible incoming radiation. Some evidence of this effect is provided in Table III which shows the decreasing trend in the maximum temperatures observed in some urban stations located outside the influence of the urban heat island like station Los Reyes (on the eastern suburbs) and stations Ajusco and

Table III. Mean maximum temperature trends and their significance for stations located under the influence of the heat island (Km 6+250, Aragon and Tacubaya, see Figure 1) showing positive trend while those located downwind (Ajusco, Los Reyes and Anzaldo) display a decreasing trend

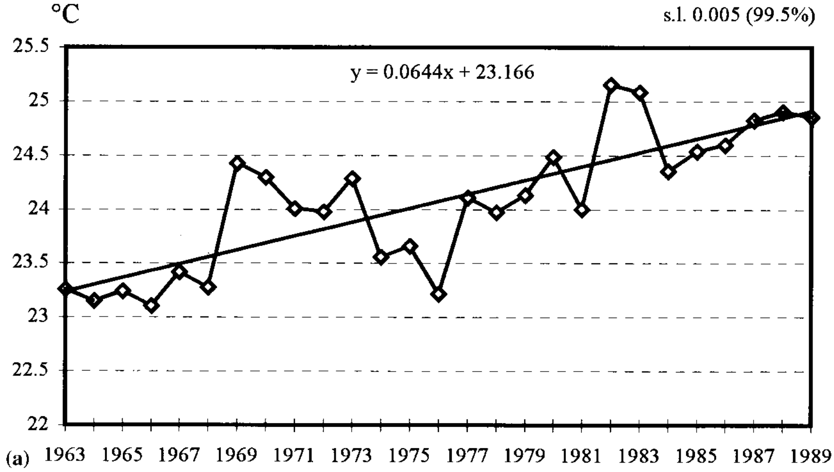
Station	Dry season		Wet season	
	Trend	Significance level	Trend	Significance level
Los Reyes	$y = -0.0632x + 24.448$	0.01	$y = -0.0277x + 24.94$	0.10
Ajusco	$y = -0.0504x + 17.443$	0.10	$y = -0.0605x + 17.6$	0.05
Anzaldo	$y = -0.0193x + 23.244$	0.10	$y = -0.019x + 23.524$	0.10
Km 6+250	$y = 0.0685x + 23.856$	0.001	$y = 0.0477x + 24.536$	0.005
Aragon	$y = 0.0574x + 23.798$	0.001	$y = 0.0449x + 24.383$	0.005
Tacubaya	$y = 0.0269x + 22.891$	0.05	$y = 0.0277x + 23.42$	0.05

Anzaldo—a rural and a suburban site, respectively (see Table I and Figure 1) to the SW of Mexico City downwind of the prevailing winds. It is evident from Table III that the rates of change of the maximum temperatures do not vary appreciably from the wet to the dry season. Both positive and negative trends are similar in magnitude and show significance levels varying from 90 to 99%. But the increasing trends that may be linked to the heat island effect show the highest significance.

Other stations located to the south and west and downwind (see Table IV) like Chalco (a suburb), Desierto (a periurban preserve), A. Oriental (urban), Sn. Gregorio (suburban), M. Alta (rural) and University (see Figure 1) show a similar annual mean maximum temperature decreasing trend (not included in Table III). However, other areas of the city (the northern half) seem to fall under the influence of the day-time heat island (see Jáuregui, 1993b) and, therefore, the trend in maximum temperatures there is positive, pointing to the dominant role of the urban warm air mass on the radiation budget (Table III). Figure 1 indicates those stations where maximum temperature shows an increasing (+) or decreasing (−) trend during the past decades. While the northern part of the city shows a trend toward warmer

Table IV. Frequency of winds at Plan Texcoco station for a dry (April) and a wet (August) month in 1993

Direction	6:00 h		12:00 h	
	Frequency %	m/s	Frequency %	m/s
April 1993				
N	16.7	1.9	10.0	2.1
NE	43.3	2.4	33.3	2.4
E	13.3	1.5	23.3	2.3
SE	0.0	0.0	6.7	2.8
S	13.3	4.7	16.7	5.1
SW	13.3	3.6	3.3	2.0
W	0.0	0.0	3.3	7.7
NW	0.0	0.0	3.3	2.4
August 1993				
N	26.7	2.3	23.3	2.7
NE	46.7	2.3	26.7	2.9
E	13.3	2.6	30.0	2.3
SE	6.7	2.3	0.0	0.0
S	3.3	3.4	6.7	5.7
SW	0.0	0.0	0.0	0.0
W	0.0	0.0	3.3	2.4
NW	3.3	2.1	10.0	2.4



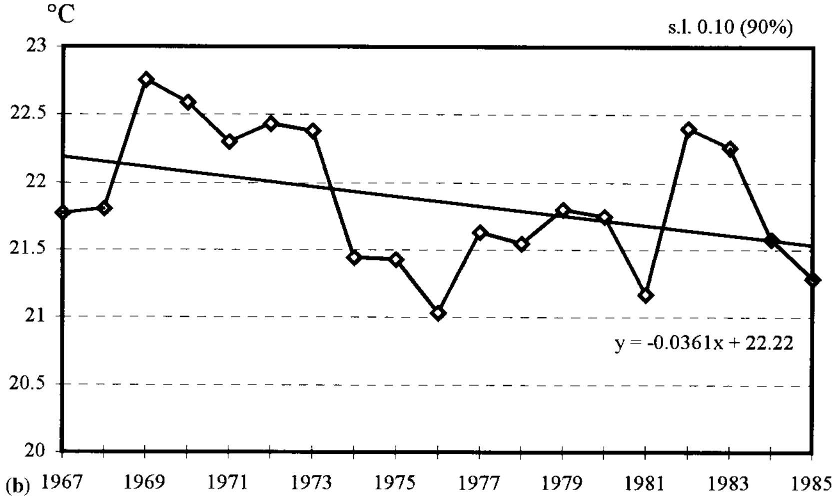


Figure 8. (a) Area averaged mean annual maximum temperature trend for urban stations (Ixhuatepec, Totolica, Molino Bco., Aragon, Km 6 + 250, Tacubaya, Egipto, see Figure 1), influenced by heat island. Period: 1963–1989. (b) Area averaged mean annual maximum temperature trend for downwind suburban/rural stations (Desierto, Ajusco, Anzaldo, Los Reyes, A. Oriental, Sn. Gregorio, M. Alta, Chalco, see Figure 1), in Mexico City. Period: 1967–1985

temperatures, in the afternoon the southern (downwind) portion has experienced a downward trend probably due to the dominant radiational cooling by aerosol particles over the daytime heat island effect. This is better illustrated in Figure 8 where areal averaged mean maximum annual temperature trends are shown for groups of stations where temperature has increased (Figure 8a) and those suburban/rural sites outside the influence of the heat island where temperature has declined (Figure 8b). On the other hand if area averaged T_{min} trend analysis is performed for the same groups of stations, as in Figure 8a and b, results show (Figure 9a and b) an increasing trend in both groups suggesting that the nocturnal heat island phenomenon has been increasing in extent and intensity as the city has grown especially during the last decades, as seen in Table V. This influence has been more marked in the downwind suburban/rural stations.

6. DISCUSSION AND CONCLUDING REMARKS

In the first part of this paper, a comparison has been made of the intensity of global radiation in Mexico City with that over the nearby rural area for the same time in order to estimate attenuation of the solar

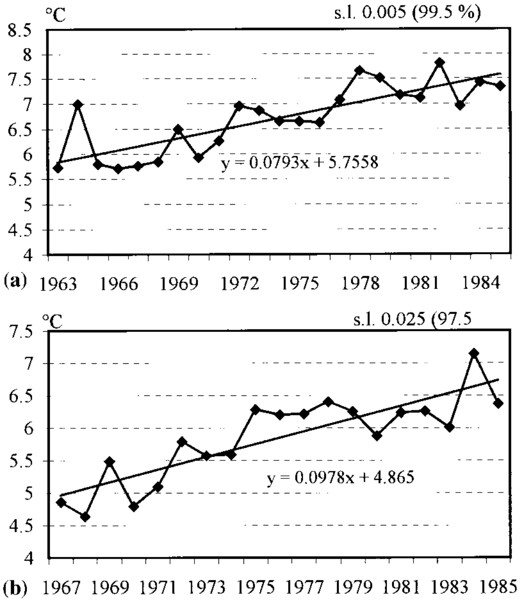


Figure 9. (a) Area averaged mean annual minimum temperature trend for urban stations (Ixhuatepec, Totolica, Molino Bco., Aragon, Km 6 + 250, Tacubaya, Egipto, see Figure 1), influenced by heat island. Period: 1963–1985. (b) Area averaged mean annual minimum temperature trend for downwind suburban/rural stations (Desierto, Ajusco, Anzaldo, Los Reyes, A. Oriental, Sn. Gregorio, M. Alta, Chalco, see Figure 1), in Mexico City. Period: 1967–1985

beam by the smog layer. Reduction of global radiation by this method is in the order of 21–22% on clear days during both the dry and the rainy seasons. Water vapour and aerosols from the pollution layer are effective in reducing solar radiation. It is interesting to note that the dimming of global radiation on clear days of the dry season (when a stable atmosphere favours higher particle concentrations in the surface layer and therefore, more frequent smog episodes) was not found to be significantly different to that observed during the rainy season when wash-out, rain-out processes and a more turbulent atmosphere tend to reduce aerosol concentrations in the urban layer as has been actually observed; (see for example Jáuregui, 1989). It is proposed that this could be explained perhaps by the increase in the size of hygroscopic aerosols as a consequence of higher humidities prevailing during the rainy season. This would imply that lower levels of aerosol concentrations during the rainy season have a similar solar reduction effect to that observed during the dry season when aerosols are more numerous and densely packed. Urban/rural global radiation variation by day-of-week shows that the rural curve describes a similar weekly modulation to that observed in the city with a minimum value occurring on Tuesdays and a maximum on Saturdays (there were cases when the extreme values happened on different days). The above result shows that even though the control was located some 8 km outside (and upwind) of the city limits, it was still reflecting the weekly variations in vehicular (and industrial) emissions. This points to the difficulty in selecting a rural control, especially when the city is located in a valley. Perhaps a better option would have been to locate the rural control on the slopes of the surrounding mountains and above the surface inversion layer.

Table V. Mexico City statistics and temperature trends for various periods

Period	Mean annual temperature trend (°C)	Population at end of period (million)	Urban area at end of period (km^2)
1900–1950	$y = 0.0073x + 14.766$	3.2	230
1951–1970	$y = 0.0275x + 15.348$	8.7	363
1971–1990	$y = 0.037x + 15.669$	14.4	1150
1900–1996	$y = 0.0197x + 14.5$		

In view of the above results it may be concluded that the attenuation values reported here are an underestimation. It is well established that tropospheric aerosols are known to influence air temperature by reducing the insolation reaching the surface in otherwise clean air. In order to test this hypothesis, long-term maximum mean temperature series from urban/suburban and rural climatological stations have been examined. Surprisingly the temperature trends over the city are not uniform. Instead, the northern and central areas of the city show an increase in maximum temperature probably linked to the influence of the daytime heat island. In contrast, in the southern portions of the capital city (away from the nucleus of the urban warm air mass) the net thermal effect of aerosols seems to be a decrease in sensible heat as shown by a decline in maximum temperatures in recent years. This decreasing trend does not seem to change appreciably with the seasons and although less significant, is of the same order of magnitude as the observed positive trend related to the heat island effect.

The above results suggest that a cooling effect of the aerosol cloud over rural areas at a considerable distance and downwind of the urban conglomeration may be taking place in the Mexico Basin as shown by negative maximum temperature trends in rural stations. These considerations tend to support the view expressed by Oke (1993), that cities play a central role in regional (and global) climate change.

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