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Long-term association between pan evaporation and the urban heat island in Mexico City

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RESUMEN

Se pretende determinar las características evaporativas de diferentes areas de la Ciudad de México y su entorno ubicada en un valle interior elevado y de latitudes tropicales, contando con una red de 16 estaciones urbanas, suburbanas y rurales. Se ha observado un crecimiento paralelo significativo entre la evaporación y la intensidad de la isla de calor en la parte central y oeste de la Ciudad de México para el periodo 1967-88. Se sugiere que el incremento en la evaporación está ligado al aumento en la intensidad de la isla de calor, relacionado a su vez con un acelerado crecimiento urbano de la ciudad. En comparación, aun con el aumento en la intensidad de la isla de calor, los suburbios del este de la ciudad muestran un descenso en la evaporación debido posiblemente a la presencia de una gran área revegetada (9500 Ha). También se exploró la relación de la evaporación con otros elementos climáticos como son la insolación, la precipitación y la velocidad del viento.

ABSTRACT

Using a network of 16 urban/suburban and rural pan evaporation (pe) stations in Mexico City and its environs, an attempt is made to assess the comparative evaporative characteristics of different areas in a large city located in an elevated inland valley in the tropics. Significant parallel increases in pan evaporation and heat island intensity have been observed in the central and western portions of Mexico City for the period 1967-88. It is suggested that pan evaporation increase is linked to the observed increase in the intensity of the heat island related to the accelerated urbanization of the capital City. In contrast over the eastern suburbs the establishment of a large (9500 Ha) adjacent revegetation project has apparently influenced pan evaporation to decline in spite of the increasing presence of the heat island. Association of pan evaporation to other climatic elements such as insolation, precipitation and wind velocity is also explored.

Key words: urban pan evaporation, heat island, tropical urban climate.

1. Introduction

The theory underlying micro-meteorological methods of measuring the local water vapour flux over a surface (homogeneous and with low aerodynamic roughness) is well established . These methods are: aerodynamic, Bowen-ratio-energy balance and eddy correlation (Oke, 1987). In order to obtain accurate measurements of evapotranspiration in an urban site using the micro-meteorological approach the instrument height must be considerable relative to the height and horizontal spacing of the urban elements so that they are effectively combined into and integrated signal (Oke *et al.*, 1988). These authors note that the time required to obtain suitable averages of turbulent states depends on instrument height and atmospheric stability.

Using the eddy-correlation approach, the turbulent sensible heat flux and the net radiation were measured in a suburb of Mexico City to estimate the heat storage and evaporation terms of the energy balance equation (Oke *et al.*, 1992). Although only two of the four main fluxes were measured, the Bowen ratio values confirm a significant contribution of evaporation to the turbulent heat transport in the city, even during the dry season.

A second group of methods to estimate evaporation includes statistical algorithms and physically-based models that utilize hydrometeorological data i.e. Penman's method (Penman, 1948; Monteith, 1965). Since this method requires the use of almost routine meteorological data it has been widely applied for rural sites under different climate and irrigation conditions. Applying Penman's approach Jáuregui *et al.* (1978), found that potential evaporation estimates showed good agreement with pan evaporation observations made in a rural site near Mexico City. Correlation was particularly good during the wet season, when the oasis effect is minimal. However, any attempts to estimate potential evapotranspiration by such methods in an urban area are bound to end in disappointment. The spatial inhomogeneity of thermal and aerodynamic properties of the urban elements render the measurement of urban evapotranspiration a very difficult problem.

Therefore, as noted by Oke *et al.* (1988) it is very unlikely that areal evapotranspiration can be evaluated by using observations from standard hydroclimatological stations located in urban sites. Moreover, the use of class A pans to derive estimates of evaporation from natural surfaces raises many doubts. The energy transfer through the sides of the pan, together with the turbulence created by the pan itself make it difficult to relate results to evaporation from an irrigated or natural surface.

Notwithstanding the above limitations, class A evaporation pans in the words of Swinbank (1987) "have a useful role to play in assessing comparative evaporative needs of different regions eventhough the quantitative indications must be interpreted with caution". Higher pan evaporation in urban areas with respect to the rural surroundings has been reported by Adebayo (1991) for a tropical city (Ibadan) while Balling and Brazel (1987) have identified an increase in pan evaporation in Phoenix that they attribute to the increase in air temperature and wind speed.

Recently, Grimmond and Oke (1991) have developed a physically-based model to simulate evapotranspiration in urban areas. The authors suggest that if the model is applied in tropical cities (where intense rainfall events are likely to occur) it would be advisable to conduct evaporation measurements (with lysimeters) and adapt it accordingly. Grimmond *et al.* (1992) have compared measurements of evapotranspiration from portable minilysimeters (at one hour resolution) with that of the eddy correlation approach instrumentation. Their results show that both measurements are comparable and they conclude that the minilysimeter is an alternative to measure evapotranspiration in heterogeneous terrain (i.e. urban) where water vapour flux is possibly not constant in the near-surface layer. However, their measurements refer to discrete and very local evaporation fluxes from pervious surfaces-not areally averaged evaporation fluxes from extensive portions of the urban fabric. In the present paper we examine areal and temporal variations of pan evaporation in a large urban area (Fig. 1) in an attempt to link the observed changes to urban-induced changes in some of the forcing climate variables (i.e. temperature, insolation, humidity and wind) related to the pan evaporation process.

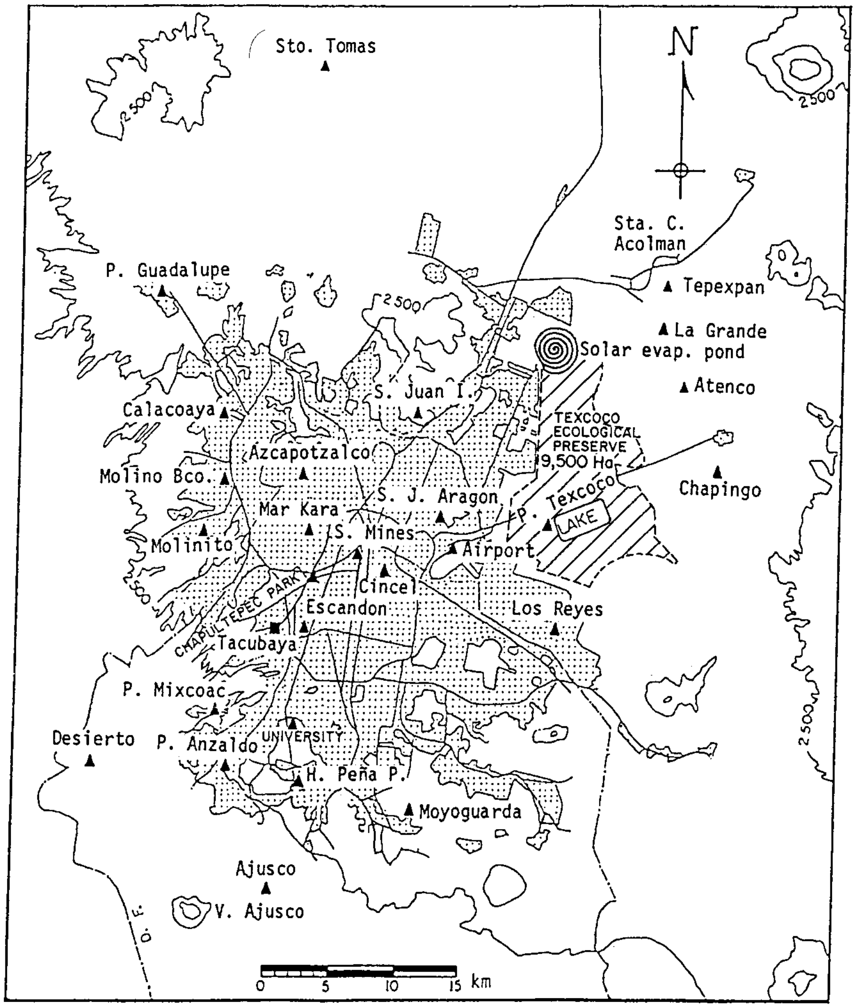

Fig. 1. Location of climatological station used.

2. The data

Pan evaporation data (period 1967-88) were obtained from 16 urban/rural stations in Mexico City and its environs (Fig. 1 for locations). Records of mean annual minimum temperature and precipitation were available for several urban/suburban stations. Humidity, wind and insolation annual data correspond to the Tacubaya Observatory located to the west of the city.

3. Results

Evaporation relies largely on the precipitation pattern at the scale of the Mexico Basin. Figure 2 shows distribution of pan evaporation for the period 1961-88. The observed pattern of high evaporation to the east of the city where drier conditions (precipitation~400mm/yr) prevail and the lower evaporation to the west where more humid (precipitation 900mm/yr) and cooler climate (due to higher elevation) is present, may be explained by looking at the distribution of isohyets for 1987, in Figure 3. The maximum pan evaporation observed in Fig. 2 over the downtown area seems to be located in the vicinity of the average position of the nocturnal heat island for a dry month (November 1981) (Fig. 4) and somewhat to the west (near the airport) of the mean daytime location of the core of this phenomenon as determined by the maximum temperature isolines as illustrated in Figure 10 in Jáuregui (1993). From the above it may be hypothesized that the excess pan evaporation in downtown could be in part a response to the additional sensible heat provided by the heat island phenomenon.

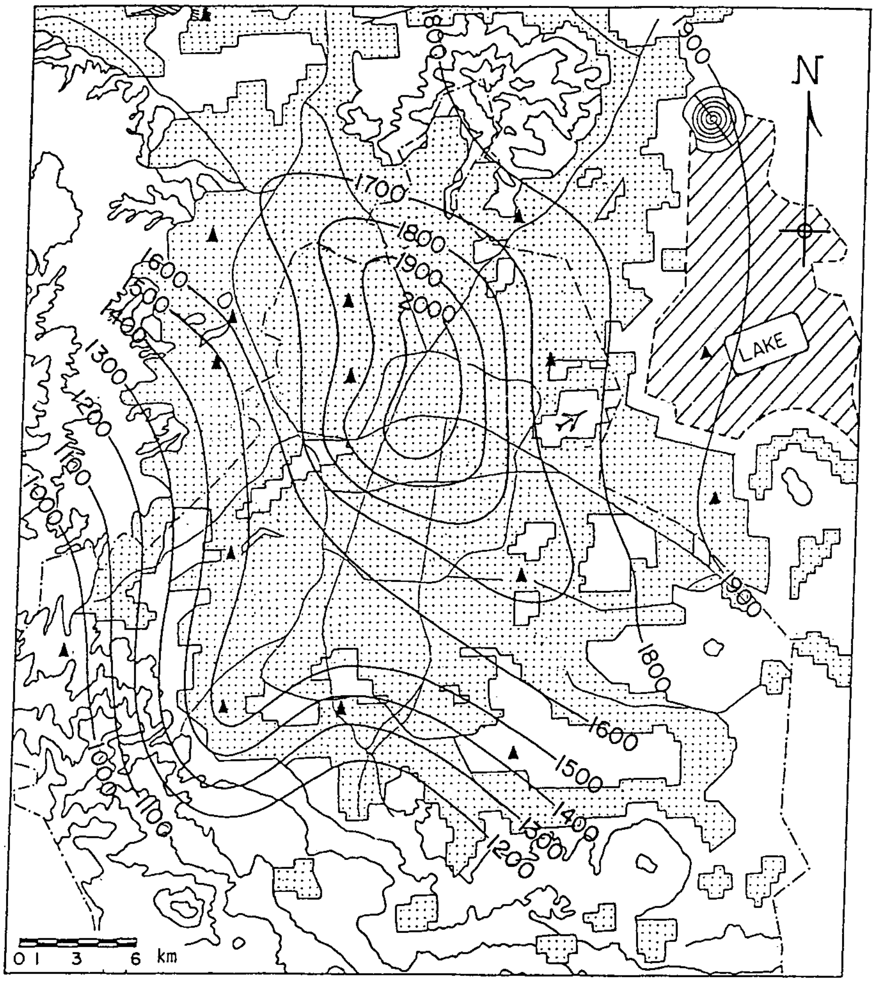

Fig. 2. Isolines of mean pan evaporation (mm/yr).

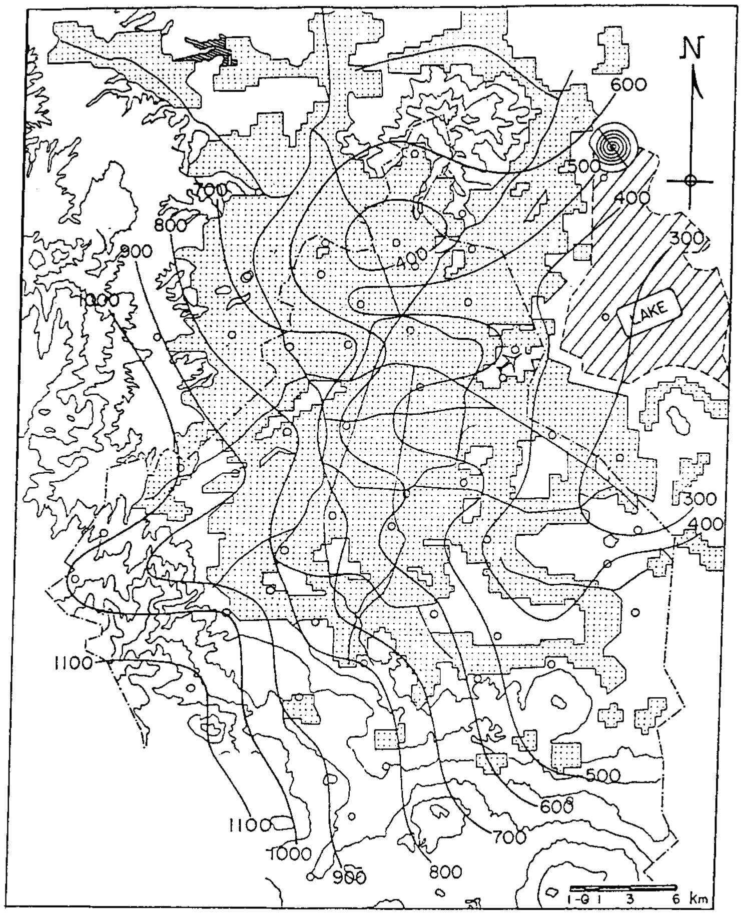

Fig. 3. Annual isohyets (mm) for year 1987.

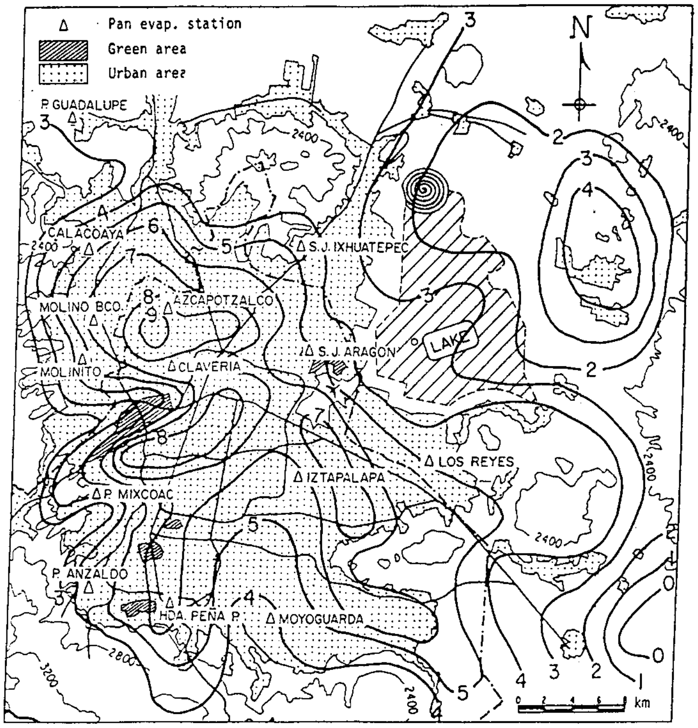

Fig. 4. Mean minimum temperature (°C) for November 1981 (Jauregui, 1986).

Pan evaporation temporal changes in relation to long-term urban-induced temperature and humidity changes

Figure 5 shows annual pan evaporation at stations Azcapotzalco, Anzaldo and Calacoaya located on the west side of the city (see Fig. 1) and for period 1967-88. An increasing trend is clearly evident for the three stations. In particular, the increasing trend shown for the Azcapotzalco station, which from the three is closest to the core of the heat island, displays the higher level of significance (0.005) Simultaneous with this increase and as a response to the accelerated urbanization that occurred during the period, the intensity of the heat island has also increased as evidenced by the mean annual minimum temperature tendency shown by urban stations Azcapotzalco, Tacuba, Tacubaya and Escandon (see Fig. 4 for location) in Figure 6. All of these stations are located in the vicinity of the heat island as illustrated in Figure 4. Consequently, the observed increase in pan evaporation seems to be (at least in part) linked to the observed increase in sensible heat associated with the heat island phenomenon.

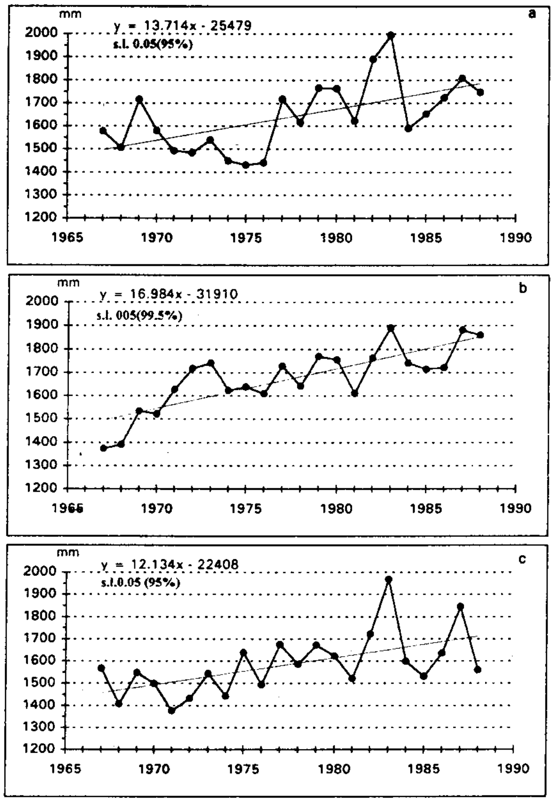

Fig. 5. Annual pan evaporation for a) Calacoaya, b) Azcapotzalco and c) Anzaldo. Period 1967-88.

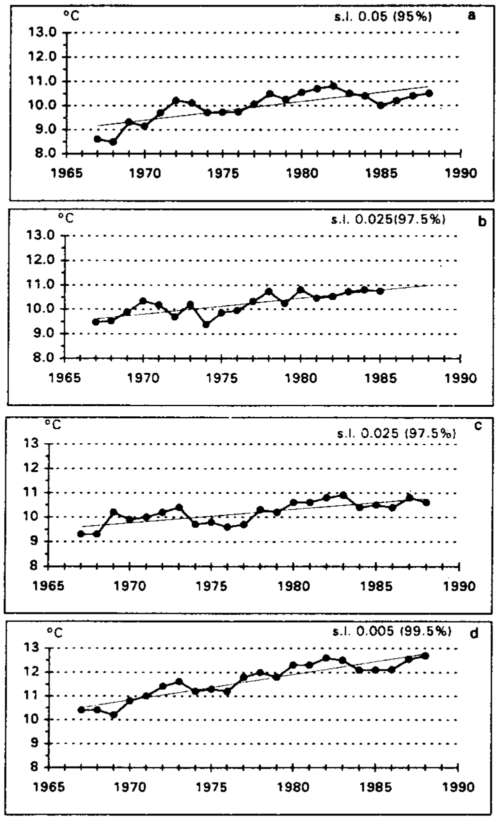

Fig. 6. Mean annual minimum temperature for a) Azcapotzalco, b) Tacuba (1967-85), c) Tacubaya, and d) Escandon for period 1967-88.

Long-term humidity trend

The influence of urbanization on humidity has been studied in European cities since the 1950's (Kratzer, 1956; Chandler, 1967). While relative humidities tend to be lower in the city as compared to the rural surroundings (due to the higher temperatures of the urban air, for the case of Mexico City see

Jáuregui, 1986), the specific humidities have been found to be frequently higher particularly at night (Chandler, 1967; Ackerman, 1987; Jáuregui and Tejeda, 1997). This last result has been attributed to the fact that combustion processes and industrial activities release substantial amounts of water vapour into the urban atmosphere or through evapotranspiration of urban parks into a stable atmosphere. In order to look for long term changes in the water vapour content of the urban air that would favour larger saturation deficit conditions that in turn promote more active pan evaporation, estimation of absolute humidities for Tacubaya station was made. As shown in Figure 7a it is clear that no significant trend in specific humidity (q) is evident for the period 1967-88. Given the increasing temperatures associated with rapidly developing urban heat island, relative humidity values would be expected to decrease in the vicinity of the Tacubaya Observatory. However, when the same period 1967-88 is considered to illustrate the mean annual relative humidity variation no significant trend is observed as illustrated in Figure 7b. It is clear from this figure that the increasing trend observed in the first part of the series (1967-76) compensates the decreasing trend observed in the second portion of the series. The adjacent source of moisture represented by Chapultepec Park (500 Ha) located 600 m upwind from Tacubaya appears to have a modulating effect on the local atmospheric moisture levels tending to reduce the saturation deficit downwind. (See Fig. 1 for location of park).

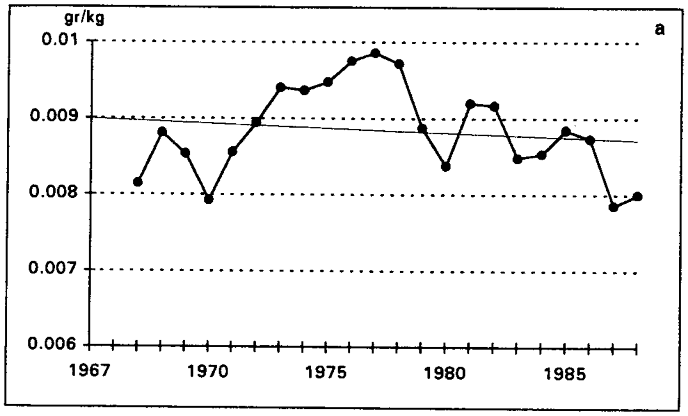

Fig. 7a. Mean annual specific humidity for Tacubaya. Period 1967-88.

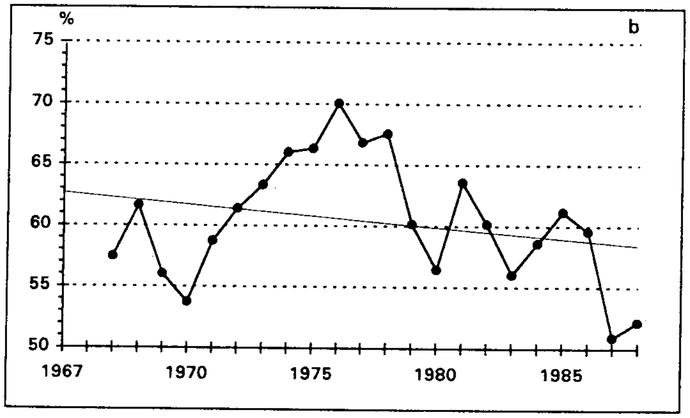

Fig. 7b. Mean annual relative humidity for Tacubaya. Period 1967-88.

In contrast to what is observed on the west side of the city, changes in long-term pan evaporation on the eastern side of the urban area show either no change or a slightly decreasing trend. This in spite of the fact that minimum temperatures display an increasing trend (suburban stations S. J. Aragón and Airport) suggesting that the eastern suburbs are also under the influence of the heat island (Fig. 8). In contrast, Sto. Tomás station located in rural surroundings (Fig. 1) shows a slighthly decreasing trend. Most of the 22 year pan evaporation series for these stations are significantly correlated (at 5% significance level) as shown in Table 1. This result would give more confidence on the spatial consistency of the evaporation observations in the 3 stations, some of them more than 30 km apart. It is worth noting that Sto. Tomas station in spite of being located in a rural location 20 km to the north of the city limits (Fig. 1) displays a behaviour similar to the group of three suburban stations on the eastern side of the city. Sto. Tomas was included in the analysis in order to compare pan evaporation values in a rural setting with those observed on the eastern city suburbs. Figure 9 shows that only in exceptionally dry (i.e. 1982) or wet years (i.e.

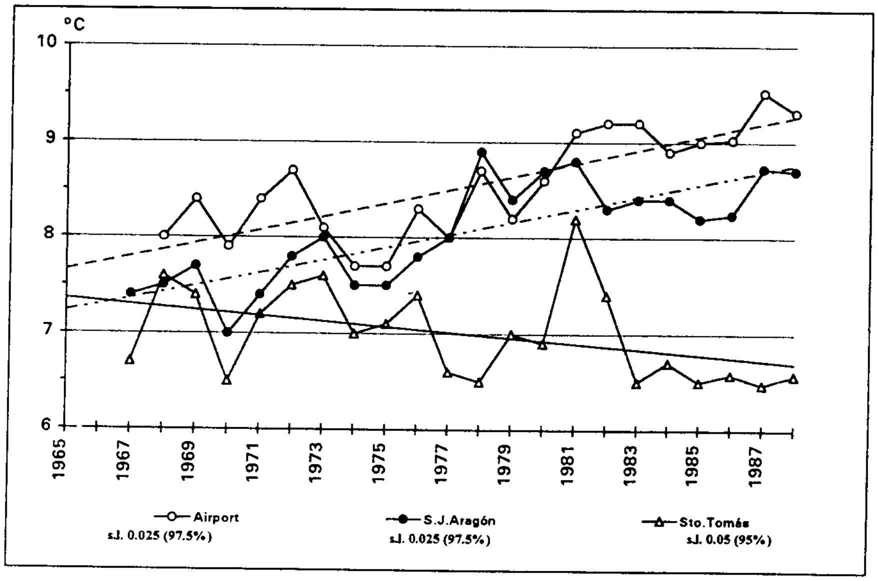

Fig. 8. Mean annual minimum temperature and trend for three eastern suburban stations and rural station Sto. Tomás to the north of Mexico City. Period 1967-88.

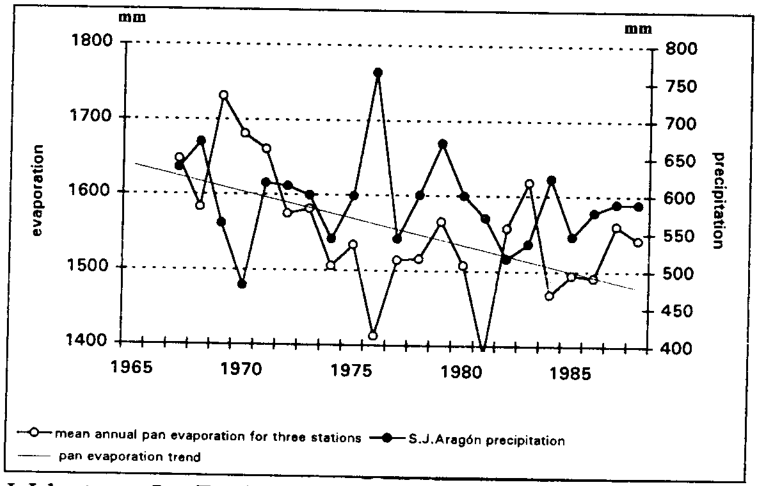

Fig. 9. Three-station (S. J. Ixhuatepec, Sto. Tomás. S. J. Aragon) mean annual pan evaporation and precipitation at S. J. Aragon. Period 1967-88.

1976), there is some inverse correspondence of precipitation totals with the mean annual values of pan evaporation to the east/north semi arid side of the city. Sometimes as in the case of 1982, the impact of a dry year (Fig. 9) on pan evaporation generates high values of this variable on the following year as observed simultaneously in the eastern stations (S. J. Ixhuatepec, Sto. Tomás and S. J. Aragón).

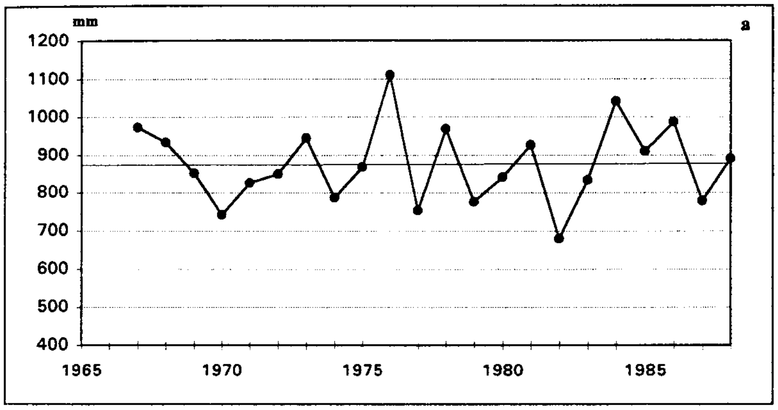

Fig. 10a. Five-station (Tacubaya, Desviación Alta, Calacoaya, Molinito, Molino Blanco) mean annual rainfall on the western suburbs of Mexico City for period 1967-88.

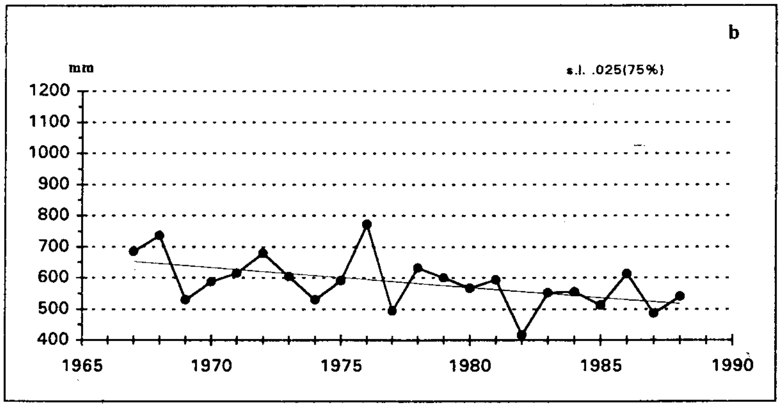

Fig. 10b. Four-station (S. J. Aragon, L. Reyes, Chalco and Tlahuac) mean annual rainfall and trend on the valley plains. Period 1967-88.

Conversely, low values of evaporation were observed on this group of stations during the wet year of 1976. In contrast to the mean annual precipitation trend for 5 stations on the western part of the city, which shows no appreciable trend (Fig. 10a), precipitation in the valley plains shows a decreasing trend as illustrated by rainfall series for 4 stations (Fig. 10b) and therefore pan evaporation should be expected to be on the rise for the period in question. But this being not the case, other sources of moisture have to be looked for to explain the observed decline in evaporation in the semiarid plains of the Mexico Basin. A possible indication for this decline could be attributed in part to the additional source of moisture represented by the gradual repasturization of about 8,000 Ha and construction of several large ponds (more than 1,000 Ha, see Fig. 1) on ex Lake Texcoco grounds that have been undertaken since 1975 in the center of the valley. These actions have apparently resulted in a 1° to 2°C dew point increase and reduction in the vapour pressure deficit at the airport located downwind of the repasturization area (Jáuregui, 1990/91).

Table 1. Pan evaporation correlation coefficients between several rural/urban stations on eastern Mexico City.

	S. J. Ixhuatepec evap.	Sto. Tomás evap.	S. J. Aragón evap.
S. J. Ixhuatepec evap.	1	0.80*	0.63*
Sto. Tomás evap.		1	0.58*
S. J. Aragón evap.			1

*S.l: 0.05

Pan evaporation and insolation trend

Another climatological variable that is likely to be related to pan evaporation variations is insolation as a surrogate for solar radiation. Changes in sunshine can be related to changes in atmospheric circulation patterns at the global and regional as well as at the local scale. At the global scale Henderson-Sellers (1986) suggests that in a warmer world cloudiness will increase and therefore sunshine will decline. At the regional scale Quinlan and Karl (1986) reported an increase in sunshine over the southern plains of the U.S. during the dust bowl years while Chagnon (1981) has found that sunshine has decreased over the Mid-West since the 1960's. For a tropical region like the Mexico basin changes in sunshine have not always been coincident with those observed in mid-latitudes. While the long-term curve displays in general a declining trend with high insolation amounts prevailing during the 1920's and 1930's, and reaching a minimum during the 1950's it shows a significantly increasing trend during the period 1967-1988 as illustrated in Figure 11 for the Tacubaya Observatory. While this increase could be attributable to changes in the air flow patterns at the regional scale (i.e. higher frequency of anticyclonic conditions), one could hypothesize that this increase in insolation is likely to have been prompted by the subsiding branch of convective cells induced by the heat island that during the day time hours is frequently positioned to the east of Tacubaya Observatory (Jáuregui, 1993). Since insolation has increased on the western part of the

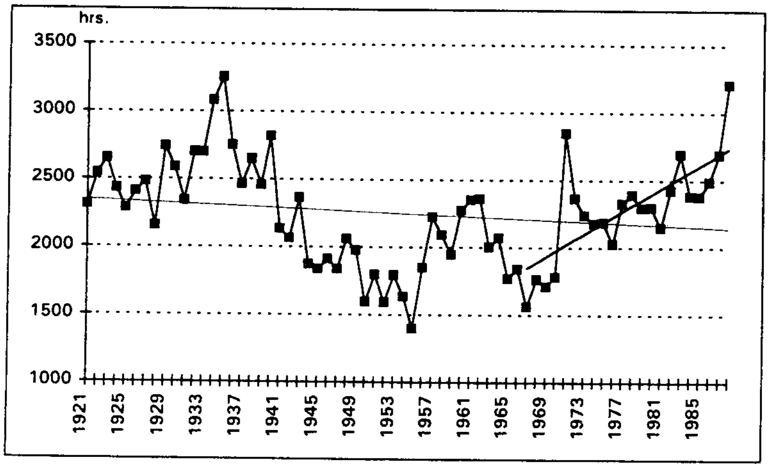

Fig. 11. Annual insolation (hours) for Tacubaya. Period 1921-88.

city a decrease in day time cloud cover would have to be expected. However, no significant changes in the number of cloudy days seem to have occurred during the period, as shown in Figure 12. While cloudy days were on the rise during the first 10 years of the period, (when sunshine decreased) they display a decline after 1976. The increase in sunshine hours could be a contributing factor to the observed increase in urban pan evaporation on the west side of the capital city. The measure of the effectiveness of the increasing sunshine (~43 hrs/yr) on pan evaporation on the west side may be judged by examining Table 2 that shows the mean annual hours of insolation for two stations representing the insolation regime on the west (Tacubaya) and on the east at Plan Texcoco, a rural station on the center of the valley plains (Fig. 1), where the characteristic subsiding air during the day time hours favours higher frequency of clear skies, while to the west cloudy skies are more frequent due to orographic effect. There is a marked contrast in sunshine hours as one goes from the west to the eastern suburbs. The increase is of the order of 231 hrs. (or 11%) between the Plan Texcoco and Tacubaya stations. If pan evaporation has been observed to decrease on the eastern suburbs (in spite of comparatively more abundant insolation) it is clear that, as already mentioned, the supply of moisture provided by the reclamation project is probably more important than insolation in determining the evaporation trend.

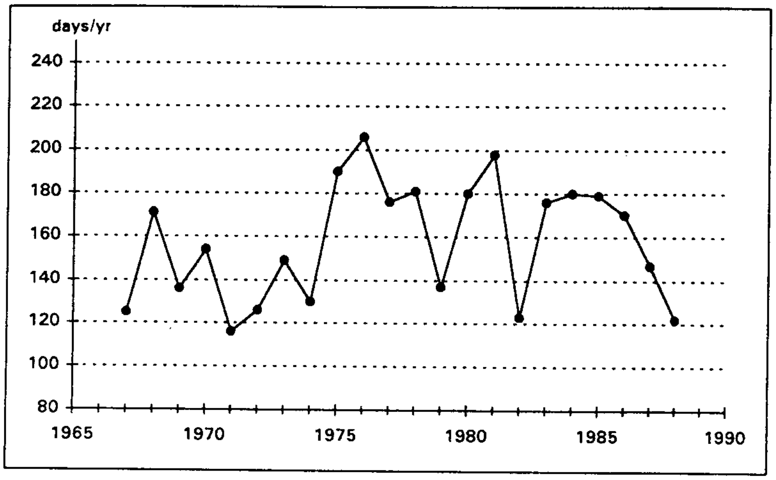

Fig. 12. Annual number of cloudy days observed at Tacubaya Observatory. Period 1967-88.

Table 2. Annual insolation (hs.) for two stations in Mexico City. Period 1977-79.

Station	1977	1978	1979	Avg.
P. Texcoco (rural)	2497	2229	2563	2429.7
Tacubaya (urban)	2239	2126	2231	2198.7

Pan evaporation and wind speed

The effect of urban areas on local wind speed has been examined by several authors (Chandler, 1965; Draxler, 1986). A significant increase in early morning wind speeds during the period of rapid heat island development has been reported by Balling and Cevemy (1987) for the city of Phoenix. Winds traversing urban areas are generally decelerated during the day time when upwind rural speeds reach a critical value.

At night, when the urban/rural thermal contrast is considerable and under weak regional pressure gradient conditions a convergent surface circulation develops. The rural wind in Mexico city has been found to be related to low wind speeds associated to anticyclonic conditions (Jáuregui, 1988). During the afternoons of the windy season (February-April) it is usual that upwind (from the northeast) rural winds with speeds of 6m/s (at the Texcoco station, anemometer at 10m) are drastically decelerated to less than 3 m/s as they reach the urban station School of Mines in downtown (anemometer at 24 m above street level) (Fig 1) as illustrated in Table 3. Eventhough the nocturnal rural winds are less intense, they display similar deceleration as they traverse the urban area. As the fetch over the city has increased, wind speeds have declined for period 1931-67 on the western suburbs of the city where the Tacubaya observatory is located (anemometer at 25 m above street level) (Fig. 13).

TABLE 3. Mean daily variation of wind speed (m/s) at a rural (plan Texcoco) and a downwind urban (School of Mines) site in Mexico City for a windy month (march 1993), see Fig. 1 for location of stations.

hr	2	4	6	8	10	12	14	16	18	20	22	24
Plan Texcoco	2.5	2.2	1.9	2.0	2.1	2.7	3.2	5.3	6.2	5.1	4.1	3.0
School of Mines	1.0	0.9	0.8	0.9	1.4	1.7	1.9	2.4	3.0	2.4	1.9	1.5
Diff.	1.5	1.3	1.1	1.1	0.7	1.0	1.3	2.9	3.2	2.7	2.2	1.5
%	60	59	59	55	67	37	41	55	52	53	54	50

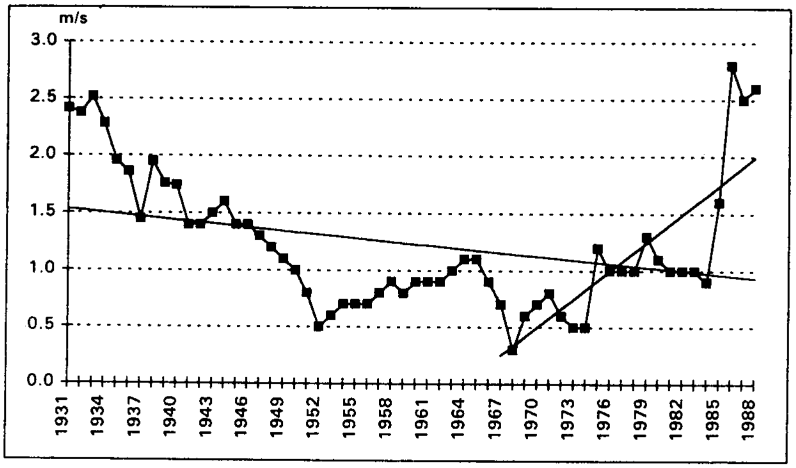

Fig. 13. Mean annual wind speed to Tacubaya Observatory. Period 1931-88.

On the other hand, it is clear that in recent years (1967-88) mean annual wind speeds increases, albeit small, have been on the rise (Fig. 13). This increase has been in accordance with pan evaporation on the western suburbs (Fig. 14). However, the level of association is only significant for one station

(Azcapotzalco) (Table 4). This was to be expected since on the one hand the relative importance of wind in determining pan evaporation has been found to be second to radiation (or its surrogates insolation and temperature) (Mukamal and Bruce, 1960). Moreover, wind speed observed at one urban station and at one height is likely to be an extremely crude measurement of turbulence for another urban site.

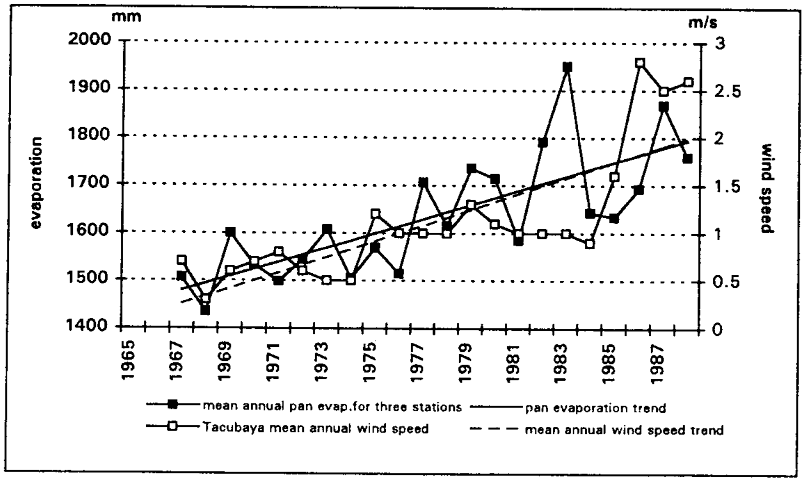

Fig. 14. Three-station (Azcapotzalco, Calacoaya, P. Anzaldo) mean annual pan evaporation, trend and wind speed for Tacubaya on the western part of the city for period 1967-88.

Table 4. Correlation coefficients between pan evaporation, insolation, wind speed and air temperature for several urban stations in Mexico City.

	Calacoaya evap.	Azca. evap.	P. Anzaldo evap.	Azcap. temp.	Tacubaya temp.	Tacubaya insolation	Tacubaya wind speed
Calacoaya evap.	1	0.64*	0.80*	0.53*	0.72*	0.60*	0.52*
Azcap. evap.		1	0.63*	0.85*	0.80*	0.93*	0.57*
P. Anzaldo evap.			1	0.49*	0.57*	0.61*	0.41*
Azcap. temp.				1	0.84*	0.81*	0.43*
Tacubaya temp.					1	0.78*	0.48*
Tacubaya insolation						1	0.66*
Tacubaya wind speed							1

* correlation coefficients greater than 0.50 are statistically significant at the 0.95 confidence level.

4. Correlations

In order to estimate the degree of association between pan evaporation and forcing factors such as temperature and insolation (a surrogate for the available energy for the evaporation process) cross correlations were calculated for two groups of stations. The first group corresponding to those urban stations west/central part of the city where increase in evaporation apparently responds to the increase in heat island warmth. Table 4 shows that pan evaporation in this group of stations is significantly linked to temperature and insolation.

The second group has been selected from suburban stations on the east upwind side of the city where drier environmental conditions prevail. No significant relation was found between pan evaporation, temperature and precipitation.

5. Concluding remarks

In this paper an attempt is made to assess the comparative evaporative characteristics of different areas in a large city in the tropics. Significant parallel changes in pan evaporation and heat island intensity have been observed in the central and western portions of Mexico City for the period 1967-88. These changes appear to be also related to congruent increases in other climate parameters such as insolation and wind speed. Since the spatial thermal and aerodynamic inhomogeneities of the urban elements and the fact that the use of pan evaporimeters provides only a crude estimate of evaporation from urban areas, no attempt is made in this paper to use the observed absolute values of pan evaporation. Areal and temporal pan evaporation changes seem to respond to urban-induced temperature changes that have occurred in the capital city as a result of accelerated urbanization process. Pan evaporation has increased on the western side of the city (at about 15 mm/yr) in an apparent response to the observed increases in air temperature and insolation during the period in question. However, the observed changes in pan evaporation and temperature have not been accompanied as would be expected, by a significant decrease in air humidity.

On the other hand, over the eastern suburbs pan evaporation, while displaying a high degree of homogeneity, shows a tendency to decrease, this in spite of the heat island effect evident on this side of the city. It is hypothesized that the new source of moisture represented by the reclamation of the grounds of ex Texcoco Lake located upwind has favourably modified the humidity environment on the eastern suburbs of the capital city.

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