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URBAN EFFECTS ON CONVECTIVE PRECIPITATION IN MEXICO CITY

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Abstract—This paper reports on urban-related convective precipitation anomalies in a tropical city. Wet season (May–October) rainfall for an urban site (Tacubaya) shows a significant trend for the period 1941–1985 suggesting an urban effect that has been increasing as the city grew. On the other hand, rainfall at a suburban (upwind) station apparently unaffected by urbanization, has remained unchanged. Analysis of historical records of hourly precipitation for an urban station shows that the frequency of intense (> 20 mm h^{-1}) rain showers has increased in recent decades. Using a network of automatic rainfall stations, areal distribution of 24 h isoyets show a series of maxima within the urban perimeter which may be associated to the heat island phenomenon. Isochrones of the beginning of rain are used to estimate direction and speed of movement of the rain cloud cells. The daytime heat island seems to be associated with the intensification of rain showers. Copyright © 1996 Elsevier Science Ltd

Key word index: Urban precipitation, Mexico city, urban climatology, urban hydrology.

1. INTRODUCTION

The possible effects of urban areas on enhancement of rainfall have attracted increasing attention regarding heavy storms of convective nature, mainly in mid-latitude cities (Lee, 1994; Stulov, 1993; Chagnon, 1992; Kairulin and Yakovlev, 1990; Muchnik, 1989; Shafir and Alpert, 1990; Chagnon *et al.*, 1991; Traicu, 1987). Chandler (1965) suggested three main factors as possible causes for urban-induced changes in precipitation: mechanical turbulence resulting from increased surface roughness, the addition of sensible heat from the urban warm air and the anthropogenic condensation nuclei floating in the urban air. In a series of studies in U.S. cities Chagnon (1969) reached the same conclusion.

However, Simmonds and Kawal (1986) conclude that the heat island effect is not a dominant mechanism in producing rain in Melbourne since days when rain occurs are cooler than average. Also Khemani and Murty (1973) arrive at similar conclusions in studying rainfall in Bombay. Earlier attempts (Jauregui and Klaus, 1982) have been made to characterize some aspects of urban effects on rainfall in Mexico City. With more detailed rainfall data available for the capital city this paper provides further evidence of the so-called rain-island effect in a tropical city. This information is of potential use for runoff/sewage water design in areas of the city affected by severe rainstorms.

2. CLIMATE AND DATA

The capital of Mexico is located in an elevated (2250 m) inland basin in the tropics (19°N lat.). The mid-latitude Westerlies that dominate from November to April imprint a characteristic anticyclonic weather with usually light winds and near cloudless skies. During the wet season much of the rain is associated with convective thunder showers embedded in the deep moist trade wind current that prevails from May to October.

During the rainy season most precipitation (convective) systems move from an easterly northeasterly direction. Occasionally, and especially during the transition months (May, October), thunderstorms may display movement from a southwesterly direction.

The average annual precipitation pattern indicates a distinct gradient from northeast in the semi-arid (400 mm yr^{-1} in a dry year) center of the valley to the humid (1000 mm yr^{-1}) south and west area where orographic influence is evident at the foothills, as illustrated in Fig. 1.

Hourly precipitation data for urban station Tacubaya Observatory were used for period 1939–1990. Annual totals of precipitation for this station and for San Juan Aragon near the airport were available for the period 1941–1985 (see Fig. 1 for location of these stations). In addition, 24 h data from an automatic pluviometric network were utilized for the period

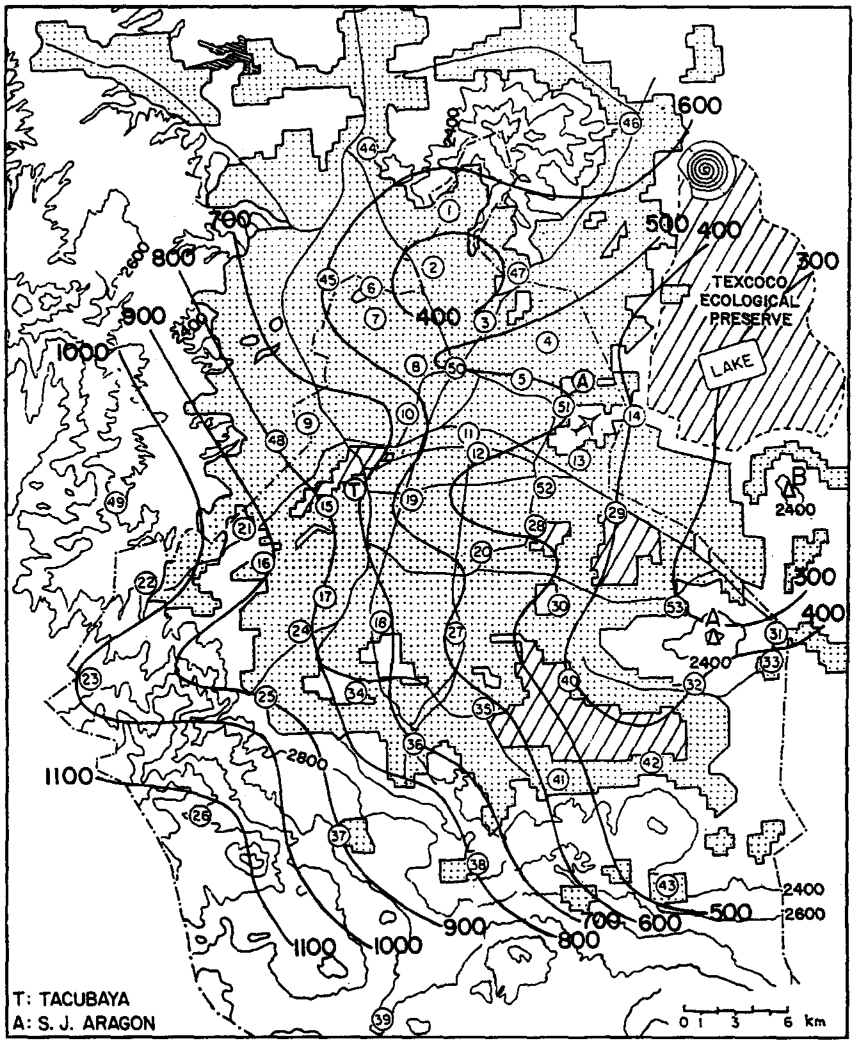

Fig. 1. Location of stations and annual rainfall (mm) for 1992.

1982–1992. Most of the urban stations lie in relatively flat terrain, but others are located on the foothills (and near the watershed) of the mountains surrounding the basin to the north, west and south.

In order to cope with the problem of flooding of streets due to sudden release of large volumes of wet-season rainfall runoff in a short period, the Hydraulic Operations Department of the city has put into operation since 1982 a telemetric network of automatic pluviometric stations for instantaneous monitoring of precipitation. The network of 55 stations covers the urban area of the capital city and some surrounding rural sites (see Fig. 1 for location). The system is able to display in a computer at any desired moment, the accumulated rain, intensity, time of beginning and end of each rainfall event. For a detailed description of the system see Anonymous (1993).

3. METHOD

In order to try evaluate the urban effects on precipitation, rainy season rainfall ratios were used for a pair of urban and rural (no effect) stations with a long (1941–1985) record. This technique permitted evaluation of time trend in urban effects and in addition, as suggested by Chagnon and Huff (1973) it provides a simple measure of the magnitude of this urban-induced effect. Using the automatic rainfall network data, space analysis of 24 h very localized anomalies of rainfall could be made to locate the most frequent position of intense thunder showers. Analysis of isochrones allowed to identify the movement of rain storms.

4. RESULTS

Figure 2 shows the May–October rainfall for urban (Tacubaya) and suburban (upwind) station San Juan Aragon for the period 1941–1985. While this last station does not show any trend Tacubaya displays a significant

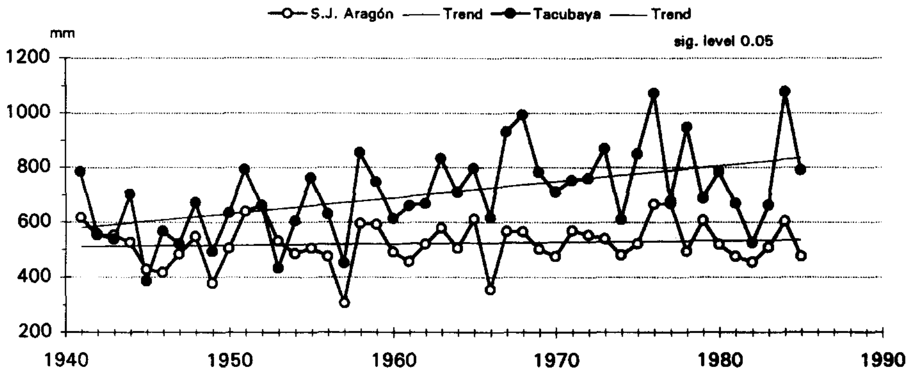

Fig. 2. Wet season (May–October) rainfall trends for Tacubaya and San Juan de Aragón stations. Period 1941–1985.

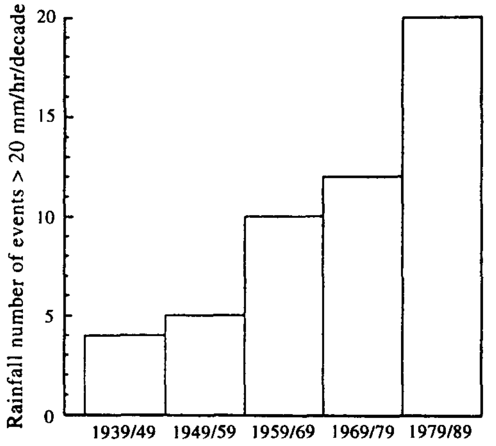

Fig. 3. Frequency of intense rainfall events $> 20\ \mathrm{mm\,h^{-1}}$ in Mexico City in July–September 1939–1989.

(to the 0.05 level of significance) increase during the period. The above, relatively simple empirical analysis suggests the existence of an urban-induced effect on convective precipitation in Mexico City that seems to be increasing in magnitude as the city grows in extent. The rainfall ratio method between the same pair of stations showed similar results (not shown). Balling and Brazel (1987) have observed more frequent late afternoon storms in Phoenix producing greater rainfall totals during recent years of explosive population growth. These authors suggest a link between the developing urban heat island and the observed substantial change in the diurnal patterns of rainshowers. In this respect, when comparing the decadal frequency of intense rainfall events (greater than $20\ \mathrm{mm\,h^{-1}}$) observed at Tacubaya (urban) station for the period 1939–1989 a significant increase is observed, as shown in Fig. 3.

An apparent shift in the diurnal pattern of these intense showers (more frequent now in the afternoon) seems to have taken place when the capital city began its accelerated growth during the 1960's, as illustrated in Fig. 4. On the other hand, when all rainfall events (for the period July–September) greater than 1 mm $\mathrm{h^{-1}}$ are considered, a recent increment (1981–1990) in evening showers is observed with respect to the 1940s as seen in Fig. 5. This would suggest that although intense rainstorms have not modified their diurnal pattern in recent decades, light and moderate rain events are now more frequent during the evening (19–24 h) in the capital city.

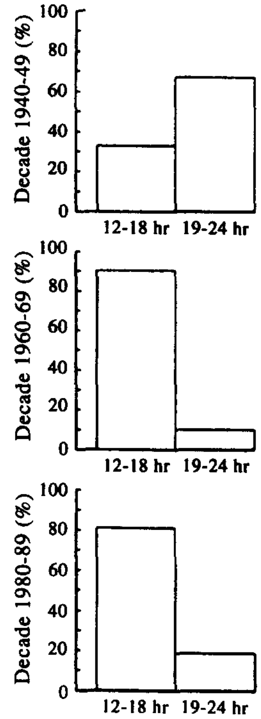

Fig. 4. Frequency of intense rainfall events $> 20\ \mathrm{mm\,h^{-1}}$ for three decades by time of day in Mexico City.

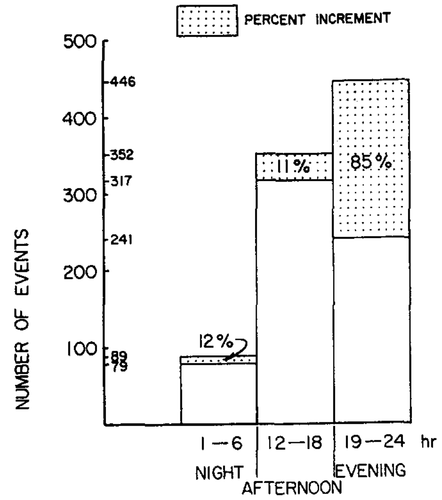

Fig. 5. Frequency of rainfall events (July–September) > 1 mm h^{-1} for two decades 1941–1950 and 1981–1990 for three periods during the day at the Tacubaya Observatory.

4.1. *Space rainfall analysis*

In what follows an example is presented to illustrate a typical case of distribution of maximum rainfall cells that are frequently observed over Mexico city's urban area.

The large-scale synoptic setting on this occasion was a disturbed deep easterly current typical of the rainy season and affecting most of the country. On 26 September 1992 clear skies prevailed during the morning favoring convective cloud formation, first over the valley plains and foothills to the West in the early afternoon, and later on, over the whole basin. Generalized precipitation began soon after from well developed convective clouds.

Figure 6 shows isoyets for 26/27 September 1992 displaying several rainfall anomalies located toward the center and south of the city. It is interesting to note that in this case precipitation decreased toward the foothills to the west. The weak rainfall observed around the city on the plains (to the east) and even on

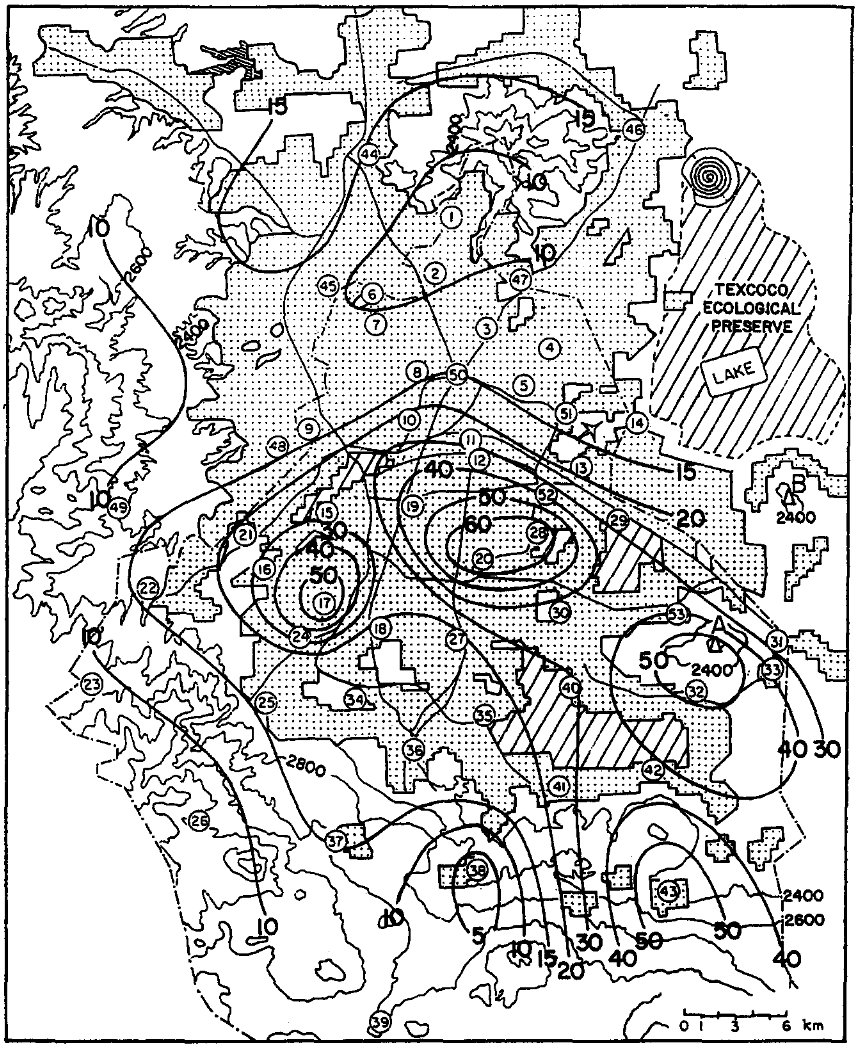

Fig. 6. Isoyets (mm/24 h) for 26/27 September 1992.

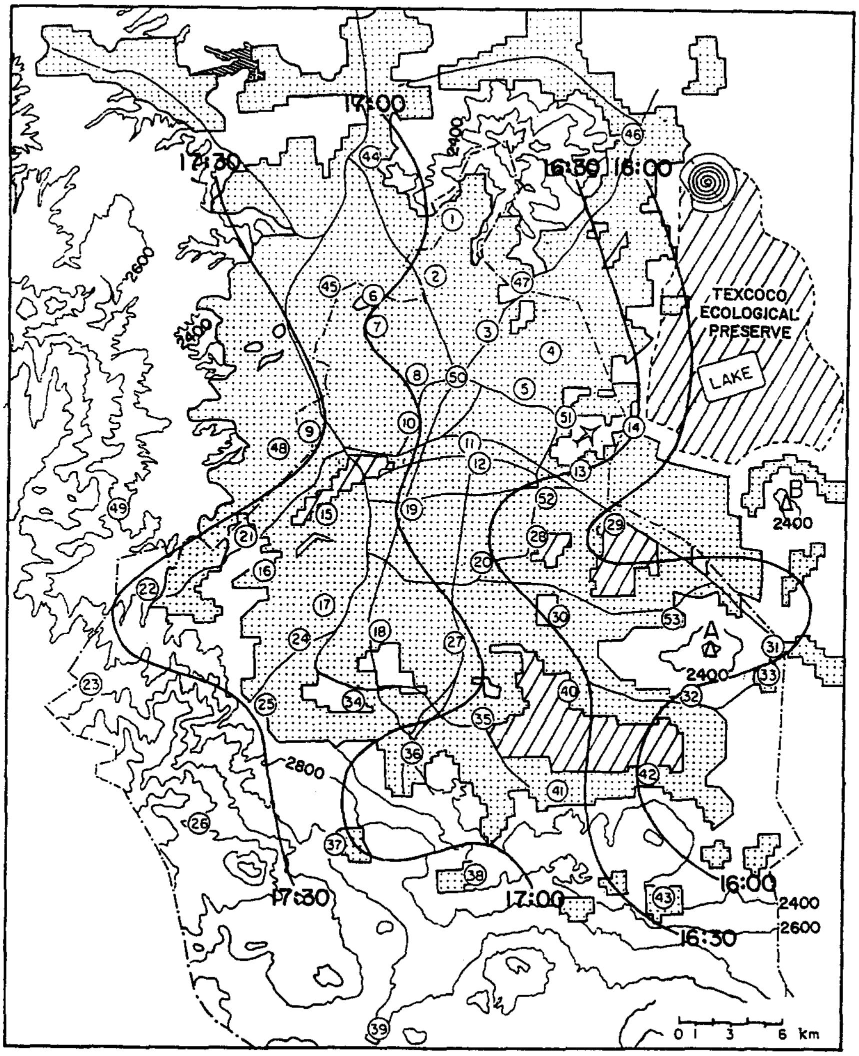

Fig. 7. Isochrones of beginning of precipitation. 26/27 September 1992.

the foothills to the west and south is likely to be in part the result of the subsiding nocturnal gravitational drainage. In addition, one could hypothesize that the bubble of warm air over the urban area tends to reinforce a low-level centripetal circulation as the evening progresses. The resulting subsidence would inhibit the development of rain clouds in the suburbs on the plains (to the east) as well as on the foothills that surround the city as is evident in Fig. 6. For this case (and a few others) rainclouds moved from an easterly direction. During that period three heavy rainfall cells were aligned in an E–W direction along the south-central portion of the city as shown in Fig. 6. The magnitude of the intensity increased to a maximum (60 mm/24 h) as the rain clouds reached the center of the city. As the convective clouds moved toward the western edge they produced a third maximum of 50 mm/24 h. It is worth noting that isoyets in this last high precipitation cell declined to the west reaching a minimum value at station Desierto (number 23) located 750 m above the valley plains and near the watershed line. In this case the orography did not affect the rainfall distribution as would be expected and rainfall amounts did not increase with height to the west. This would suggest that the descending branches of the urban warm air played a role in preventing further development of convective clouds there. A cell of minimum precipitation is observed to the south. Here, the low value reported at station 38 could be perhaps explained by the fact that this station is at the bottom of a small narrow valley.

Another cell of minimum rainfall is located downwind of the Guadalupe ranges that limit the city to the north illustrating the rain shadow effect. This is apparently a quasi permanent feature of the area since it is also displayed on an annual basis in several recent

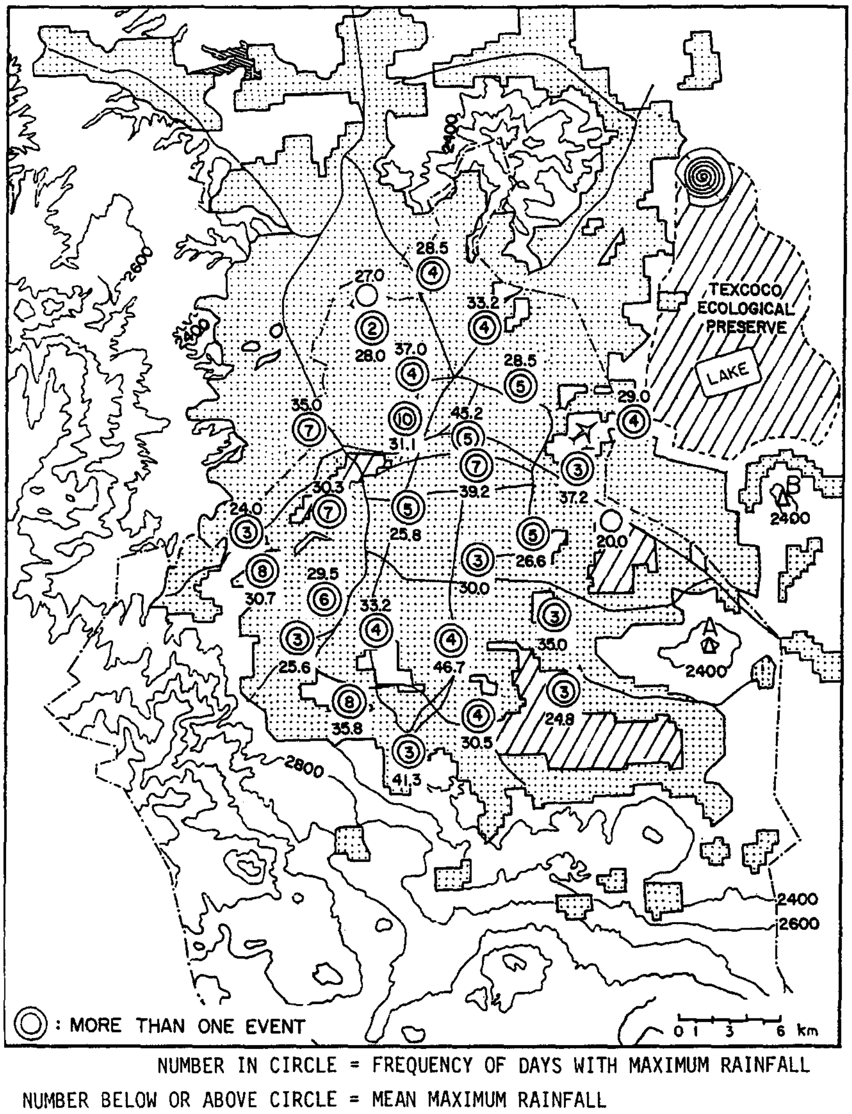

Fig. 8. Location of sites where nonsimultaneous distinct maximum rainfall values (mm/24 h) were observed during May–October 1990.

years, i.e. in 1987 as seen in Fig. 1. A maximum of precipitation is located at the foothills of the mountains that close the Mexico basin to the south. Here it is more clear that this maximum is mainly of orograpic origin.

4.2. *The precipitation cell movement*

The displacement of the rain clouds may be derived from the isochrone map in Fig. 7 that illustrates the propagation of rain for 26/27 September 1992. The speed of the cloud cells is greater at the northern half of the city north of the airport where the terrain is mostly flat whereas in the southern part, where there are several hills (marked B and C on Fig. 7 and about 150 m high), the movement is slower and less uniform due to the increasing roughness.

The analysis of rainfall displacement gives NE–SW as a predominant direction with a speed of around 15 km h^{-1} (4.2 m s^{-1}); this is about the velocity of the trade wind current Riehl (1965) and it is at the lower end of the range (3–12 m s^{-1}) observed in mid and late summer at a Mediterranean city (Lorente and Redaño, 1990).

Finally, Fig. 8 shows the number of days when maximum rainfall was observed at the various station locations and the corresponding mean precipitation observed for the 1990 season. Rain shower maximum anomalies centers were more frequent in downtown and in a NE–SW corridor. During that year the total amount of events of this type during May to October was 121.

5. DISCUSSION

Evidence of urban-induced increases in convective precipitation was found in the daily and seasonal precipitation in Mexico City. A long-term significant increase in the wet-season precipitation during recent years is evident for urban station Tacubaya. In Mexico City intense thunderstorms occur mainly during the afternoon and early nighttime hours. A variety of severe conditions are associated with these thundershowers such as damaging winds, deadly lightning and heavy rainfall resulting in flash flooding of streets.

Since the mean value of the daytime heat island (as measured by the difference of urban/rural maximum temperatures) is, during the rainy season, of the order of 2° to 3°, it is likely that shower intensification may be associated to the thermal contrast. While severe (more than $20\,\mathrm{mm\,h^{-1}}$) rain showers have increased their frequency in the afternoon, all rainfall events (greater than $1\,\mathrm{mm\,h^{-1}}$) have become more frequent in the late afternoon and in the evening during recent years. The substantial changes observed in the diurnal pattern of rainfall events seem to be linked to the accelerated increase in the urban sprawl of the capital city in recent decades which in turn has induced an intensification of the heat island effect.

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