MEXICO CITY'S URBAN HEAT ISLAND REVISITED

With 11 figures and 2 tables

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Zusammenfassung: Die Wärmeinsel von Mexico City - ein Rückblick

Die Arbeit gibt eine Darstellung der klimatologischen Grundzüge der Wärmeinsel von Mexico City, indem sie die mittleren monatlichen Maximum- und Minimum-Temperaturen ausgewählter Paare von städtischen und ländlichen bzw. suburbanen Beobachtungsstationen über den Zeitraum des städtischen Wachstums von 1896 bis 1980 miteinander vergleicht. Während sich in dieser Zeit das Stadtgebiet um das 62fache vergrößerte, hat sich die Intensität der mittleren monatlichen Wärmeinsel von etwa 2 °C auf 8 °C erhöht. Im Jahre 1933 lag der Maximalwert der mittleren monatlichen Differenzen der Minimum-Temperatur zwischen Stadt und Land bei etwa 6 °C. Die räumliche Analyse auf der Basis einer beschränkten Zahl von Klimastationen, die während der dreißiger Jahre eingerichtet worden waren, führt zu der Annahme, daß sich die Warmluft in einem täglichen Zyklus über die Stadt bewegte.

Obwohl das gegenwärtige Netzwerk von Beobachtungsstationen keine detaillierte Beschreibung des Temperaturfeldes erlaubt, ist zu beobachten, daß die Position der Spitzenwerte der Wärmeinsel bei Tagesanbruch nicht generell mit der Lage während des Auftretens der Maximum-Temperaturen am Nachmittag übereinstimmt. Diese Diskrepanz kann durch die verschiedenen Ursachen erklärt werden, welche die Temperaturdifferenz zwischen Stadt und Land hervorrufen: Die wichtigsten Faktoren in der Nacht sind wahrscheinlich die Canyon-Geometrie und die thermische Trägheit, während sich am Tage dem langwelligen Strahlungsaustausch (mit stationärer Lage) ein turbulenter Wärmefluß (im Zeitablauf nicht stationär) hinzugesellt, der durch die sonnenbedingte (und anthropogene) Aufheizung der städtischen Oberflächen verursacht wird. Die beobachteten zeitlichen und räumlichen Wechsel der Warmluft können zu irrtümlichen Schlußfolgerungen führen (z. B. hinsichtlich des Vorkommens einer Kälteinsel während des Tages), wenn lediglich ein einzelnes Paar von städtischen und ländlichen Klimastationen herangezogen wird, um den täglichen und saisonalen Zyklus der städtischen Wärmeinsel zu beschreiben.

1 Introduction

It is well established that the warm air observed in cities is the result of urbanization. The replacement of original rural land by the urban elements induces changes (among other variables) in temperature. The heat island in mid-latitudes (where it has been intensively studied by SUNDBORG (1950), CHANDLER (1966); for a review see OKE (1982), is best developed during summer (when space heating is negligible) while in tropical latitudes the urban/rural thermal contrast is most marked during the dry period (OGUNTOYIMBO 1986, JAUREGUI 1986, BAHL a. PADMANABHAMURTY 1979, PHILIP et al. 1973). The observed seasonal variation of the heat island in tropical urban areas has been found to be linked especially to seasonal changes in the admittance (μ) of surrounding rural soils (OKE et al. 1991). Thus (as suggested by these authors), largest thermal contrasts observed during the dry season in Mexico City are likely to be the result of a marked reduction in admittance of surrounding rural soils that have lost most of their moisture especially at the end of this period. Day-time heat island intensity (including the tropical areas) appears to be less marked (or even reversed). This has been attributed to the obscuring effect of turbulent mixing prevailing in and outside the urban fabric in the daylight hours when radiative exchange includes the short-wave band. The object of this paper is, using climatological data from urban/suburban/rural stations, to describe the characteristics of the night/day time urban canopy heat island of Mexico City during different times corresponding to stages of its growth from a small town (16 km^2 in extension) in 1895 to a megacity of recent times (about 1000 km^2). Previous studies of urban/suburban thermal contrasts suggest that the heat island in Mexico City was mainly a nocturnal phenomenon, whereas during the day the city's air was found to be either cooler or it maintained the same temperature as the suburbs (JAUREGUI 1986). Early attempts to describe the morphology of the capital city's nocturnal heat island (on a particular day in February 1972) presented the warm air mass as having a monolithic character (JAUREGUI 1973).

This was mainly due (then and at present) to the relatively limited number of available observation stations (about 30, see Fig. 9 for location) with respect to the extensive urban area (1000 km^2 approximately) and therefore imposing broad interpolations that may not accurately depict the temperature pattern across the capital city. In a later work (JAUREGUI 1986) and

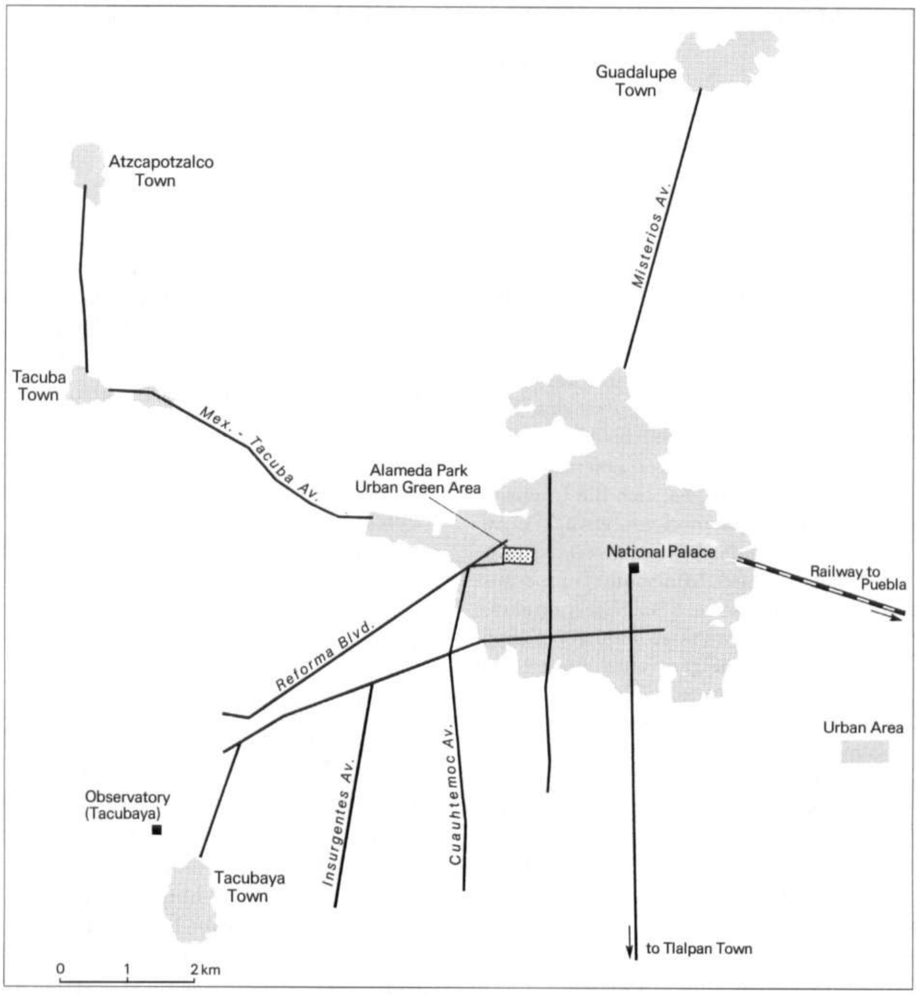

Fig. 1: Urban area of Mexico City at the end of the 19th century (after VIDRIO 1978)
Stadtgebiet von Mexico City zu Ende des 19. Jahrhunderts

using the same number of stations but for another month the mean monthly minimum temperature distribution for November 1981 in Mexico City displayed two heat islands separated by a tongue of cool air coming from a large (450 Ha) urban park (Chapultepec). Mean heat island configuration for 4 periods during the day for the capital city has also been presented in a paper examining the link between heat island intensity and the resulting centripetal surface wind circulation (KLAUS et al. 1988). However, the scant data available at the time (7 stations) precluded an accurate representation of the temperature patterns. Studies by CHANDLER (1961) for London, GEHRKE et al. (1977) for the city of Freiburg and WEISCHET (1979) suggest that spatial patterns of urban temperature are not likely to be monolithic but rather be conformed of multiple "islands" revealing the impact of the complex urban fabric. A relatively recent satellite-based thermal scanning system (Advanced Very High Resolution Radiometer) holds promise of an alternate approach for determining the surface (and eventually derived) air temperature patterns in urban areas (BALLING a. BRAZEL 1988, STOLL a. BRAZEL 1992).

Results presented in this paper suggest that the mass of warm air sitting over the city changes in form and position during the course of the day; the great extent of the city gives rise to a complex temperature field and day-time cool or heat islands emerge according to the pairs of urban/suburban/rural sites selected. Maximum and minimum temperature records for the years 1896, 1921–40, 1933 and 1980 for a network of urban/suburban/rural stations in the capital city were used in the analysis.

2 Mexico City's urban heat island in 1896

During the last decade of the XIX century MANUEL MORENO (1899), a climatologist at the National Weather Service, published a paper on the urban/rural thermal contrasts observed in Mexico City. MORENO used maximum and minimum temperature records observed at two sites: one located in the National Palace in the (geometric) center of town, the other was (according to the description of MORENO) on a hill 50 m above the valley floor in open field one km to the West of the town of Tacubaya, which was located about 6 km to the West of the capital city (Fig. 1).

MORENO found a mean annual temperature difference of 1.4 °C for the year 1896 between the two sites with the largest values observed during the dry months. While MORENO even went a step further and corrected for the difference in altitude (0.3 °C obtaining a mean temperature difference of 1.1 °), he did not elaborate on the possible causes for such thermal contrasts.

Using MORENO's data Fig. 2 shows the mean monthly maximum and minimum temperature variation for 1896. The nocturnal heat island shows a maximum of 2 °C at the end of the dry season and a minimum during the wet period (Jun.-Sept.). The observed seasonal variation of urban/rural temperature contrasts at about the time of minimum temperature occurrence illustrates the possible effect of changes in admittance (μ) of the rural control on the maximum heat island intensity mentioned in Section 1. On the other hand, the day-time heat island displays an opposite seasonal behaviour: it is well marked during most of the year, being minimal during the cool period. The day-time small temperature contrast in the dry season could be explained by the fact that evapotranspiration from rural vegetation could have been then more important during the afternoon (resulting in a higher rural admittance and thus smaller temperature contrast). The large observed values of the day-time heat island during the wet season is likely to be the result of intense day-time solar absorption by the urban fabric in a city with shallow canyons and little (if any) smog.

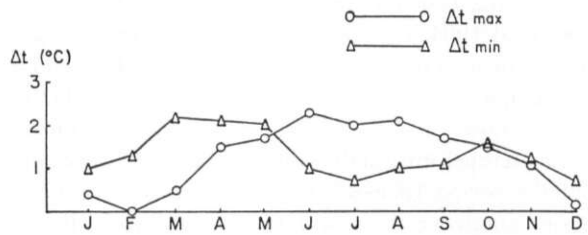

Fig. 2: Seasonal variation of heat island intensity between National Palace (urban) and Tacubaya (suburban) in 1896

Jahreszeitliche Variation der Wärmeinsel-Intensität zwischen dem National-Palast (städtisch) und Tacubaya (suburban) im Jahre 1896

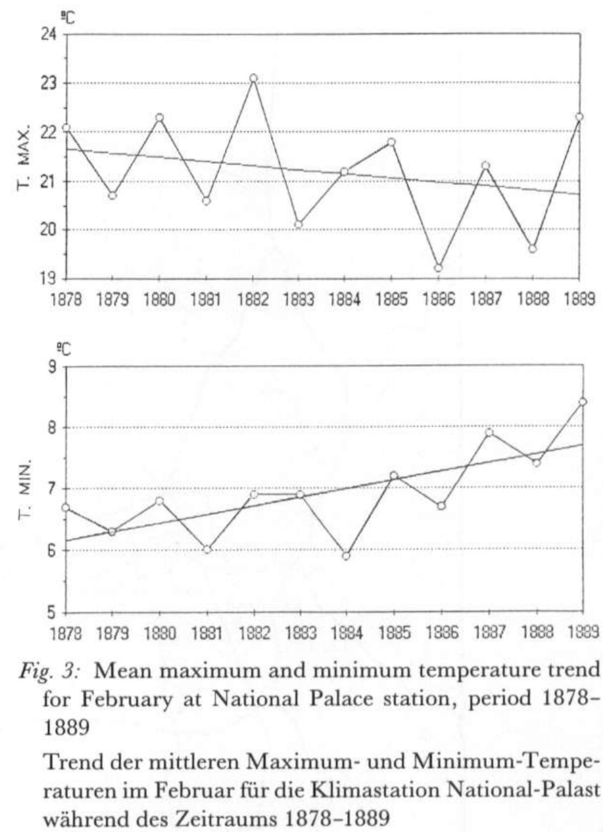

Fig. 3: Mean maximum and minimum temperature trend for February at National Palace station, period 1878–1889

Trend der mittleren Maximum- und Minimum-Temperaturen im Februar für die Klimastation National-Palast während des Zeitraums 1878–1889

Table 1: Population and urban growth in Mexico City, 1900–1980 (after UNIKEL 1988)

Wachstum der Bevölkerung und der Fläche von Mexico City zwischen 1900 und 1980

Year	Population (in 1,000)	Area (km²)	Increase pop. (%)	Increase area (%)
1900	471	26.0		
1921	906	46.4	92	78
1930	1,200	86.1	32	86
1940	1,760	117,5	47	36
1950	3,203	240.6	98	105
1960	5,240	450.0	63	88
1970	8,875	650.0	69	44
1980	14,000	850.0	58	31

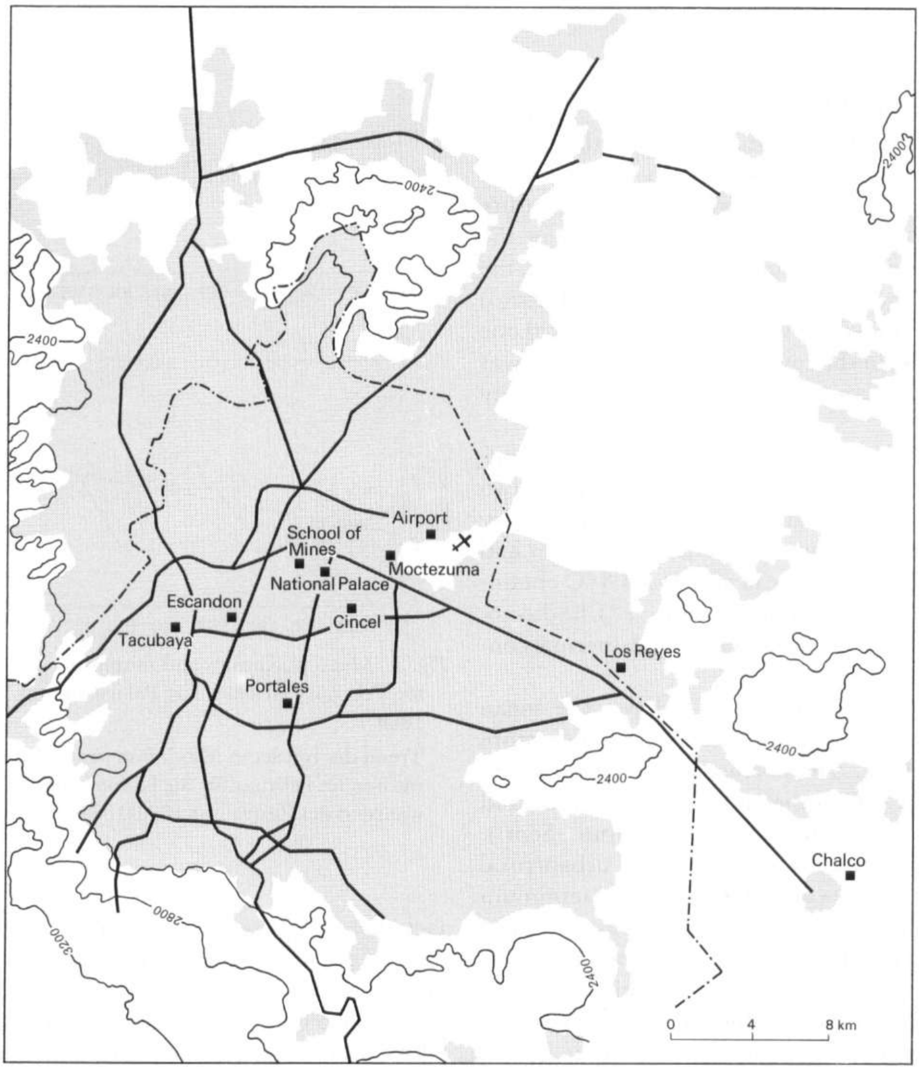

Fig. 4: Location of stations used
Lage der benutzten Meßstationen

From 1858 to 1900 the capital of Mexico underwent a phenomenal growth and its urban area increased four times as much (GARZA 1988) due to the introduction of the urban transport system (electric trams). During that period the city grew from 185,000 to 471,000 inhabitants (GARZA 1988) and at the end of the century the urban area covered about 26 km².

3 Urban effects on temperature in Mexico City during the 1880's

Several studies have attempted to quantify the effect on the temperature records of increasing levels of urbanization for mid-latitude regions (CAYAN a. DOUGLAS 1984, KUKLA et al. 1986, KARL et al. 1988). Fewer of such investigations have been published for the tropics (CHOW 1986, JAUREGUI 1992a, 1992b). Fig. 3 shows the mean February minimum and maximum temperature at the National Palace Observatory for the period 1878–89. In agreement with mid-latitude experience the minimum temperature is in this case more significantly affected by urbanization than the maximum temperature. As illustrated in Fig. 3, the minimum temperature increased, particularly during the second half of the 12 year period. The mean maximum temperature for February however shows a larger variability but no appreciable trend.

Fig. 5: Nocturnal mean heat island intensity trend between School of Mines (urban) and Tacubaya observatory (suburban) for period 1921–1940, for months January through April

Trend der mittleren nächtlichen Wärmeinsel-Intensität zwischen der School of Mines (städtisch) und der Station Tacubaya (suburban) im Zeitraum 1921–1940, Monate Januar bis April

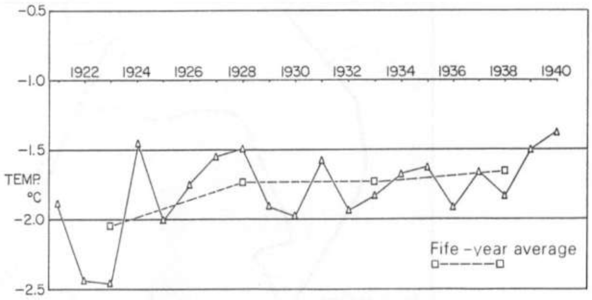

Fig. 6: Mean for maximum temperature differences (January through April) between School of Mines (urban) and Tacubaya observatory (suburban) for period 1921–1940

Mittelwerte der Differenzen der Maximum-Temperaturen (Januar bis April) zwischen der School of Mines (städtisch) und der Station Tacubaya (suburban) im Zeitraum 1921–1940

4 Mexico City's heat island intensity and urban growth during the 1921–40 period

During the 20-year period from 1921–40 the capital city experienced an accelerated growth and almost doubled its population. Correspondingly, its urban area increased by a factor of 2 (Table 1). During this period t_{max} and t_{min} were available for urban station School of Mines (S.M.) and for the then suburban Tacubaya Observatory, west of downtown (see Fig. 4).

Most of the constructions 1 km around the urban site (S.M.) are 2 to 4 storey high massive buildings of historical value and therefore it is unlikely that the *ensemble* of surface characteristics changed during the 20-year-period. Although the city experienced an expansion of its urban fabric in all directions the preferred area of the new one to two storey settlements was toward the NE and E that is in the upwind direction in the vicinity of the airport. This area receives the full impact of duststorms during the dry season from the flat clay soils of ex-lake Texcoco bed (Jauregui 1988).

Fig. 5 shows the mean heat island intensity trend for the 1921–40 period averaged over January through April, when the urban/rural temperature contrasts are more marked. The mean nocturnal heat island increase over the period as expressed by the mean minimum temperature contrast between School of Mines (S.M.) and Tacubaya (TCY) is of the order 1 °C (from 3.2° to 4.2°).

Since the canyon radiative geometry and the thermal properties (e. g. thermal admittance) remained practically unchanged in the vicinity of the urban site it is likely that the observed increase in nocturnal heat island intensity may be attributed to modified air reaching the urban site after traversing a longer fetch over the urban area.

Fig. 6 shows the decreasing negative contrast in maximum temperatures between the same pair of stations over the 1921–40 period. Since the day-time rural heating rate (with smaller rural thermal admittance) is greater than that corresponding to the urban structures the city's air is about apparently 1.5 °C

Table 2: Mean seasonal variation of the heat/cool island intensity in Mexico City as given by t_{max} and t_{min} differences between School of Mines (urban) and C. Valle station (rural) in 1933

Mittlere monatliche Variation der Intensität der Wärme- bzw. Kälteinsel in Mexico City, ausgedrückt durch die Differenzen von t_{max} und t_{min} zwischen der School of Mines und der Station C. Valle im Jahre 1933

	J	F	M	A	M	J	J	A	S	O	N	D
Δt_{min}	5.2	5.2	5.6	6.0	5.3	3.4	2.6	1.8	2.2	2.4	4.3	5.7
Δt_{max}	−2.5	−2.2	−2.3	−2.7	−2.5	−2.3	−1.9	−2.4	−2.4	−2.1	−2.8	−3.1

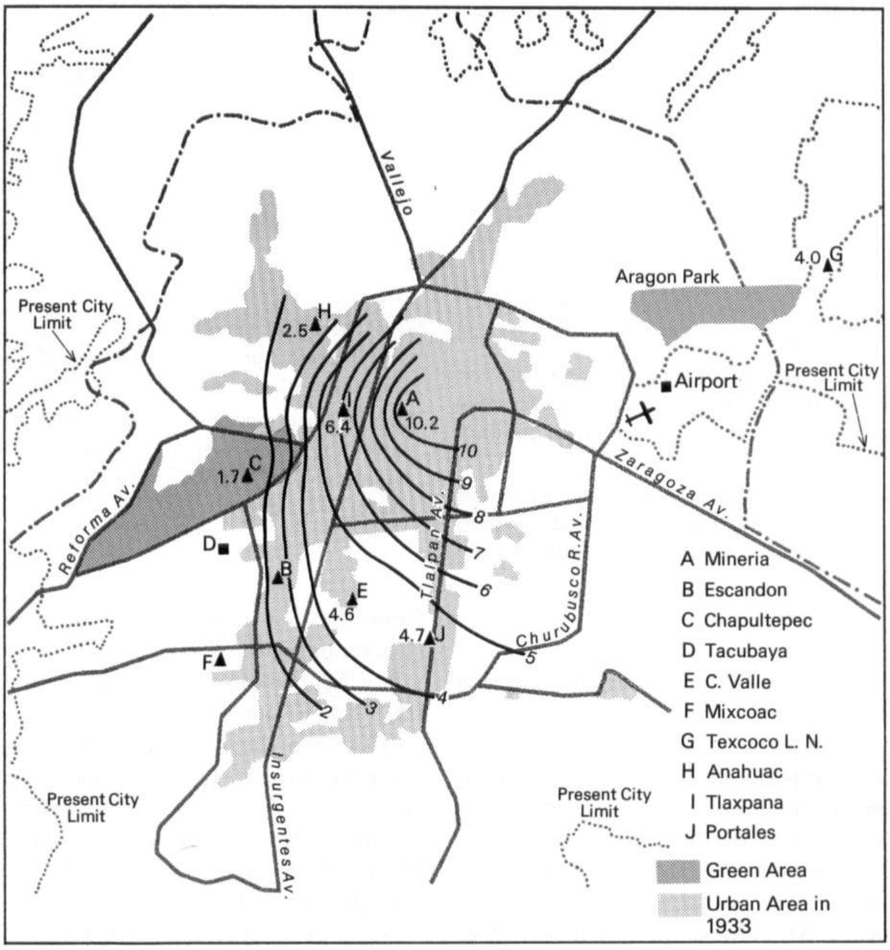

Fig. 7: Distribution of mean minimum temperature (°C) for March 1933 in Mexico City
Verteilung der mittleren Minimum-Temperatur für den März 1933 in Mexico City

cooler than the suburbs during the early afternoon for this pair of stations.

Table 2 shows the seasonal variation of the urban heat/cool island during the 1930's (1933) when the capital of Mexico had reached a bit over one million inhabitants and had doubled its urban area with respect to that of the 1920's. From this table it is readily seen that the intensity of the nocturnal heat island in Mexico City increased in proportion to its size to about 6 °C during the dry period. Again, as mentioned in Section 1, the seasonality of the nocturnal heat island with its high values during the dry season is in agreement with results obtained by Oke et al. (1991) from simulations with energy balance models in order to assess the relative importance of the geometry and admittance of the urban fabric with respect to the rural substrate.

Other pairs of urban/rural stations (not shown) displayed a maximum "cool" island during the second half of the dry period (March–May). The "cool" island during the day could be explained by attributing (assuming small latent heat flux and atmospheric turbulence) the urban interface a higher thermal inertia than the rural control. But again the "cool" air could result from the shifting of the warm air mass. Thus, negative temperature difference values at t_{max} obtained from the pair School of Mines (SM) (urban) and C. Valle (suburban) stations during 1933 (Table 2) show the presence of a "cool" island with small seasonal variation.

When t_{min} and t_{max} monthly values from the small network of climatological stations are plotted on a map of the city (Figs. 7 a. 8) the analysis shows an apparent displacement of the warm air from its center

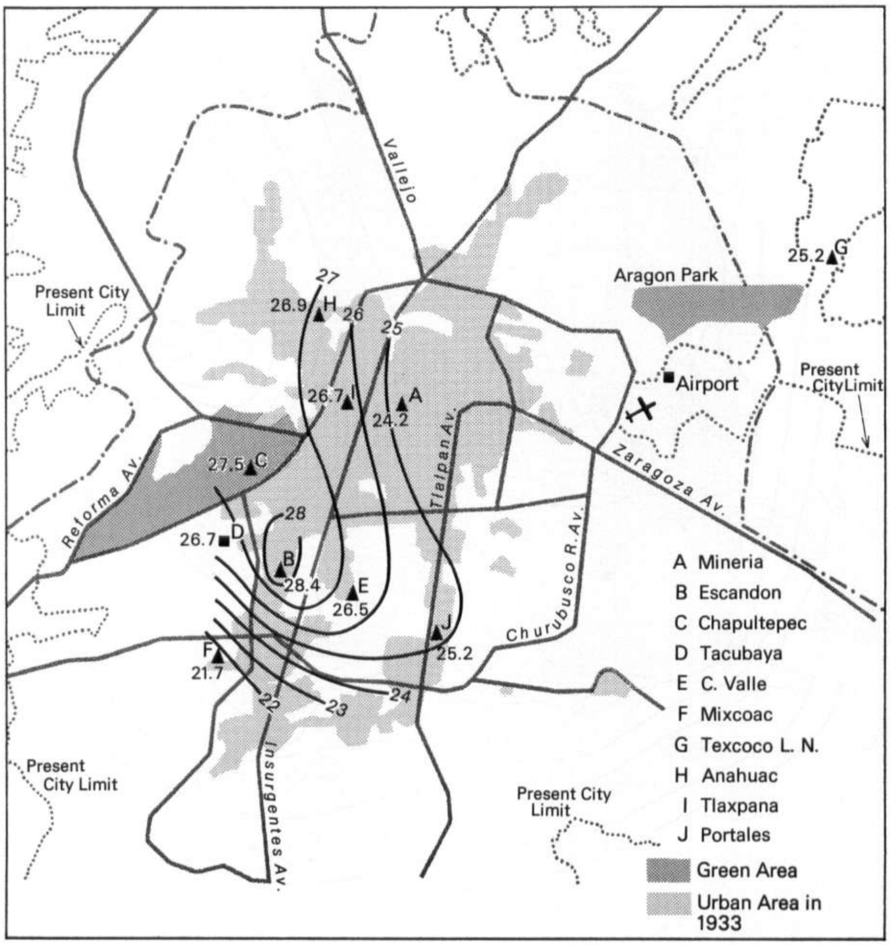

Fig. 8: Distribution of mean maximum temperature (°C) for March 1933 in Mexico City
Verteilung der mittleren Maximum-Temperatur für den März 1933 in Mexico City

of town position at day break to a location in the southwestern suburbs in early afternoon. The above results suggest that the analysis of heat island development in the course of a day using only a pair of point measurements may not be representative for the whole urban area, especially in large cities and may lead to erroneous conclusions.

5 Urban heat island characteristics in recent times

Figs. 9 a. 10 show the distribution of the mean monthly minimum and maximum temperature for the month of March 1980. The analysis is based on temperature data collected from 30 urban/rural climatological stations. Since there will always be differences in the times of occurrence of minimum and maximum temperature at the various observing stations it cannot be claimed that the maps represent the temperature distribution at any one instant; but any such differences are likely to be small.

As has been observed in mid-latitude cities the isotherms in the nocturnal heat island are fairly close together (Fig. 9) and follow more or less the densely built area. The slope winds flowing down the hills from the West act also as a barrier to the spread of warm air (JAUREGUI 1988). Conversely, the day-time heat island is characterized by a more weak horizontal temperature gradient with its peak value near the eastern city limits (Fig. 10).

It is clear from Figs. 9 a. 10 that the location of the maximum value of the heat island at day break does not always correspond with the position of the maximum urban/rural thermal contrast during the

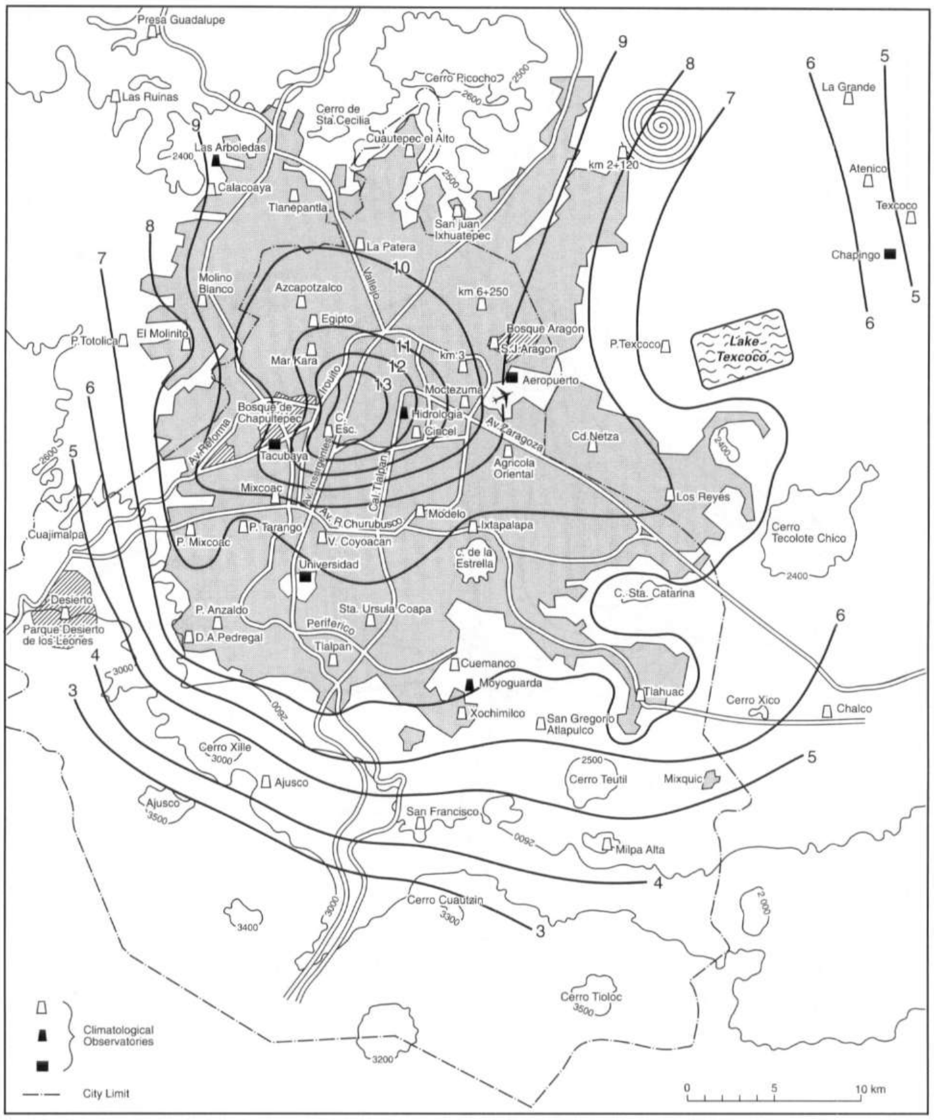

Fig. 9: Distribution of mean minimum temperature (°C) for March 1980 in Mexico City
Verteilung der mittleren Minimum-Temperatur für den März 1980 in Mexico City

afternoon. This may be explained by the different dominating causes giving origin to the thermal contrast: at night the main factors are likely to be the canyon geometry and thermal inertia, as shown by Oke (1981, Oke et al. 1991), while during the day to the enhanced mechanical convection is added the buoyancy by solar heating of the urban surfaces. The reduced water vapour availability (especially during the dry season) leads to an increase of day time Bowen ratio and thus to a strong turbulent heat transfer to the air. This is true particularly in the north industrial sector of the city characterized by flat terrain and uniform 2 to 4 storey high constructions with scant vegetation.

The shift in the mean position of the warm air mass in the course of the day may be appreciated in Fig. 11 that shows mean monthly minimum and maximum temperature profiles across the city from west to east for the month of March 1980. It is clear from this figure that while the highest mean minimum temperature lies on the western sector of the city at Escandon station the warm air has moved to the eastern area in the vicinity of the airport at station Moctezuma during the afternoon. Also, it is evident

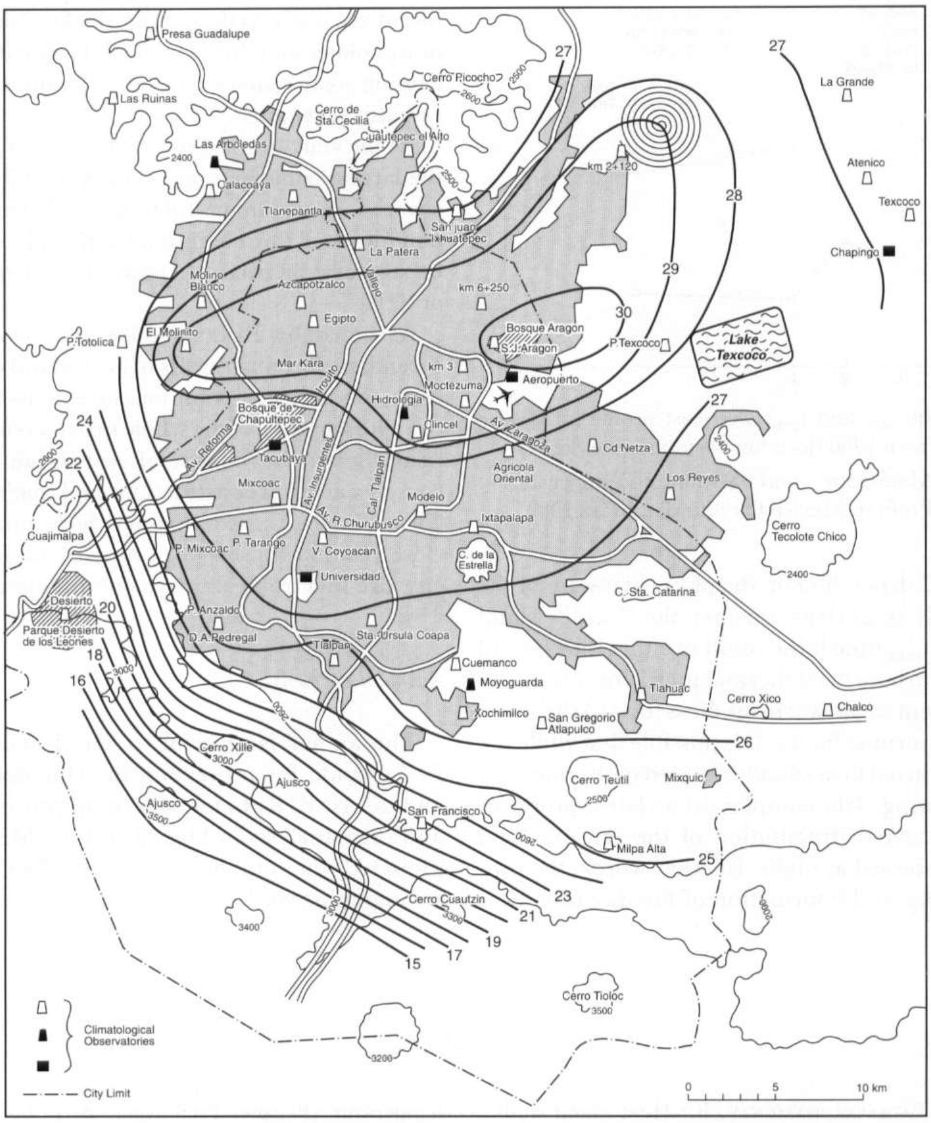

Fig. 10: Distribution of mean maximum temperature (°C) for March 1980 in Mexico City
Verteilung der mittleren Maximum-Temperatur für den März 1980 in Mexico City

that while station Tacubaya is warmer (4 °C) with respect to the airport at day break, during the afternoon the situation is the reverse giving rise to an apparent "cool" island.

6 Concluding remarks

In the present paper an outline is given of the climatology of Mexico City's screen-level heat island as revealed by a comparison of urban/rural monthly mean maximum and minimum temperatures at various stages of its urban growth beginning in the mid-nineties of the XIX Century to 1980. At the turn of the century it was possible to estimate the urban/rural thermal contrasts from temperature records from a single pair of stations. The mean heat island intensity was then commensurate (2 °C) with the size of the small city. By the 1930's an urban/suburban network of climatological stations was established in the capital city and description of the temperature field for t_{max} and t_{min} time was feasible for the first time. The analysis showed that the mean nocturnal heat island intensity during the 1930's had increased

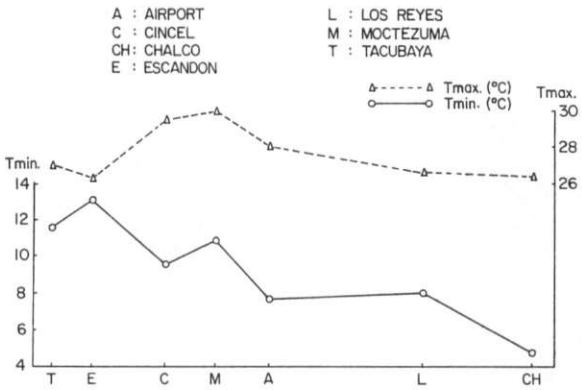

Fig. 11: Mean t_{max} and t_{min}: west-east profile in Mexico City for March 1980 (location of stations see Fig. 4)

Mittlere Maximum- and Minimum-Temperaturen: West-Ost-Profil in Mexico City für den März 1980

to up to 6 °C depending on the physical nature of the rural site. It is unclear whether the "cool" island observed at t_{max} time is the result of either the effect of contrasting urban/rural thermal inertia or it is due to a displacement of the warm air mass toward the south during the morning hours. It is possible that while the intense nocturnal heat island is eroded in the morning the solar heating of the complex urban fabric produces a different spatial distribution of the sensible heat than that observed at night. In other words, the processes leading to the formation of the day-time heat island are likely to depend on the local surface urban morphology that directly affect the partitioning of incoming solar radiation rather than on the long-wave radiative exchange.

At the start of the 1980's Mexico City was among the largest conurbations in the world; its urban area covered more than 1000 km². Accordingly, the magnitude of the maximum nocturnal mean monthly urban/rural thermal differences increased to about 8° or 9 °C.

As noted by PARRY (1963) it is necessary to be carefull in deriving results of heat island development from only a pair of point measurements that may not be representative of the whole urban area. This is particularly true in the case of vast urban areas with a complex array of constructions and roads like Mexico City. Finally, an example has been provided of the close relationship between heat island intensity and city size in a tropical urban environment.

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