# REGULAR CIRCULATION STRUCTURES IN THE TROPICAL BASIN OF MEXICO CITY AS A CONSEQUENCE OF THE URBAN HEAT ISLAND EFFECT

With 12 figures

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*Zusammenfassung:* Regelhafte Zirkulationsstrukturen im tropischen Hochbecken von Mexiko Stadt als Folge des Wärmeinseleffektes

Während der Nacht- und in den frühen Morgenstunden entwickelt sich in den zentralen Bereichen von Mexiko City eine Wärmeinsel. Diese wandert im Laufe des Vormittags infolge der Reduktion der Einstrahlung, die durch die starke Luftverschmutzung in den zentralen Stadtteilen bedingt wird und verstärkt durch den Oaseneffekt, der Folge des hohen Wasserverbrauchs im Stadtbereich ist, an den östlichen Stadtrand. Die städtische Wärmeinsel induziert während der Nachtstunden Flurwinde, die durch Kaltluft, die von den die Stadt umgebenden Bergen abfließt, verstärkt werden. Resultat des Wärmeinseleffektes ist eine Luftmassenkonvergenz im Stadtgebiet von Mexiko City. Die Intensität dieser Konvergenz korreliert signifikant mit der Intensität der Temperaturdifferenz zwischen dem Stadtzentrum und dem Stadtrand.

*Summary:* During the night and the early morning hours a heat island develops in the central parts of Mexico City. During the late morning and early afternoon hours this heat island migrates to the eastern outskirts of the city as a result of the radiation reduced by air pollution and an oasis effect. The urban heat island effect produces urban winds in the night hours which are reinforced by cold air flows from the mountain ranges surrounding the city. The urban heat island effect produces a convergence. The intensity of the convergence correlates significantly with the intensity of the temperature difference between the central city and the suburbs.

## *Introduction*

According to forecasts by the United Nations, in the year 2005 more than half of the world population, which will then be 7 billion, will live in cities. The number of megacities with more than 10 million inhabitants will have increased from currently 15 to 26 by then. The majority of these megacities will be sited in the tropics.

With a current population of just under 20 million, the agglomeration of Mexico City, situated on about 20°N, can be regarded as an example of the problems of urban climate facing present and future tropical megacities (TRUCE 1996). In 1940, the built-up area of the city was 90 km$^2$, and in 1995 about 1500 km$^2$ (EZCURRA a. MAZARI-HIRIARTI 1996). Today, the agglomeration of Mexico City occupies one fifth of the in total 7500 km$^2$ of the basin of Mexico (Fig. 1), whose flat interior with an average elevation of between 2200 and 2300 m is cut off from the large-scale air movements of the Mexican upland by mountain ranges 3000–5000 m in altitude. Only from the northern direction is the basin interior more easily accessible via gentle swells.

As a consequence of the basin's isolation, its hygrometric, thermal and air hygiene conditions have been dramatically altered by the growth of the megacity. The air of the metropolis is so currently polluted by three million motor vehicles and 3000 industrial plants that visibility, solar radiation conditions and atmospheric pollution have changed drastically for the worse (JAUREGUI 1973, 1993). The burgeoning built-up area has altered the radiation absorption, the heat storage capacity as well as the ventilation and hygrometric conditions in large parts of the basin. The regular occurrence of inner-city overheating in the order of up to 10 °C was demonstrated for Mexico City (JAUREGUI 1973, 1993; KLAUS et al. 1988). The dynamics and impacts of this inner-city heat island on the wind field in the basin of Mexico are the subject of this study.

## *Data material*

The hourly temperature, radiation and wind data for the stations whose position is given in Figure 1b were analysed for 1995. The monitoring network is operated by the Environmental Office of the Federal District Department with climatronic sensors for temperature and wind according to the guidelines of the US Environmental Protection Agency (EPA 1983). The temperature, radiation and wind data from two other stations of the Center of Atmospheric Sciences of the National University of Mexico were also included in the analyses. Furthermore, radiosonde data from the station at Mexico City airport were also taken into consideration.

The data were first examined for completeness and homogenity. About 10% of the data were incorrect or not available. By correlation with neighbouring sta-

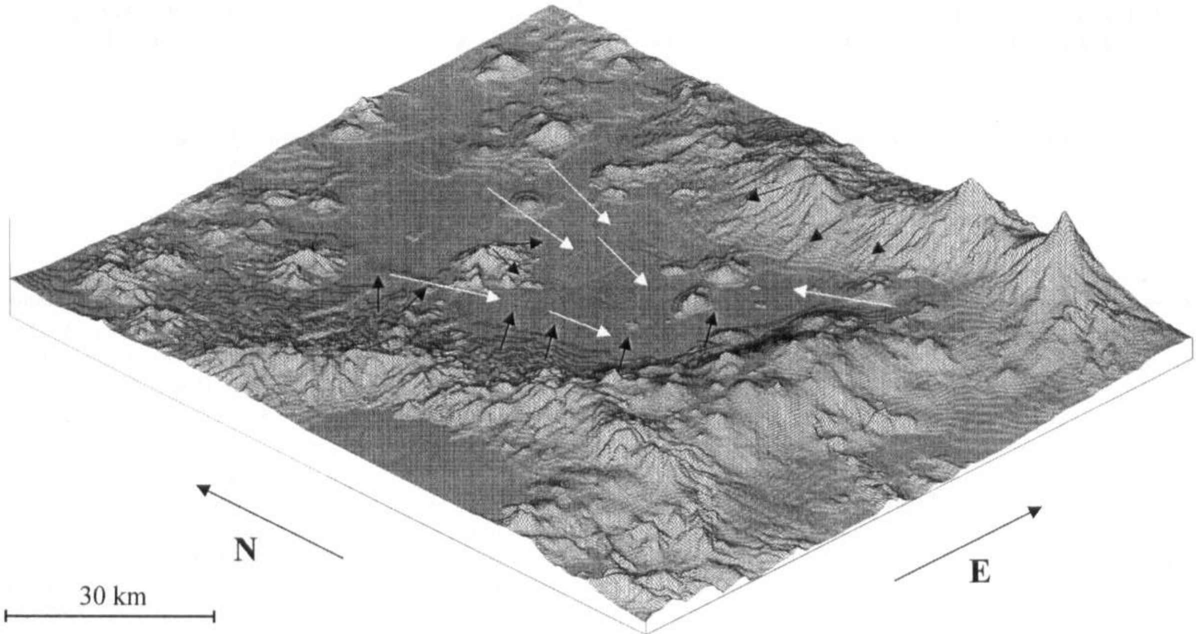



*Fig. 1a:* 3D-View of the basin of Mexiko. The prevailing winds during the daylight (white) and night hours (black) are shown
Dreidimensionale Ansicht des Hochbeckens von Mexiko. Die vorherrschenden Winde während der Tagesstunden (weiß) und der Nachtstunden (schwarz) sind angegeben

tions, it was possible to replace about 5% of the incorrect and missing values by plausible values.

*Circulation conditions in the rainy and dry seasons*

The climate of Mexico City is characterized by a rainy season from May to September and a dry season from October to April. In the rainy season, the tropical easterly upper air flow is dominant and just under 500 mm of precipitation falls according to a long-term average. In the dry season, the upper air flow is determined by the mid-latitudes westerlies and precipitation levels remain significantly below 100 mm. Figure 2 shows this seasonal change in wind direction for the 500 hPa level, which is on average about 2400 m above the level of the mountain basin.

At the 700 hPa level, which on average can be assumed to lie about 700 m above the level of the mountain basin, the seasonal change in direction between tropical easterly flow and mid-latitude westerly flow can no longer be identified (Fig. 3a, e and b, f). In contrast, a diurnal change in wind direction is apparent, attributable to topographic influences.

If the wind directions at an altitude of 700 m are compared with those at ground level (Texcoco) a counter-current in the upper and surface wind direction can be identified. In the early hours of the morning (6.00), a southerly upper air flow dominates with a simultaneous northeasterly flow close to the ground, corresponding to the prevailing synoptic gradients at the ground level and reinforced in the night by cold air flows from the mountain ranges to the east of Texcoco (Fig. 1a). In the late hours of the afternoon (18.00), at elevated altitudes northerly winds frequently occur in addition to the south-southeast winds, whereas the south-southwest direction is the most frequent wind direction at ground level. The near-ground flows are initiated at the 18.00 time by local overheating occurring in the Texcoco region especially in the dry season months. On the whole, both at the 6.00 as well as at the 18.00 time, a counterflow to the ground flow develops frequently during the dry season at an altitude of 700 m.

In the months of the rainy season, the counter-current is only weakly in evidence. At the 6.00 time, the frequency of flows from the westerly and northerly direction increases greatly at the 700 hPa level. At the 18.00 time, the frequency of ground flows from northeasterly directions increases so greatly that even at this time of day upper and ground flows are seldom opposed to each other.

The mean diurnal ranges of the near-ground wind direction and wind speed for the rainy season months are shown for a few stations in Fig. 4 a–d. In Texcoco, northeasterly flows dominate throughout the day, reaching maximum wind speeds at about 17.00 and

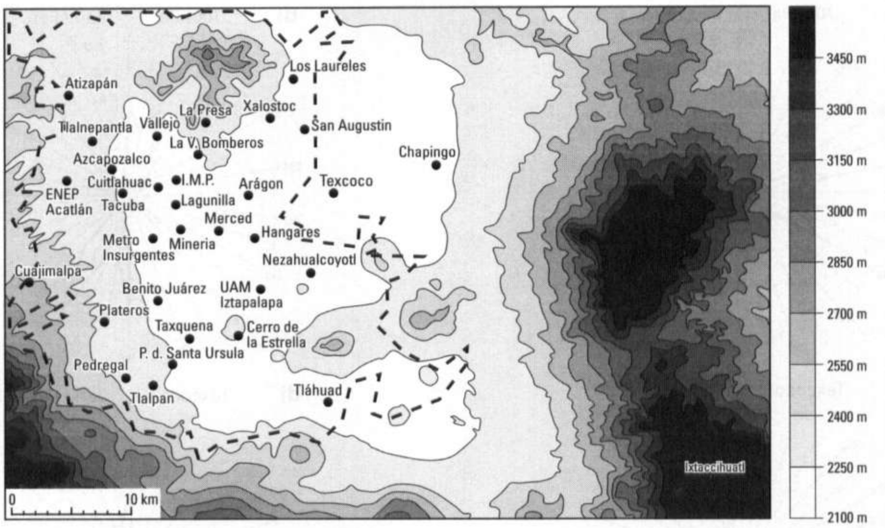



*Fig. 1b:* Position of Mexico City and the monitoring network in the basin of Mexico

Lage von Mexiko-Stadt und des Beobachtungsnetzes im Hochbecken von Mexiko

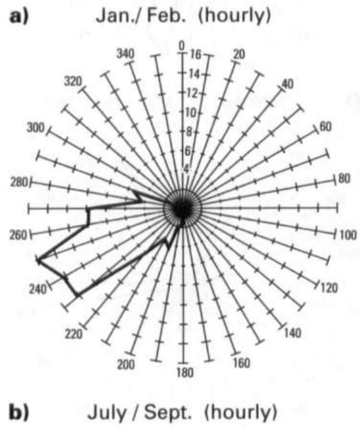



*Fig. 2:* Frequency of wind directions at the 500 hPa level for the dry season months of January and February 1995 (top) and the rainy season months of July and September 1995 (bottom)

Häufigkeit der Windrichtungen im 500 hPa-Niveau für die Trockenzeitmonate Januar und Februar 1995 (oben) und die Regenzeitmonate Juli und September 1995 (unten)

minimum wind speeds at about 5.00 (Fig. 4b). At the Tacuba (TAC, see Fig. 1b) station situated in the west of Mexico City, north-northwesterly winds occur throughout the day and take on maximum wind speeds at about 18.00 (Fig. 4a). West-northwesterly winds tend to dominate during the night hours. At the Pedregal (PED) station in the southwest of the city (Fig. 4 c), during the night hours, on average westerly wind prevails and during the day northeast wind, which reaches maximum wind speeds towards 19.00. The wind directions change in a similar manner in Merced (MER), at the centre of the city (Fig. 4d).

The north-northwest winds during the night are caused by cold air flows penetrating into the urban area from the mountain ranges in the west (Fig. 1a). The northeastern winds occurring during the night in Texcoco are also caused by cold air flow from the mountain ranges in the east-northeast of the station. The winds from the northern sector during the hours of daylight are determined by the prevailing synoptic pressure gradients at ground level in connection with the upslope winds at the rims of the basin (Fig. 1b). In the mean diurnal change of wind direction is caused by the superimposition of synoptic and local phenomena during the rainy season and even more intensively during the dry season.

### *Dynamics of the inner-city heat island*

The mean hourly temperature differences between the inner-city station of Mineria (MIN in Fig. 1b) and the field station at Texcoco (TEX) are shown in Figure 5a for 1995. The mean temperature difference

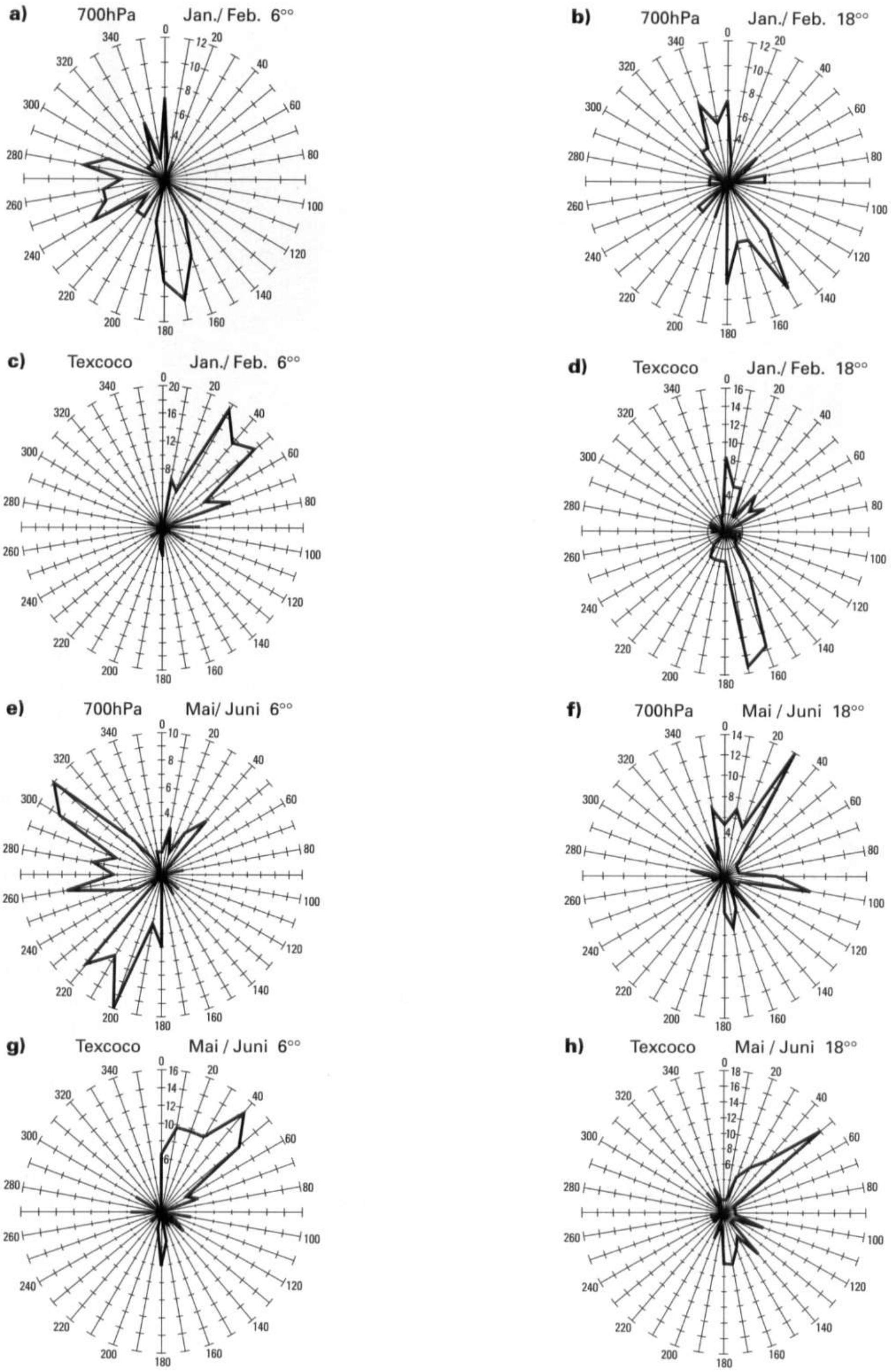



*Fig. 3:* Frequency of wind directions at the 700 hPa level and at ground level (Texcoco station) for the 6.00 and 18.00 observation time in the dry season months of January and February 1995 and the rainy season months of May and June 1995

Häufigkeit der Windrichtungen im 700 hPa-Niveau und im Bodenniveau (Station Texcoco) für den 6.00 und den 18.00 Uhr Beobachtungstermin in den Trockenzeitmonaten Januar und Februar 1995 und den Regenzeitmonaten Mai und Juni 1995

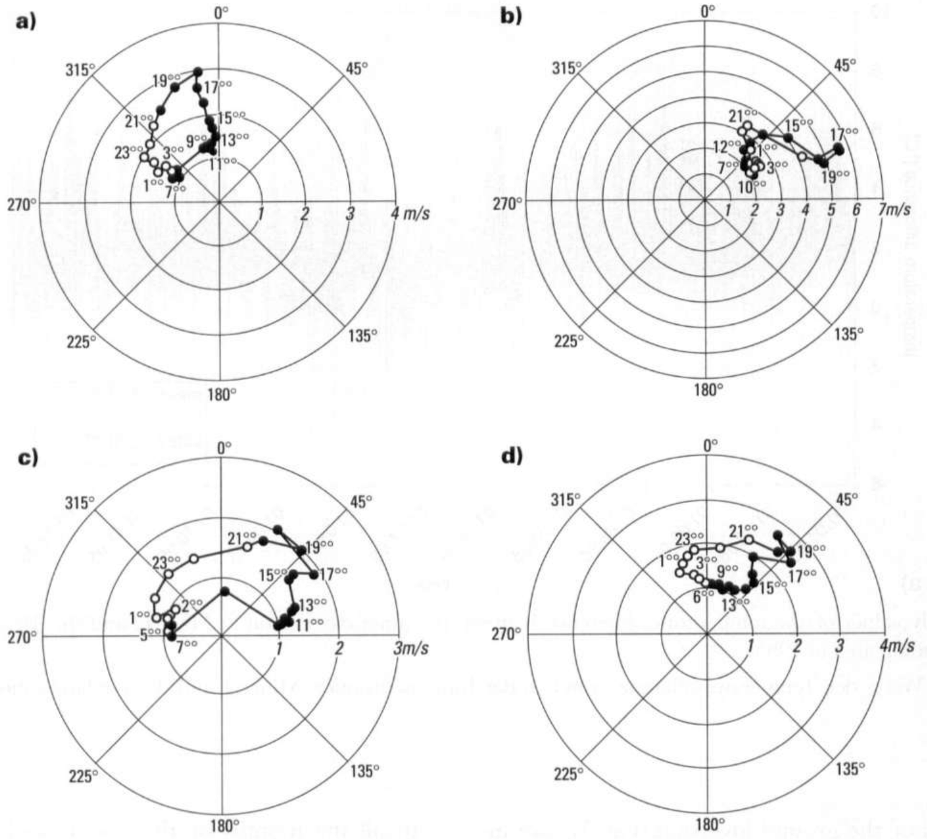


*Fig. 4:* Mean diurnal range of wind direction and wind speed plotted as hodographs for the Tacubaya (a), Texcoco (b), Pedregal (c) and Merced (d) stations for the rainy season months

Mittlerer Tagesgang der Windrichtung und Windgeschwindigkeit abgetragen als Hodogramm für die Stationen Tacubaya (a), Texcoco (b), Pedregal (c) und Merced (d) für die Regenzeitmonate

is 2°C with a standard deviation of 1.3°C. In 1995 the maximum differences are more than 7°C. Negative temperature differences occur more frequently during the rainy season. In the dry season, positive differences are dominant and indicate an overheating of the city centre.

During the dry season months, the mean diurnal temperature range shows distinct differences between Mineria in the city centre, the Texcoco suburb and the station at Hangares (HAN) on the outskirts. In the time from 10.00 to 17.30, the temperatures at Hangares are above those at Mineria, whereas at the other hours they are lower. Maximum inner-city overheating occurs on average in the early hours of the morning towards 7.00 (Fig. 5b). At the time of the daily temperature maximum, the temperatures at the Hangares station on the outskirts of the city are on average 2°C higher than in the city centre. In contrast to other cities, the inner-city overheating in Mexico City is consequently exclusively a phenomenon of the night hours. Furthermore, the maximum temperatures occur somewhat later in the city centre than on the outskirts. The mean hourly temperatures at the Texcoco station, 8 km eastward of the city boundary (TEX, see Fig. 1b), are from 10.00 a.m. to 5.30 p.m. 1–3°C lower than these in Mineria and Hangares (Fig. 5b).

The mean diurnal range of wind speeds in the dry season months displays a curve similar to that of the temperatures (Fig. 5c). Minimum wind speeds occur at the time of minimum temperatures at 7.00–8.00. However, maximum wind speeds are observed towards 18.00, i.e. about three hours after the temperature maximum.

The diurnal range of the wind corresponds approximately to that of lowland stations. During the hours of daylight, near-ground warming leads to convection, which initiates pulse transport from elevated levels thus explaining the occurrence of maximum wind speeds shortly after the appearance of temperature maxima. As a consequence of near-ground cooling, a ground inversion is formed during the night hours thus separating upper and surface flows. Light winds to be observed

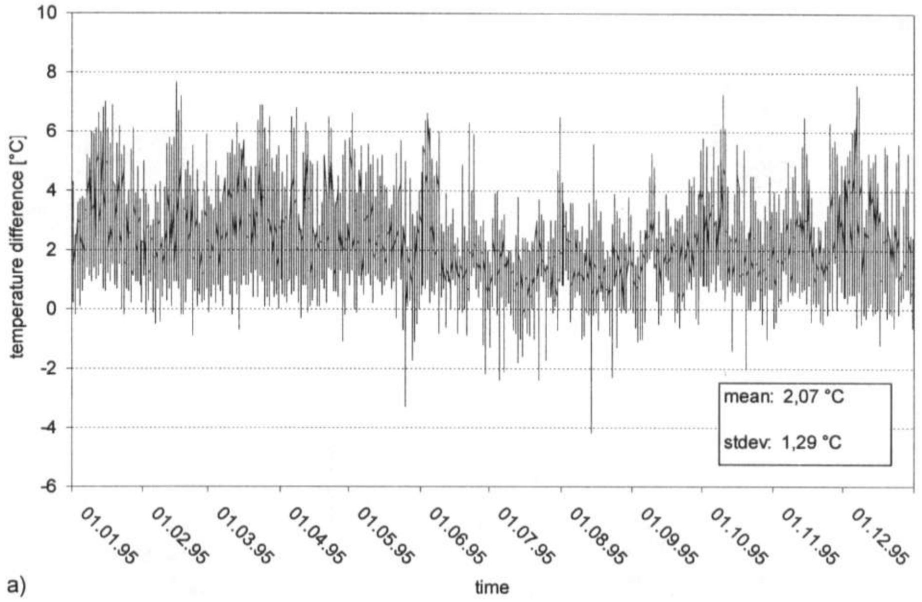



*Fig. 5a:* Hourly values of the temperature difference between the inner-city station at Mineria and the Texcoco station in the surrounding area in 1995

Stündliche Werte der Temperaturdifferenz zwischen der Innenstadtstation Mineria und der Umlandstation Texcoco im Jahr 1995

in the region of the ground inversion (Fig. 5c) are initiated by cold air flowing down the slopes of the basin under the action of gravity.

At the time of maximum inner-city overheating, the wind speeds are minimal in Mineria at the central parts of the city. In the afternoon hours, when temperatures reach their maximum at the eastern outskirts, wind speeds almost 2 m/s higher than in the city centre occur at Hangares and 3 m/s higher at Texcoco. Overheating of the urban outskirts in comparison to the centre can therefore not be attributed to a reduction of ventilation at Hangares. But the contemporary occurrence of lower temperatures at Texcoco after 18.00 may be a result of the stronger ventilation outside the city area (Fig. 5c).

In Mineria maximum temperatures are reached about one hour later than in the outskirts. In general, diurnal warming takes place much more rapidly in the surrounding area than in the central city. One reason for this can be attributed to the air pollution which is so intense in the central parts of the city that the values of the radiation balance Q are much lower at Mineria than at Texcoco (Fig. 5d). A further reason is the artificial oasis effect (OKE et al. 1992) occurring as a result of the water inputs to the city from distance sources and groundwater pumping increasing the urban evaporation rates to a multiple of than in the rural environment.

In all the months of the dry season, an intensive urban heat island is formed in the region of Mexico City, whose structure and position vary considerably in the course of the day. In the time from 5.00 to 8.00 (Fig. 6a), the urban heat island is considerably intensified in comparison to the time from 1.00 to 4.00. However, the centre of the heat island remains firmly established and stationary from 1.00 to 8.00 in the region of the city centre at Mineria. In the morning hours from 9.00 to 12.00, secondary heat islands are formed to the northwest of the city centre at Tlalnepantla (TLA) and to the east of the centre in Hangares (HAN). During the early hours of the afternoon from 13.00 to 16.00 (Fig. 6b), the centre of the heat island is on average shifted during the dry season months towards the east in the region of the Hangares airport station (HAN). The secondary centre in the region of Tlalnepantla is retained in a weakened form. During the early evening hours, the centre of the heat island migrates back into the central parts of the city, whereas in Tlalnepantla and Hangares the secondary heat islands are retained and only gradually disappear in the time from 21.00 to 24.00. The main reason for this diurnal migration of the heat island of Mexico City seems to be the strong air pollution in the central parts of the city and the resulting reduction of Q (Fig. 5d) as well as the artificial oasis effect.

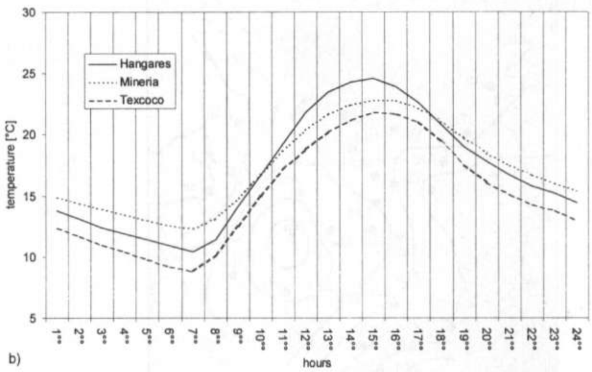



*Fig. 5b:* Mean diurnal range of temperature at the Hangares, Mineria and Texcoco stations for the dry season months of April, October, November and December 1995

Mittlerer Tagesgang der Temperatur an den Stationen Hangares, Mineria und Texcoco für die Trockenzeitmonate April, Oktober, November und Dezember 1995

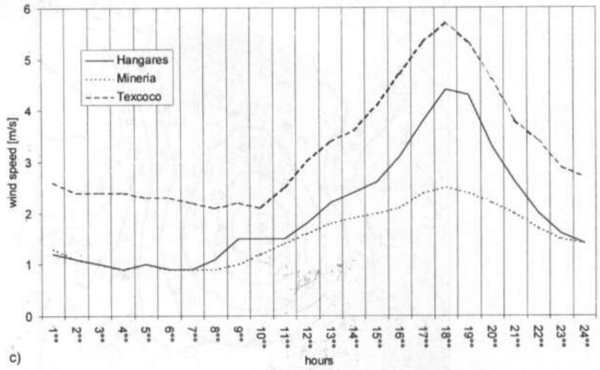



*Fig. 5c:* Mean diurnal range of windspeed at the Hangares, Mineria and Texcoco stations for the dry season months of April, October, November and December 1995

Mittlerer Tagesgang der Windgeschwindigkeit an den Stationen Hangares, Mineria und Texcoco für die Trockenzeitmonate April, Oktober, November und Dezember 1995

Fig. 6c and 6d show the mean wind speeds and wind directions for the dry season months. In the time from 5.00 to 8.00, the heat island in the city centre coincides with the zone of minimum wind speeds. The wind speeds increase perceptibly towards the outskirts. To the west of the city centre, west winds occur directed towards the centre as a consequence of the flows of cold air down the slopes. They are of major significance for the air hygiene of the city. In the south of the city, south-southwest winds preferentially occur, which can also be attributed to the downward flow of cold air. To the east of the city, winds from the eastern directional quadrant are dominant. They result from the flow of cold air down the slopes of the mountain ranges located east of the city (Fig. 1). All this currents are reinforced by the pressure gradients arising as a consequence of the inner-city heat island. On the whole, the winds in the region of Mexico City are preferentially directed towards the centre of this city in the late night hours.

In the time from 13.00 to 16.00, the zone of light winds is firmly established over the central parts of Mexico City (Fig. 6d). To the east of the city, a zone of high wind speeds is formed, whose position coincides with the position of the urban heat island (Fig. 6b and d) during this time.

An important requirement for the development of inner-city heat islands is the reduction of wind speed as a consequence of increased roughness of the ground in the urban region. The heat emitted from the substance of a building is not distributed over a large area in the case of a light wind situation but the temperatures are rather locally increased as a function of development density.

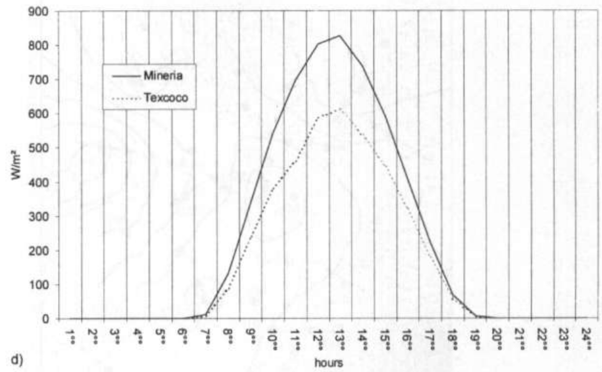



*Fig. 5d:* Mean diurnal range of radiation at the Mineria and Texcoco stations for the dry season months of April, October, November and December 1995

Mittlerer Tagesgang der Strahlung an den Stationen Mineria und Texcoco für die Trockenzeitmonate April, Oktober, November und Dezember 1995

These mechanisms cannot be responsible for the diurnal shift of the urban heat island away from the inner-city area into the outskirts towards Hangares since in comparison to the centre the wind speeds are almost 2 m/s higher in Hangares (Fig. 6d). Hangares is situated near a depression previously occupied by Lake Texcoco. This is a very flat region characterized by sediments from Lake Texcoco. The areas almost devoid of vegetation make a desert-like impression and with intensive solar radiation promote local overheating.

It can be concluded that the intensity and dynamics of the heat island in the region of Mexico City averaged throughout the months of the dry season have a

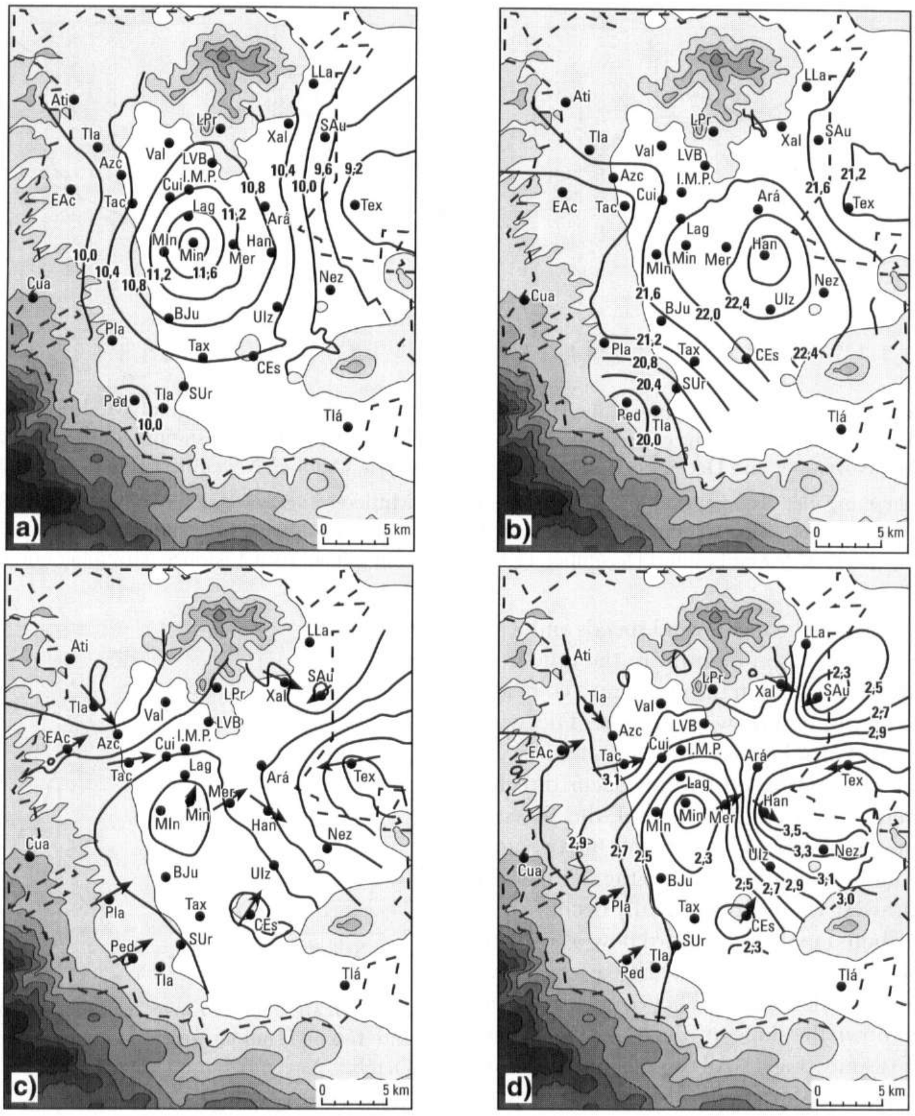



*Fig. 6:* Mean temperatures for the dry season months in the region of the urban area of Mexico City for the time from 5.00–8.00 (a) and from 13.00–16.00 (b) as well as the mean wind speed and wind direction also for the time from 5.00–8.00 (c) and from 13.00–16.00 (d)

Mitteltemperaturen für die Trockenzeitmonate im Bereich des Stadtgebietes von Mexiko Stadt für die Zeit von 5.00–8.00 Uhr (a) und von 13.00–16.00 Uhr (b) sowie mittlere Windgeschwindigkeit und Windrichtung ebenfalls für die Zeit von 5.00–8.00 Uhr (c) und von 13.00–16.00 Uhr (d)

perceptible influence on the wind field in the region of this city. In the following section, the regularities displayed by this influence will be further investigated and explanations for their occurrence presented.

*Urban and cyclonic wind in the environment of the inner-city heat island*

The occurrence of an urban wind in Mexico City will be indicated by wind directions at the stations arranged around the city [Tlalnepantla (TLA), Plateros (PLA), Pedregal (PED), Cerro de Estrella (CES), Hangares (HAN), Texcoco (TEX) and San Augustin (SAG)] oriented towards the city centre, represented by the Mineria station (MIN). In order to identify the hours at which this condition is approximately fulfilled, all the hours were determined at which the wind direction is directed towards the city centre at all the above-mentioned stations simultaneously with a tolerance of 60°. These conditions were fulfilled for 145 hours in 1995. Figure 7 shows the mean wind directions and wind

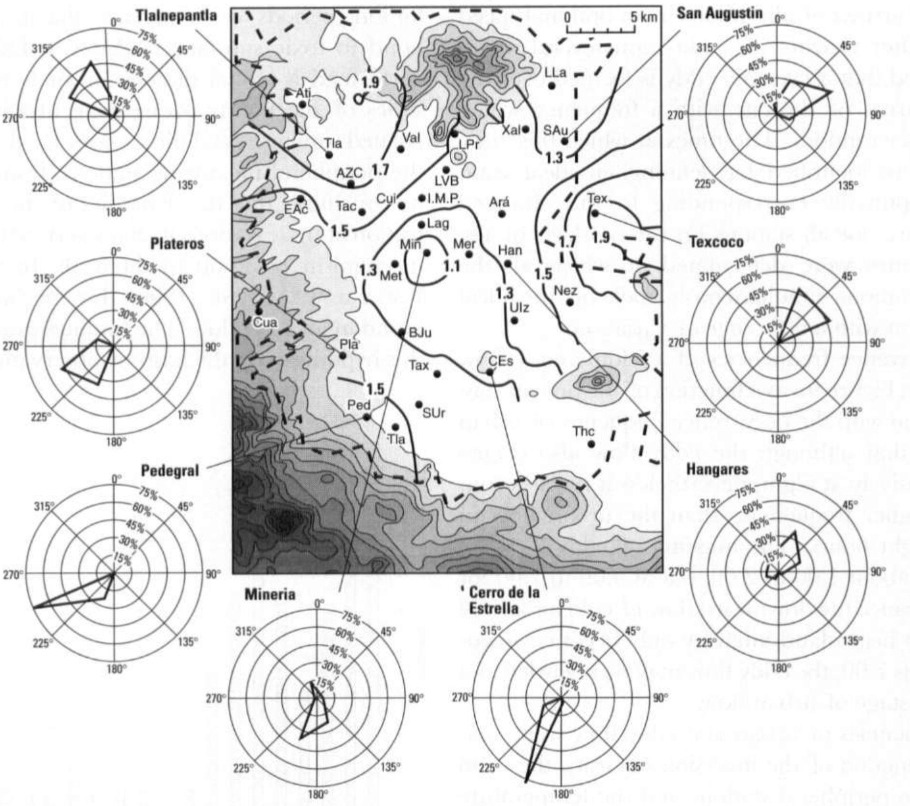



*Fig. 7:* Mean wind speed and wind direction for all the hours in 1995 when the wind directions of all peripheral stations were oriented towards the city centre. The frequencies of these wind directions are also given for some peripheral stations

Mittlere Windgeschwindigkeit und Windrichtung für alle Stunden des Jahres 1995, in denen die Windrichtungen aller Stadtrandstationen in Richtung Stadtzentrum gerichtet waren. Die Häufigkeiten dieser Windrichtungen sind für einige Stadtrandstationen ebenfalls angegeben

speeds as well as the directional frequencies for the above mentioned stations on the outskirts of the city.

The wind speeds are low in the city centre and increase towards the outskirts. The frequency diagrams for the wind directions show that the winds directed into the city achieve a great frequency. The mean wind directions characterize the urban winds less clearly. It is striking that the urban winds in the western, southern and eastern parts of the city precisely correspond to the direction of cold air flowing off.

In Figure 8, the frequency of occurrence of urban winds is plotted as a function of the time of day. Urban winds prove to be a phenomenon of the night hours. Maximum frequencies occur between 5.00 and 8.00, which indicate that the flows are reinforced by cold air flow off as well as by the urban heat island since both phenomena reach maximum intensity in the early morning hours. The basin situation of Mexico City therefore reinforces urban wind effects. The fractions attributable to both effects involved can hardly be separated.

In order to recognize other regularities in the wind field, a computer animation was prepared of the hourly wind directions and wind speeds including the upper winds. In a relief model, the animation shows the

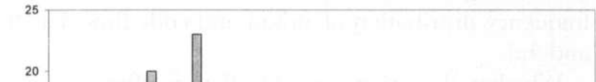


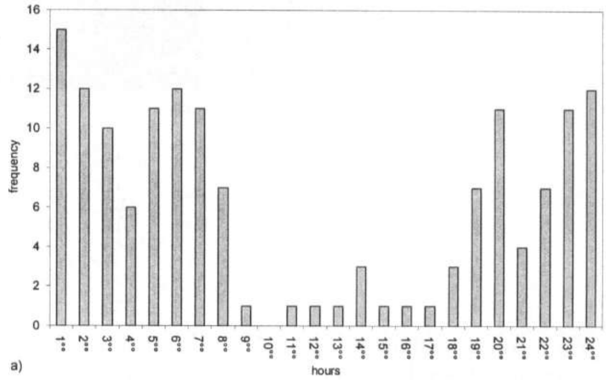

*Fig. 8:* Hourly frequencies of the occurrence of urban winds at all peripheral stations as a function of time of day

Stündliche Häufigkeiten des Auftretens von Flurwinden an allen Stadtrandstationen in Abhängigkeit von der Uhrzeit hourly wind arrows of all stations in an optional speed sequence. After viewing the animation several times, it was noticed that a cyclonic eddy is formed over the peripheral areas of the city with a frequency which was no longer random. The times at which this eddy occurred were identified by defining an ideal wind direction, optimally corresponding to the observed eddy structure, for all stations on the outskirts of the city. The times were determined at which all the peripheral stations simultaneously took on the ideal eddy direction with a 60° range of variation.

The occurrence frequencies of cyclonic eddy flow are plotted in Figure 9a as a function of the time of day. A comparison with the occurrence frequency of urban flow shows that although the eddy flow also occurs almost exclusively at night, nevertheless it reaches considerably higher frequencies than the urban flow in the early night hours. The maxima of eddy flow are recorded at about 1.00 to 2.00, but at 5.00 to 7.00 for urban flow. Since the downward flow of cold air as well as the urban heat island intensity only becomes maximum towards 7.00, the eddy flow may be regarded as a preliminary stage of urban flow.

The frequencies of urban and eddy flow were analysed as a function of the inversion intensity, the wind speeds at the peripheral stations and the temperature difference between the city centre and surrounding area. While the frequency distributions did not show any significant deviations as a function of inversion intensity and wind speed, a significant difference can be identified as a function of the temperature differences between city centre and surrounding area (Fig. 9b). With slight temperature differences between the city and surrounding area, the eddy flow reaches greater frequencies than the urban flow. Since the intensity of the nightly heat island becomes maximal towards 7.00, this finding confirms the differences in the diurnal frequency distribution of urban and eddy flow (Fig. 8 and 9a).

Whether the urban or eddy flow is effective may be of great significance for pollutant transport. The prevailing north-northeast winds during the day time hours are in general not strong enough to carry the polluted city air out of the basin. As a result, the contaminants are concentrated in the southwest of the basin as can by seen for CO in Figure 10a. During the night and the early morning hours downslope winds transport the pollution accumulations from the southeast back to the northeast and the central parts of the city (Fig. 10b). Whereas the urban flow preferentially transports pollutants towards the city centre, with a prevailing eddy flow they are directed over the peripheral zones of the city. In this way particles remain airborne for long periods which increases the likelihood they will bond to toxic substances. RAGA a. LEMOYNE (1996) performed a fractal dimension analysis of long time series of the hourly ozone concentrations. They calculated similar fractal dimensions for the time series of the peripheral measuring stations, from which it may be concluded that the dynamics of the ozone concentration at these stations is characterized by an operative mechanism common to them all. In the opinion of RAGA a. LEMOYNE (1996) this mechanism is to be found in an eddy flow. The findings presented confirm this hypothesis on the basis of observational data



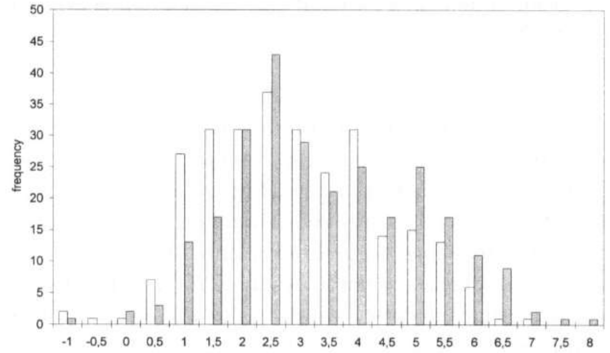




*Fig. 9:* Hourly frequency of the occurrence of a cyclonic eddy flow as a function of time of day (a). Hourly frequency of a cyclonic eddy flow (white bars) and urban wind flow (black bars) in relation to the temperature difference between the city centre and surrounding area (Mineria and Texcoco) (b)

Stündliche Auftrittshäufigkeit der zyklonalen Wirbelströmung in Abhängigkeit von der Uhrzeit (a). Auftrittshäufigkeit einer zyklonalen Wirbelströmung (weiße Balken) und der Flurwindströmung (schwarze Balken) in Abhängigkeit zur Temperaturdifferenz zwischen dem Zentrum der Stadt (Mineria) und dem Umland (Texcoco) (b) in Stunden

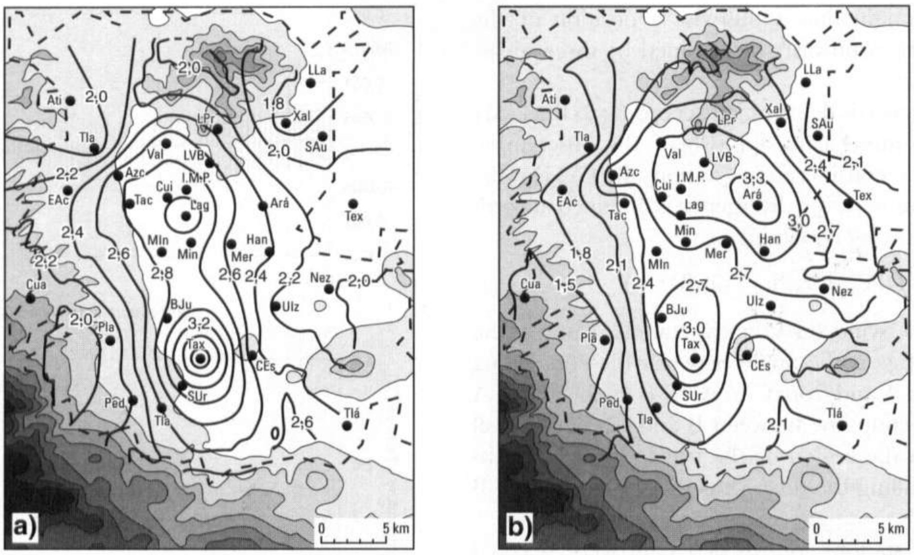



*Fig. 10:* Mean concentration of Carbonmonoxid (CO) for the dry season months in the urban area of Mexico City for the time from 11.00–15.00 (a) and from 23.00–4.00 (b)

Mittlere CO-Konzentration in den Trockenzeitmonaten im Stadtgebiet von Mexiko-Stadt für die Zeit von 11.00–15.00 Uhr (a) und von 23.00–4.00 Uhr (b)

*Convergence as a consequence of the urban heat island effect*

The urban wind directed into the city leads to convergent movements of air in the inner-city region. This was determined according to a method developed by BELLAMY (1949). The method is based on a calculation of the air mass flowing into and out of a given triangle. A necessary condition for applying the procedure is that the wind field only changes linearly between the measurement points and that the stations are not situ-

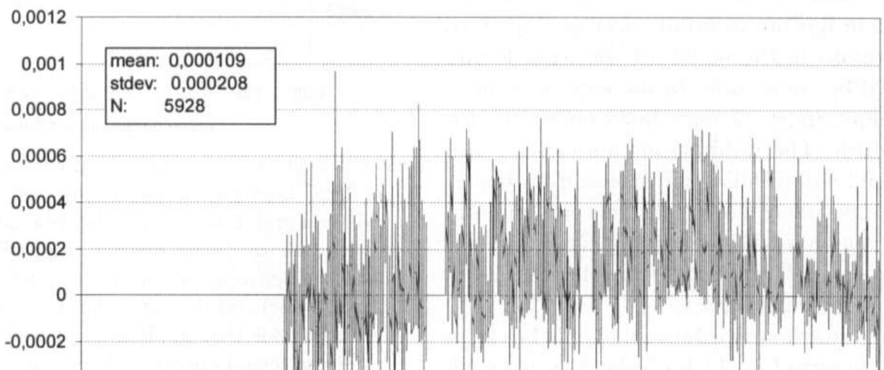



*Fig. 11:* Hourly values of the divergences in 1995. The values were determined according to BELLAMY'S method (1949) for a triangle whose corners are occupied by the stations of Enep Acatlan (EAC), Plateros (PLA) and Texcoco (TEX)

Stundenwerte der Divergenzen im Jahr 1995. Die Werte wurden nach dem Verfahren von BELLAMY (1949) für ein Dreieck bestimmt, dessen Ecken von den Stationen ENEP Acatlan (EAC), Plateros (PLA) und Texcoco (TEX) eingenommen werden ated on a straight line. Otherwise a position of the triangle can be arbitrarily determined by three measuring stations.

The divergence is determined according to BELLAMY (1949) by assuming calm for two of the observation stations under consideration (stations B, C). For the remaining station A, the divergence is obtained according to the following equation:

$$DIV_A = v_A/h_A \cdot \sin(\beta_{BC} - a) \qquad (1)$$

where a is the wind direction at station A and v the wind speed. $\beta_{BC}$ is the angle between the connecting line from B to A and from C to A. $h_A$ is the height of A on the connecting line between B and C. The overall divergence in the region of the triangular area is obtained by totalling the divergences calculated for A, B and C.

The three stations for Mexico City were selected in such a way that the central areas of the city were covered by the triangular area. Different combinations of stations fulfil this condition. Since the calculated divergences become maximal in the centre of the triangle (centroid), it was attempted to select the station combination in such a way that, if possible, the centroid is located close to the city centre.

Figure 11 shows the calculated hourly divergence values for a triangle formed from the stations of ENEP Acatlan (EAC), Plateros (PLA) and Texcoco (TEX). This triangle covers the central parts of the city. Negative divergence values result if more air mass flows into the triangle than out on an hourly average. Air mass convergence results in the region of the triangle and is compensated by convection. In the case of positive divergence values, more air mass flows out of the triangle than into it. The resulting air mass divergence is compensated by descending air masses from higher layers of the troposphere. For air-hygiene conditions in the inner-city region it is of great significance whether comparatively clean air masses from elevated levels descend or polluted city air rises.

Unfortunately, the hourly values could only be calculated for those months for which wind data were available at all three observation stations simultaneously. As a whole, convergence occurs particularly frequently over the city centre in the months of April and May (Fig. 11). The highest temperature differences between the city centre and the surrounding area are observed in January and December (Fig. 5 a). The urban or eddy flows arising as a consequence of this temperature difference are only in part responsible for the intensity of convergence in the inner-city region.

The relation between the temperature difference occurring between the inner city and the surrounding

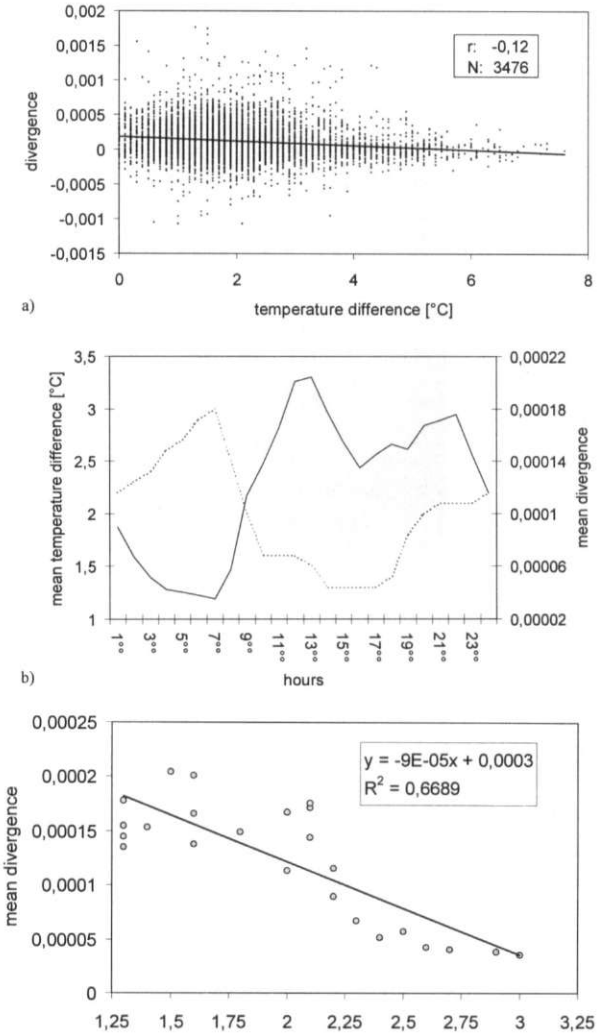



*Fig. 12:* Relation between the hourly temperature difference in 1995 between the city centre and surrounding area (Mineria and Texcoco) and the simultaneously occurring divergence (a). Mean diurnal range of temperature differences between the city centre and surrounding area (dashed line) and the mean diurnal range of divergences (solid line) for 1995 (b). Regression and correlation analysis of the relation between the temperature differences of the city centre/surrounding area and the simultaneously occurring average divergence values (c)

Zusammenhang zwischen der stündlichen Temperaturdifferenz im Jahr 1995 zwischen Innenstadt und Umland (Mineria und Texcoco) und der gleichzeitig auftretenden Divergenz (a). Mittlerer Tagesgang der Temperaturdifferenzen zwischen Innenstadt und Umland (gestrichelt) und dem mittleren Tagesgang der Divergenzen (ausgezogen) für das Jahr 1995 (b). Regressions- und Korrelationsanalyse des Zusammenhangs zwischen den Temperaturdifferenzen Innenstadt/Umland und den gleichzeitig auftretenden mittleren Divergenzwerten (c) area and the divergence observed simultaneously can be quantified by a regression analysis. Figure 12a shows the divergence values as a function of this temperature difference. For the 3476 observational pairs depicted, the threshold value for the 1% significance level is 0.10. The calculated correlation coefficient of −0.12 is therefore highly significant. The regression equation expresses the fact that an intensification of the urban heat island leads to a decrease in divergence, i.e. to convergent movements of air above the central parts of the city. However, this linear regression only explains just under 2% of the total variance, which means that 98% of the divergences occurring cannot be explained by urban climate effects related to the temperature difference between city and surrounding area.

However, this statement must be modified in view of the measuring accuracy of the wind observations, which is in the order of 10–15%. This is true both of the wind directions and wind speeds. In contrast, the inaccuracy of the temperature measurements is less than 3%.

Equation (1) shows the nonlinear linkage of wind direction and wind speed. The measuring errors in wind observation are consequently reinforced by the divergence calculation. A theory of errors shows that with small divergence values the divergence changes occurring as a consequence of measuring errors in the order of 10% reach the order of the calculated divergences, which means that due to the unavoidable measuring errors the signal is very noisy. This noise can be reduced by averaging if the measuring errors are not of a systematic nature and have a normal distribution, as can be assumed for the present data.

In Figure 12b, the mean diurnal range of divergence is plotted averaged over all the days of the dry season months. For comparison, the mean diurnal range of the temperature difference between the inner-city station of Mineria and the Texcoco station in the surrounding area was plotted for the same days. The two diurnal ranges are approximately inverse to each other. The regression analysis shows that 58% of the total variance in divergence is explained by the intensity of the urban heat island, which means that the agglomeration of Mexico City has a considerable influence on circulation conditions in the basin of Mexico.

*Conclusion*

The results presented are based on hourly wind, radiation and temperature data from 1995. Further hourly data of the pollutant concentration are available for 1995. In a next step the influence of flows related to the urban heat island effect on the pollutant concentration and pollutant transport in the area of Mexico City has to be clarified. Proven regularities between these parameters may be of great relevance for urban planning in Mexico City.

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