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The energy balance of central Mexico City during the dry season

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Abstract

The first measurements of the energy balance fluxes of a dry, densely built-up, central city site are presented. Direct observation of the net radiation, sensible and latent heat flux densities above roof-top in the old city district of Mexico City allow the heat storage flux density to be found by residual. The most important finding is that during daytime, when evaporation is very small ($<4\%$ of net radiation), and therefore sensible heat uses dominate (Bowen ratio >8), the uptake of heat by the buildings and substrate is so large (58%) that convective heating of the atmosphere is reduced to a smaller role than expected (38%). The nocturnal release of heat from storage is equal to or larger than the net radiation and sufficient to maintain an upward convective heat flux throughout most nights. It is important to see if this pattern is repeated at other central city, or dry urban sites, or whether it is only found in districts dominated by massive stone structures. These findings have implications for the height of the urban mixing layer and the magnitude of the urban heat island.

Keywords: Surface energy balance; Heat fluxes; Heat storage; Urban climate; Mexico City

1. Introduction

Cities create their own climates due to the impacts of urban development on the surface balances of heat, mass and momentum. Observations of these balances are scarce, even in the relatively well-studied cities of mid-latitude temperate climates (see Oke, 1988 for a review of the urban energy balance). The understanding of these matters in cities located in tropical and sub-tropical climates is little more than skeletal.

The first such study was undertaken by Oke et al. (1992) at a mixed residential/commercial/industrial area in the Tacubaya district of Mexico City (Fig. 1). It used direct measurements of net radiation (Q^*) and the turbulent sensible heat flux (Q_H), and parameterized estimates of the sensible heat storage in the urban materials (ΔQ_S), leaving the evaporative flux (Q_E) as the residual in the surface energy balance. Results showed considerable similarity to those from residential areas in cities with temperate climates, including the magnitude of the Bowen ratio ($\beta = Q_H/Q_E$), which was slightly greater than unity. On the other hand the fraction of the net radiation calculated to be put into storage during the daytime (36%) was significantly larger than had been observed elsewhere (typically 17–30%). This increased proportion of heat stored in the fabric of the city seemed to be at the expense of the turbulent sensible heat flux; the ratio $Q_H/\Delta Q_S$ was only about half that found at residential sites in temperate cities.

A weakness underlying the Tacubaya study was the fact that only two of the fluxes were measured directly. More complete energy balance studies have since been undertaken at suburban residential sites in two other cities which, if not strictly located in the tropics, at least experience tropical climates: Tucson, AZ (Grimmond and Oke, 1995, 1999a) and Miami, FL (Grimmond and Oke, 1999a). In terms of atmospheric moisture and

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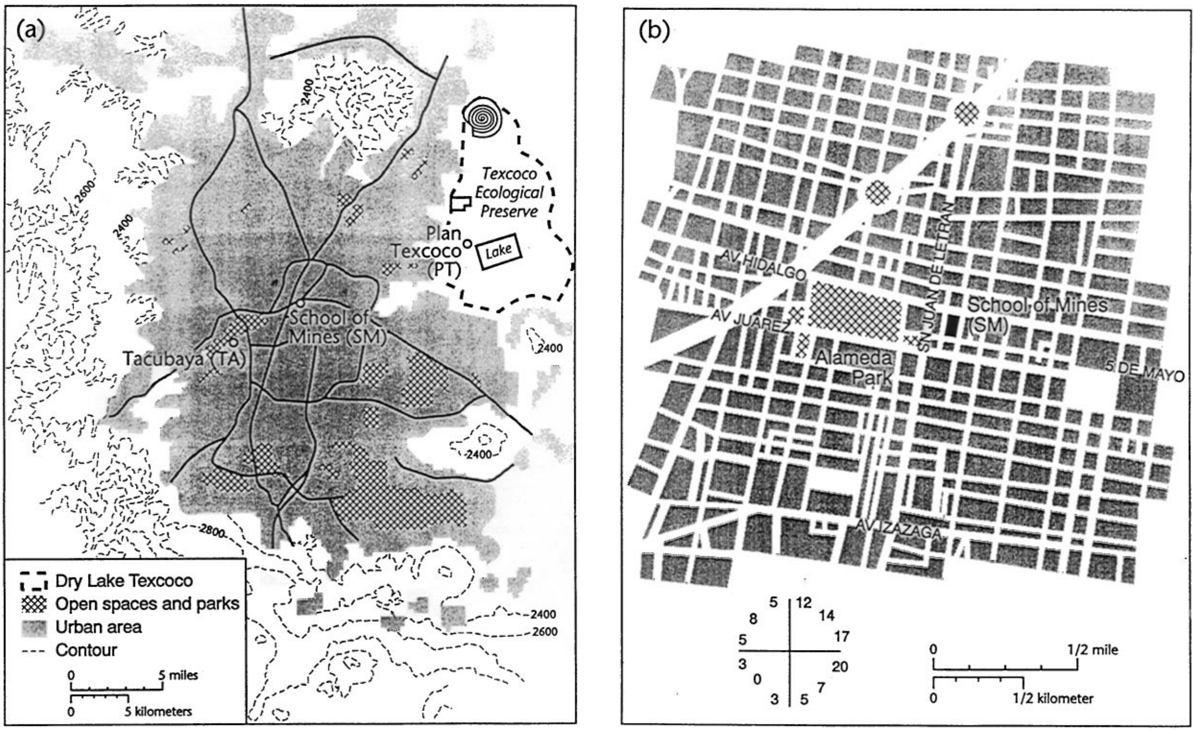

Fig. 1. (a) The location of the School of Mines (SM), Tacubaya (TA) and Plan Texcoco (PT) sites in the Mexico City area. (b) Surface cover in the vicinity of the SM site. Shading key: solid – buildings; cross-hatch – open (parks, vacant land); no shading – flat, impervious (roads, squares). Inset: – wind rose of percent frequency wind direction for daytime ($Q^* > 0$) hours.

surface water availability these two cities lie near either end of the range of tropical climate types. Tucson is the closest analogue to Mexico City in the dry season, but the building density at the Tucson residential site is considerably lower, and the vegetation cover much greater, than the downtown one presented here.

Almost all previous observations of the urban energy balance have been conducted over extensive residential (often called suburban) sites, due to two reasons that are linked. Firstly, especially in North American cities, this is the dominant land-use in terms of areal extent; therefore findings are likely to be widely applicable. Secondly, because the physical extent of this land-use is large it is relatively easy to find field sites suited to the use of one-dimensional micrometeorological techniques, i.e. there is sufficient fetch over reasonably homogeneous terrain (see Oke et al., 1989). Whilst heavily developed city areas such as downtown districts are expected to exhibit the greatest urban climatic effects, they are difficult to investigate because there is usually a wide range of building heights and therefore they lack sufficient fetch. This leads to overwhelming complications due to organized vertical flows and advective effects.

The aims of this study are twofold: firstly, to contribute to the nascent understanding of the energetic basis of tropical urban climates, and secondly, to initiate studies of the energy balance at intensely developed sites. The latter focus seeks to help develop understanding of the role of urban morphology in intra-urban differentiation of local climates. Although central Mexico City is not entirely free of the complications that have stopped others from working at densely built-up urban sites, it provides the opportunity to obtain pilot observations. The historic core of Mexico City consists of large areas of old, massive stone buildings which are relatively similar in height and structure, making it possible to use eddy correlation equipment to measure areally representative turbulent fluxes in an area with almost no natural surfaces.

2. Experimental

2.1. Urban setting

Mexico City, DF (19°25′N, 99°10′W) is located in an inland elevated valley at an altitude of about 2250 m a.s.l. in central Mexico. The climate is highland tropical, with a well-defined rainy season (May–October). By the end of the dry season maximum daily air temperature is around

29°C, and minimum temperatures near 0°C, at rural sites. There is a sharp gradient in annual rainfall across the city, from 400 mm in semi-arid rural areas to the north-east, 650 mm in downtown, to more than 700 mm in the southwestern suburbs (Jáuregui, 1973). The urban area is extensive ($\sim$1200 km^2) and heavily developed. As a result there are marked urban effects on climate and air quality (Jáuregui, 1973, 1986, 1988, 1993; Jáuregui and Klaus, 1982). Heat island intensities of up to 10°C have been observed in the urban canopy layer (UCL) using automobile surveys on clear, calm winter nights (Jáuregui, 1973).

2.2. Site

The observation site is located on the western edge of the core of the old town consisting of blocks of massive buildings (Fig. 2). Land-uses are dominantly institutional (e.g. government offices, museums, churches, post office, educational) and commercial. Instruments were mounted on masts on the roof of the School of Mines (SM) building. The site is not far from the observed location of the maximum nocturnal UCL heat island (Jáuregui, 1993). This site and measurement period is also referred to as Me93 in other publications by our group (e.g. Grimmond and Oke, 1999a, b).

The characteristics of the surface morphology surrounding the SM downtown site were assessed by field surveys and entered in a surface geographic information system (GIS). The detailed survey was conducted for an area with a radius of 0.5 km in all directions from the tower. Assessments beyond this zone were based on map analysis. The dimensions of the source areas of the turbulent fluxes for each hour were calculated, using the FSAM model of Schmid (1994, 1997), and overlain on the GIS database following the method of Grimmond and Souch (1994) and Grimmond (1996). The daytime turbulent source areas had a length dimension (for the 90% source weight) of less than 200 m in all cases, and typically a cross-wind dimension of less than 400 m. At night these dimensions increased to a median of approximately 600 and 700 m for length and width, respectively.

Combining the calculated source area with its corresponding materials, morphology, height, etc., the exact nature of the surface contributing to the flux measurements was calculated for each hour of observation. In addition it was possible to calculate the area of built and greenspace covers, together with the fractions of the complete (3-D) surface area (A_c) occupied by vegetation and water (A_v), impervious ground materials (A_i), roofs (A_r) and building walls (A_w). Since there are parks and large open spaces in the 181–360° sector from the tower, only flow from 0–180° are considered here. The following are the average hourly source area fractions (plus in brackets the absolute range for the day): A_v – 1% (0–3%); A_i – 25% (22–31%); A_r – 32% (26–34%); and A_w – 42%

Fig. 2. The tower site at the School of Mines site in central Mexico City. The flux instruments (not visible) are mounted on the cross-arm at the top of the lattice section and just below the model owl (used to deter birds from perching on the sensors). Instruments were levelled; due to ground subsidence in this area the building top is not level. The shorter mast at the right was used for standard observations of temperature, humidity and wind.

(39–50%). Hence, vegetation cover is virtually negligible, ground only occupies an area equal to about one half that of buildings (i.e. $A_r + A_w$), and walls are areally more important than roofs. The distribution of surface cover (buildings, impervious surfaces such as roads and squares, and parks/vacant lots) in the vicinity of the SM site, is given in Fig. 1b.

The mean building height (z_{Hb}) in the source areas located in the 0–180° sector around the SM tower is 18.4 $\pm$ 6.6 m. The ratio of the three- to the two-dimensional surface area (i.e. the complete area to the bird's eye view), known as the *active area ratio*, is a measure of the increase in effective surface area due to the rugosity of the urban interface. At the SM site the active area ratio is 1.78. This is a significant increase in area available for exchange compared with a flat surface, but not as great as for a high-rise downtown such as Vancouver, BC where it is 2.20 (with a mean building height of 34 m and some structures exceeding 100 m, Grimmond and Oke, 1999b) or probably for some of the more modern areas of central Mexico City. In the street canyons and alleys adjacent to the tower the sky view factor varies from about 0.22 to 0.51. This indicates there is both considerable shade by day, even at relatively low solar zenith angles, and long-wave screening of the horizon by buildings all day.

Most buildings in the SM area are built of stone or concrete with roofs of concrete, tar, sheet metal or tile. The roads are paved with concrete or asphalt, or are surfaced with tiles, cobble- or flagstones. With the exception of Alameda Park (6 ha) (which is not included in the 0–180° directions considered here) there is little vegetation, open water or irrigation in the SM area, but there are small sources of moisture due to vehicle combustion, air-conditioning and street-washing.

2.3. Measurements

Observations are expected to be representative of the integrated response of buildings and roads, etc. over horizontal length scales of about 10^2–10^3 m, which we refer to as the local scale. The approach, laid out by Oke (1988) and Oke et al. (1989), is to measure the radiative and turbulent component fluxes of the surface energy balance above roof level, and to express the heat storage change in the underlying city volume, as equivalent fluxes through the top of the volume (i.e. the instrument level). At SM the net all-wave radiation (Q^*), and the convective sensible (Q_H) and latent (Q_E) heat flux densities were measured directly so the storage heat flux density (ΔQ_S) was found by residual from the energy balance. This means that net errors in other fluxes accumulate in this term. It should also be appreciated that this is a balance constructed from measured terms. It does not explicitly include sources of anthropogenic (combustion) heat, or sources/sinks due to advection from cooler or warmer surfaces upstream. The magnitude of the flux densities reported here are therefore not exactly the same as those of the commonly written urban energy balance which includes separate anthropogenic (Q_F) and advective (ΔQ_A) terms. The measured terms presented here, however, do include the influence of Q_F and ΔQ_A, i.e. they are incorporated in the measured and residual fluxes. We anticipate that these effects do not contribute more than a few tens of W m^{-2} to any one flux. The approach has been shown to give plausible and reproducible results in several cities (Grimmond and Oke, 1995, 1999a).

The flux instruments were mounted near the top of a 10 m mast placed on the flat roof of the School of Mines (Fig. 2). The elevation of the ground at SM is 2270 m a.m.s.l. and the building is 18.4 m high, i.e. essentially at the mean roof height for the area. Thus the measurement height (z_m) is approximately 28 m above ground, and probably roughly 15–17 m above the zero-plane displacement (Rotach, 1994; Grimmond and Oke, 1999b). Ideally, the sensors for the turbulent fluxes should be located above the roughness sub-layer so that they exist in the constant flux layer, if one exists above such terrain. Using several formulae Grimmond and Oke (1999b) calculate that the roughness sub-layer at SM is likely to be somewhere between about 30 and 70 m above ground. Thus, at the best, z_m is near the base of the roughness sub-layer.

An indication of the adequacy of the SM arrangement can be drawn from the studies of Rotach (1993a, b, 1995). He analyzed data from turbulence and gradient sensors arranged in profiles from ground-level to roof-level and up into the layer above both the roof and the canyon. The mean building height, and the upper measurement height, in the Rotach study are almost identical to those at SM. The canyon widths are slightly more variable at SM. Rotach finds horizontal inhomogeneity becomes negligible (smaller than measurement uncertainty) at less than $z_m/z_{Hb} = 1.55$, and that above this height conditional sampling analysis shows turbulent sweeps and ejections which tend toward inertial sub-layer behaviour. Similarly, Rotach's velocity and temperature variances and spectra agree with those found in the surface layer over rural terrain, although there are differences, such as greater variability, especially in the case of temperature. We conclude that the SM experimental arrangement ($z_m/z_{Hb} \sim 1.55$) is in the lower part of the roughness sub-layer, but meets Rotach's criterion, and is capable of generating reliable data.

The net all-wave radiation was measured using a net pyrradiometer (Swissteco, S1), and the turbulent sensible and latent heat fluxes were measured directly using the eddy correlation approach. The fast response instruments, mounted less than 0.15 m apart, consisted of a one-dimensional sonic anemometer and fine-wire thermocouple system (Campbell Scientific Inc., CA27) to measure the fluctuations of vertical wind velocity and temperature, and a krypton hygrometer (Campbell Scientific Inc., KH20) to measure those of absolute humidity. The vertical wind velocity, air temperature and humidity fluctuations were sampled at 10 Hz. Covariances were determined for 15 min periods. Flux corrections were made for oxygen absorption by the sensor (Tanner and Greene, 1989) and air density (Webb et al., 1980).

Standard climatological measurements of air temperature, humidity, wind speed and wind direction were made at about 6 m above roof top on a separate mast (Fig. 2). Infrared radiation thermometers (Everest Interscience, 4000A) were used to obtain the apparent surface temperature of the SM roof, a south-facing wall and the floor of an east–west, and a north–south oriented canyon adjacent to the site. A surface wetness sensor was placed in contact with roof surface.

Observations were conducted during the period December 1–7, 1993 (YD 334–341). No rain fell during the period, indeed except for partial cloud on YD 338 it was almost cloudless. Air temperature typically varied from 9 to 10°C in the morning to 20–23°C in the afternoon. This was paralleled by a diurnal variation in vapour pressure deficit from about 0.2 to 0.6 kPa near sunrise to 1.8–2.4 kPa in mid-afternoon. The wind field followed a fairly regular diurnal pattern. Winds were about 1 m s^{-1} from the east at night, but through the day they tended to speed up and veer until they were typically from the northwest at about 3 m s^{-1} at sunset, after which they subsided quickly. An earthquake before dawn on YD 336 resulted in a few hours of spurious data, but that, plus a short break late on day YD 340, were the only interruptions in an otherwise continuous series. All times have been corrected to local mean solar time (local apparent time, LAT).

3. Results

The period of observation was so uniform, in terms of prevailing weather, that a simple ensemble mean day (consisting of a mean of all data for each hour) gives a representative picture of energy partitioning between terms in the energy balance (Fig. 3) for the cloudless case.

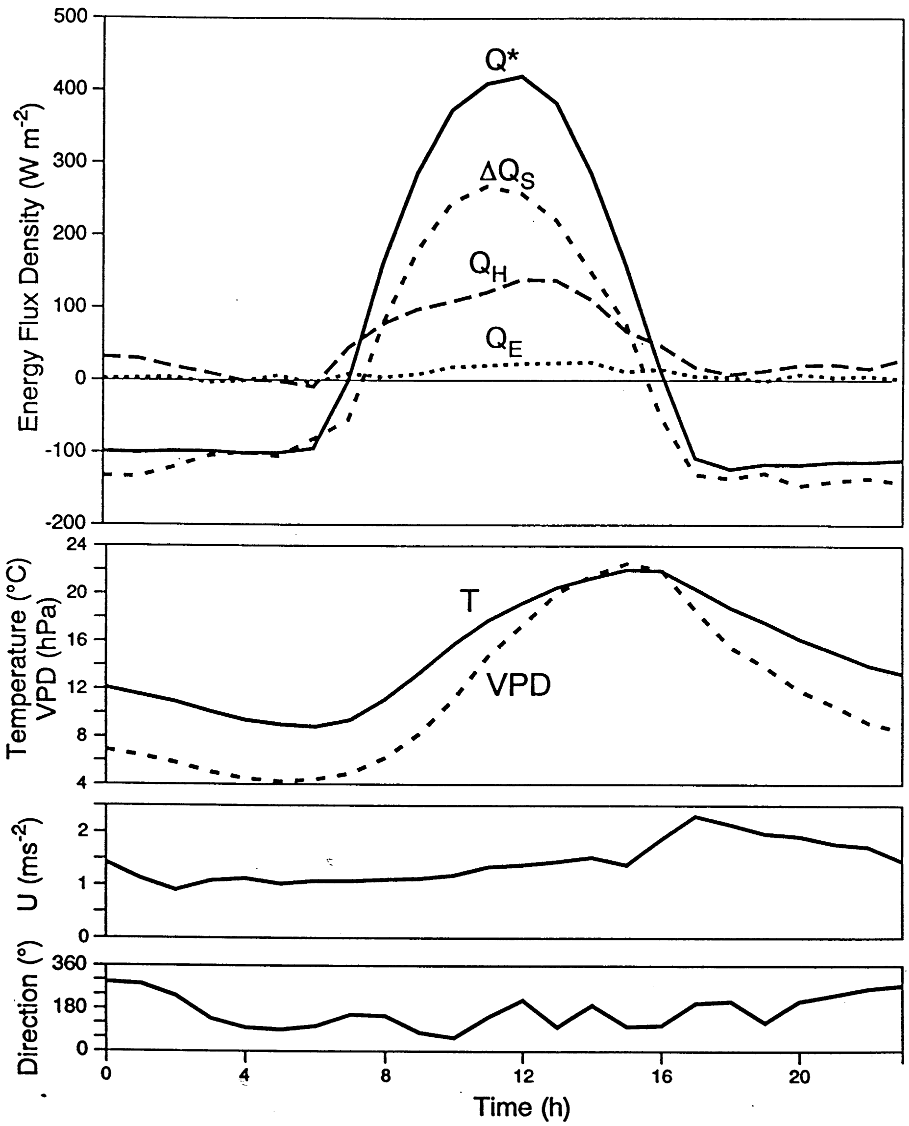

Fig. 3. Ensemble average fluxes for the School of Mines site in central Mexico City for six almost cloudless days in early December, 1993. Also included are the ensemble mean air temperature, vapour pressure deficit (VPD), and wind speed for the same period.

Table 1
Daytime ($Q^* > 0$) and daily (24 h) mean observed fluxes and flux ratios for cloudless and all-sky conditions at School of Mines (SM), Mexico City for hours when the wind direction at the midpoint in the hour is within the direction 0–180°. N is the number of hours of data. For the daily total missing time periods are filled into give 24 h values. Units of the fluxes are MJ m^{-2} d^{-1}, all others are non-dimensional

	N	Q^*	Q_H	Q_E	ΔQ_S	Q_H/Q^*	Q_E/Q^*	$\Delta Q_S/Q^*$	β	$Q_H/\Delta Q_S$	$(Q_H+\Delta Q_S)/Q_E$
Daytime ($Q^* > 0$)											
Cloudless	37	8.98	3.40	0.39	5.20	0.38	0.04	0.58	8.8	0.65	22.1
All-sky conditions	44	8.71	3.34	0.34	5.03	0.38	0.04	0.58	9.9	0.66	24.6
Daily total (24 h)											
Cloudless	72	3.64	3.65	0.35	− 0.36	1.00	0.10	− 0.10	10.4	− 10.1	9.4
All-sky conditions	81	3.38	3.61	0.31	− 0.54	1.07	0.09	− 0.16	11.6	− 6.73	9.9

A summary of energy balance statistics shows little difference between hours with cloudless skies versus the complete dataset (Table 1).

The daytime period is characterized by relatively low net radiation (average peak value slightly higher than 400 W m^{-2}, but never more than 440 W m^{-2}) despite these cloud-free, sub-tropical conditions. There are several possible reasons for this: the observation period is near the winter solstice, the polluted urban boundary layer attenuates shortwave radiation, the atmosphere is relatively thin and dry at this high altitude which reduces incoming sky radiation and aids the loss of longwave radiation, a feature which is further exacerbated by the high temperature of the urban surface (roof-top apparent temperature about 40–45°C near midday). Solar attenuation during the period was observed (as approximated by differences between SM and Plan Texcoco (PT) in the rural area to the east, Fig. 1). In the mean the reduction was about 8%, based on daily totals, but varied between 1 and 12% for single days. It seems less likely that the low Q^* is due to an anomalously high surface albedo. The buildings are constructed of cream or reddish-brown stone or grey concrete but roofs are mostly dark grey or brown and the shading and multiple reflections found in the street canyons are likely to increase absorption. The point deserves study.

At night the net radiative loss is large. Ensemble hourly average values range from about − 120 W m^{-2} just after sunset to about − 90 W m^{-2} near sunrise. Individual hourly values can be in excess of − 130 W m^{-2}. Again the relatively warm surface and the thin atmosphere are probably responsible for this large loss.

Evaporation and condensation are almost absent from the balance. By day hourly averages are always positive, but never exceed 45 W m^{-2}. Only about 4% of the daytime ($Q^* > 0$) net radiation is expended in evaporation (Table 1). Since there is ample energy and airflow, and a significant vapour pressure deficit in the afternoon (Fig. 3), the low evaporation is attributed to lack of available moisture. At night there is a tendency for weak evaporation to continue, but values are not significantly different from zero for most of the time. At no time did the surface wetness sensor on the SM roof indicate the presence of surface moisture (i.e. dewfall). Because evaporation continues throughout the night, on a daily basis it consumes about 9–10% of the daily net radiation (Table 1).

Given the small evaporation, greatest interest centres on energy sharing between the two sensible heat fluxes: conduction into the underlying buildings and ground (ΔQ_S), and convection to the air (Q_H). At this central city site, heat storage is the largest energy sink for most daylight hours. In the mean, the storage flux peaks before the net radiation (although on some days it remained large into the early afternoon), whereas the convective flux almost always reaches its maximum in the afternoon. As a result the role of the convective sink increases in importance through the daytime. Nevertheless, fully 58% of the total daytime net radiation is stored in the urban fabric, compared with 38% convected to the lower atmosphere (Table 1).

At night the average hourly heat release from storage is massive (Fig. 3). For most hours ΔQ_S is the sole source of energy for the system. Storage release supplies energy equivalent to between 1.0 and 1.3 times the net radiation; hence it is sufficient to support weak evaporation and a consistently upward-directed convective heat flux density at night. In fact, over the full 24 h period, urban heat storage has a net deficit, i.e. the system is cooling on a net basis, as expected during cloudless conditions in winter (Table 1).

The nocturnal partitioning of fluxes at SM is quite unlike that of most natural surfaces. The pattern is particularly well illustrated by the night of YD 338/339 (Fig. 4). Day 338 experienced partly cloudy conditions at midday, in the late afternoon and near midnight. The average hourly fluxes clearly show that Q_H stays positive through the entire period. Even at night it attains values

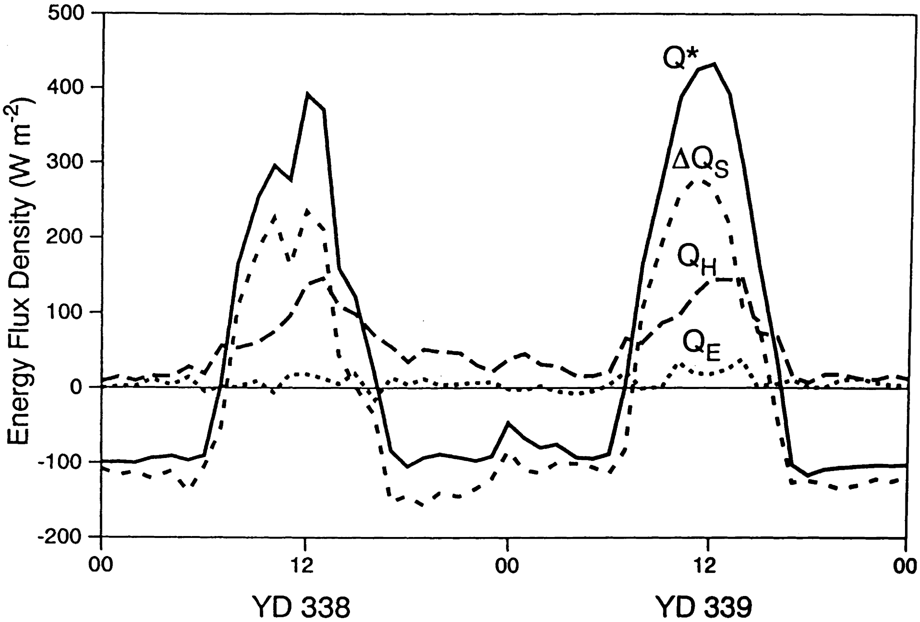

Fig. 4. Hourly average heat flux densities at the SM site on YD 338/339.

of 20–50 W m^{-2}. Small surges of Q_H were observed in the instantaneous trace at night. These seemed to be associated with increases in airflow (i.e., increased aerodynamic conductance) or increases in cloud cover (probably reducing the net longwave radiative loss). It is also possible that these surges are due to canyon "thermals". Air in the canyons is likely to be warmer than at roof-level because: the net longwave drain is reduced by the small sky view factor in the canyon, the air volume is bounded on three sides by warm surfaces, and air exchange and mixing is reduced by shelter and friction. The latent static instability inherent in this arrangement may be triggered by wind bursts into or across the top of the canyon, or by cooler air which slumps down off the roofs under-cutting the warmer canyon air. On the night of YD 340/341 a surge in Q_H kept values greater than 50 W m^{-2}, for several hours and peak bursts were as large as 85 W m^{-2}.

Given the small magnitude of the evaporative flux, Bowen ratio values are rather unstable, and hence do not give a smooth diurnal pattern. Most of the variability is due to occasional very small negative values of Q_E which are not significantly different from zero. Nevertheless, the following generalizations can be made about the course of the ensemble mean value of β. In daytime hourly values are typically in the range from 4 to 12 with a mean close to 10 (Table 1). Such high values, typical of desert conditions, are not entirely unexpected over a site with so little vegetation, but what is remarkable is that this occurs with such relatively low convective sensible heat fluxes (e.g. $Q_H \sim 0.38\ Q^*$). At night β remains positive because both turbulent fluxes, though small, are usually directed upwards.

When normalized by the net radiation, the course of each of the three fluxes is straightforward. Q_H/Q^* is positive throughout the daytime (0.29–0.51) and is mostly negative at night (typically about -0.04– -0.18) when the radiative and turbulent fluxes have opposite signs (Fig. 5). The course of the ratio Q_E/Q^* follows a similar pattern except that values are very small. The ratio $\Delta Q_S/Q^*$ remains positive both day and night, except near sunrise and sunset, when Q^* suddenly changes sign. It generally declines through the daytime from about 0.7 to 0.5, hops up to about 1.2 immediately after sunset, after which it drifts down to just below unity near sunrise (Grimmond and Oke, 1999a).

4. Discussion

4.1. Comparisons

At SM we see a system in which heat storage dominates, indeed it must be one of the most effective heat storage systems known. For the period when Q^* is positive the input to storage averages 155 W m^{-2}, which is 58% of the net radiation. For the longer period when Q^* is negative the rate of release from storage averages -121 W m^{-2}, which represents about 123% of the net radiation loss for that period. Since evaporation is almost

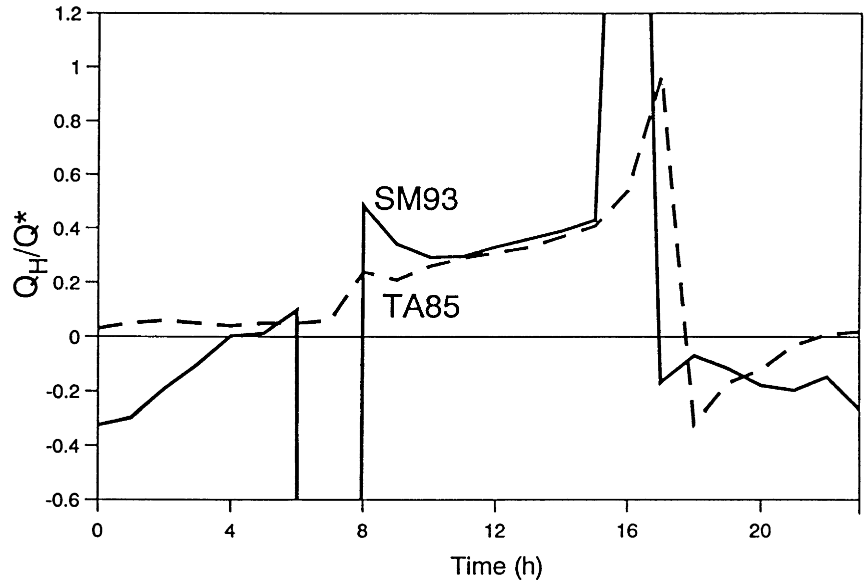

Fig. 5. Diurnal variation of the ratio $\chi = Q_H/Q^*$ at two sites in Mexico City. One is for the central city site on six mostly cloudless days in December 1993 (SM93), the other for the Tacubaya site on 15 cloudless days in February and March 1985 (TA85).

negligible the sensible heat sharing between the city and the air is a statement of the relative thermal admittances of the two systems. Clearly, at SM, conduction dominates over convection.

Only extensive dry and dense systems (e.g. concrete, asphalt, rock) and deep water bodies rival the central area of Mexico City in channelling that much of their net radiative forcing into heat storage. Given that a city has a "honeycomb" structure, with air included in the building interiors, streets and insulation of the walls and roofs, this is remarkable. Two characteristics in addition to dryness which aid this result are the large active surface area for absorption and the shelter provided by the canyon morphology. Storage is so effective that it is able to support an upward flux of sensible heat to the air at all times of the day and night. The availability of this heat store probably underlies the characteristic "tail" of high Q_H values seen in the late afternoon and must be the source of positive Q_H at night.

The ability to lock up heat by day, and release it in the evening and night, constitutes significant thermal inertia. The relatively high thermal admittance of the city core is probably not due to the thermal properties of the constituent building materials alone. It is likely to respond to the nature of the integrated system (landscape), including its characteristic surface morphology, especially its geometric form.

The daytime $\Delta Q_S/Q^*$ ratio of 0.58 is the largest of any urban area so far studied. Grimmond and Oke (1999a) show comparable values for residential districts in North American cities to range from 0.17 to 0.31 (Table 2). The same survey shows that a light industrial site in Vancouver, BC, consisting of one- and two-storey flat-roof buildings with only 4% vegetative cover, has a ratio of 0.48.

It has generally been supposed that as the proportion of urban land occupied by built, rather than vegetated, uses increases so does the ratio Q_H/Q^*. For example, Clarke et al. (1982) show a consistent increase in Q_H from a rural site (6% built) to an urban residential site (30% built) to an urban commercial site (84% built) in St. Louis. Oke (1988) reviews their findings, and results from other cities, and notes the same tendency which he links to surface water availability, because the Bowen ratio tends to increase along with the decrease in greenspace (although the role of garden irrigation has to be factored in). The SM results show that such statements are too simplistic.

As noted above, a site with similar energy partitioning to that at SM is a light industrial area in Vancouver, BC (Vl 92). It has about the same surface area given over to vegetation (A_v – 4%) and impervious cover (A_i – 32%) as SM, but the area of roofs is larger (A_r – 37%) and of walls smaller (A_w – 27%). The proportion of Q^* used in convection at Vl92 is slightly larger, and in storage slightly smaller, than at SM but otherwise the nature of energy partitioning is similar (Table 2). Thus there seems to be some convergence in results from two dry, heavily built-up sites, but if we try to extend this notion to the Tacubaya 1985 site (TA85) complications arise. The SM

Table 2
Flux ratios for daytime ($Q^* > 0$) conditions at two sites in Mexico City and other cities. The results are ordered according to the ability of the site to partition energy into sensible rather than latent heat (last column). All quantities are non-dimensional. Data from this study, Oke et al. (1992), Cleugh and Oke (1986) and Grimmond and Oke (1999a)

City	(Site year)	Land-use	UTZ[a]	Q_H/Q^*	Q_E/Q^*	$\Delta Q_S/Q^*$	β	$Q_H/\Delta Q_S$	$(Q_H + \Delta Q_S)/Q_E$
Mexico City, DF	(SM93)	Central city	A2	0.38	0.04	0.58	9.9	0.7	24.6
Mexico City, DF	(TA85)	Dense urban, mixed	A3	0.34					
Vancouver, BC	(V192)	Industrial	Do4	0.42	0.10	0.48	4.4	0.9	9.4
Vancouver, BC	(Vs92)[b]	Residential	Dc3	0.62	0.22	0.17	2.9	3.7	3.6
Vancouver, BC	(Vs89)[b]	Residential	Dc3	0.54	0.27	0.19	2.0	2.9	2.7
Vancouver, BC	(Vs83)[b]	Residential	Dc3	0.44					
Los Angeles, CA	(Sg94)	Residential	Do3	0.49	0.22	0.29	2.2	1.7	3.5
Tucson, AZ	(T90)	Residential	Do3	0.52	0.25	0.23	2.1	2.2	3.0
Los Angeles, CA	(A94)	Residential	Do3	0.43	0.26	0.31	1.4	1.4	2.8
Miami, FL	(Mi95)	Residential	Do3	0.42	0.27	0.30	1.6	1.4	2.7
Los Angeles, CA	(A93)	Residential	Do3	0.39	0.31	0.30	1.2	1.3	2.2
Sacramento, CA	(S91)	Residential	Do3	0.41	0.33	0.26	1.3	1.6	2.0
Chicago, IL	(C95)	Residential	Dc3	0.46	0.37	0.17	1.2	2.7	1.7

[a]UTZ – urban terrian zones according to the structural classification of Ellefsen (1990/91).
[b]Vs sites differ mainly due to moisture availability in each year: 1983 – moist, irrigated, 1989 – relatively dry but irrigated, and 1992 – drought, no irrigation.

and TA85 studies generally provide a good basis for comparison: the sites have the same total active surface area (Oke et al., 1992), both were conducted on cloudless days in the dry season, instrumentation for Q_H/Q^* was identical and the fluxes were measured directly so no assumptions are involved and normalization by Q^* accounts for radiation differences between the two studies. The main difference is that whereas SM has 99% of its plan surface area in built uses, TA85 is only 79% built, so water availability and evaporation are greater at Tacubaya. Despite this the daytime Q_H/Q^* ratios are closely matched at the two sites (Table 2), even tracking together closely in daytime (Fig. 5). This does not support the notion of a simple relation between built/green fraction and Q_H/Q^*. However, there are differences at night sufficient to cause the daily Q_H/Q^* ratio at SM to be 1.07 (Table 1) whereas at Tacubaya it is only 0.59. A ratio greater than unity at SM, indicates net daily heating of the atmosphere, made possible by net removal of heat from storage. This may have been in response to synoptic changes or it may just be part of the seasonal cycle.

Extending to less heavily built-up sites does not clarify matters. For example, of the seven other sites in six cities surveyed by Grimmond and Oke (1999a), none had daytime Q_H/Q^* ratios less than SM (Table 2). The closest (0.39) was the Arcadia suburb of Los Angeles (A93), but in physical characteristics this site is almost the opposite of SM; A93 is heavily vegetated and irrigated. The largest ratio (0.62) was observed over a residential suburb of Vancouver, when the surface was relatively dry because of drought and a ban on garden irrigation. The results from Tucson, a city in a dry tropical climate might have been expected to show similarities with SM, but in fact, the residential site in Tucson shows more similarity with other North American residential sites, than it does with SM (Table 2). This may be related to the lower density of development and although not large, the use of irrigation, in Tucson. At this stage it is not obvious how to weight the influence of these two controls.

We conclude that any control on the convective heat flux exercised by measures of city morphology, such as surface geometry or amount of impervious cover, does not appear to be linear. It seems probable that whilst in general Q_H/Q^* is likely to increase with the fraction of the surface covered by built/impervious surfaces, any relation is modulated by the availability of water and the effiicency of storage. Both are able to siphon energy away from the convective sensible heat flux, and into one of Q_E or ΔQ_S. Therefore, perhaps only to the extent that water availability and storage efficiency are correlated, can we expect to find a relation. These matters are explored further in Grimmond and Oke (1999a).

The values of β at SM (Table 1) are the largest so far reported in any city. The sites closest in magnitude are found in Vancouver (Table 2); one is a sparsely vegetated, light industrial site (Vl92), the second, is a residential site (Vs92), under the influence of a summer drought when no irrigation was permitted (Grimmond and Oke, 1999a). Positive nocturnal values of β, associated with upward convective sensible and latent fluxes, have been reported before (Oke et al., 1972, 1992; Oke, 1978; Kalanda et al., 1980; Ching et al., 1983). We resist detailed comparisons of β and other energy balance terms between SM and TA85, because the methods used to obtain Q_E were different (at TA85 Q_E was the residual in an energy balance which included parameterized ΔQ_S).

4.2. Urban climatic implications

The implications of high thermal inertia in central city areas, for urban–rural energy balance differences, requires knowledge of the associated rural value. This was not directly assessed in Mexico City but the following is forwarded as a reasonable scenario. Given the observed attenuation of incoming solar radiation (about 8%) it would take a significant decrease in albedo, and/or increase in incoming longwave radiation, to avoid the city having a net radiative deficit compared with its surroundings. In the dry season evaporation is likely to be very small both inside and outside the city, so this is not a large factor. Heat storage at SM is large by any standards and certainly much larger than that of the old lake sediments of the rural areas surrounding Mexico City in the dry season.

Therefore, in summary, the city with possibly less radiative input, and much more of its energy sequestered in

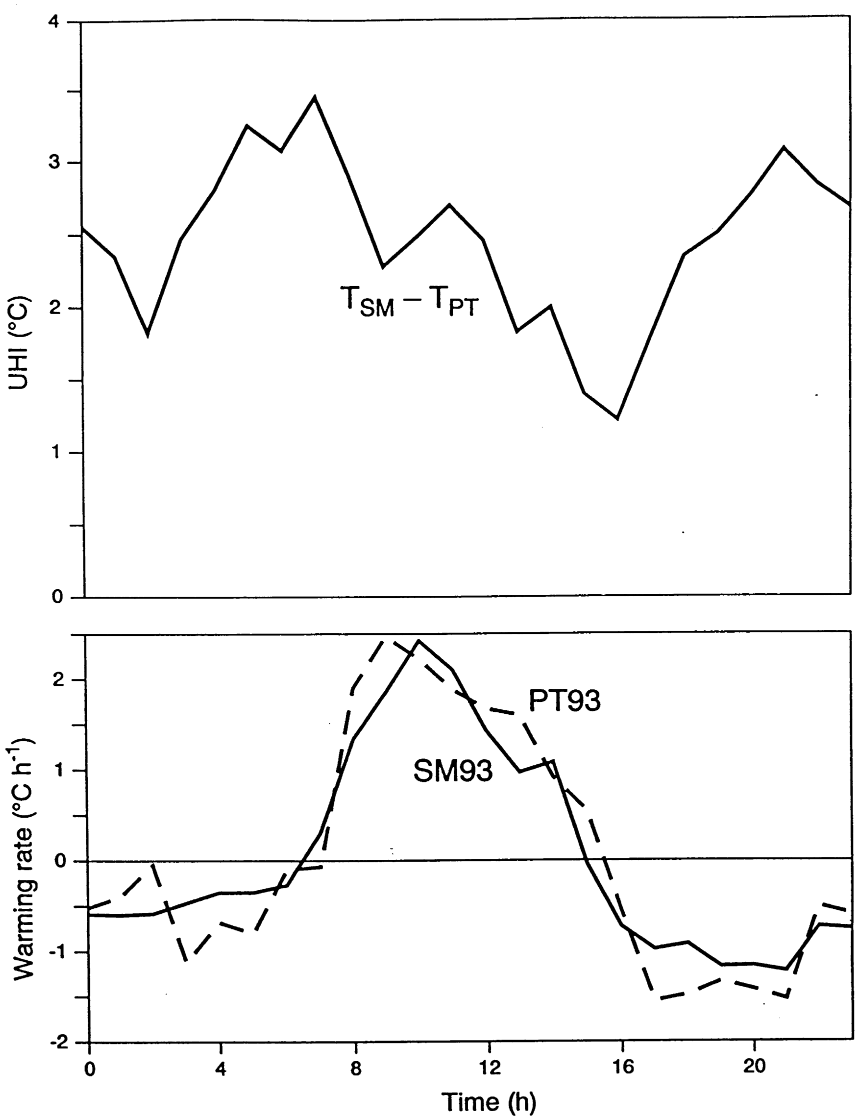

Fig. 6. Top: the UCL urban heat island of Mexico City. Bottom: the associated warming/cooling rates of the urban (SM) and rural (Plan Texcoco, PT) sites comprising the UHI. Ensemble mean values for the observation period in 1993.

storage, might well support a smaller convective heat flux than its rural environs. This is not what conventional wisdom has held. Other densely built-up and sparsely vegetated central city sites probably behave energetically in a similar manner to that of Mexico City. In fact, it could be argued that city centres around the world are climatically more like each other than their extremely diverse rural surroundings (forests, agricultural fields, swamps, deserts, scrub, bare soil, rock, snow, water, etc.). Hence it is possible that $Q_{\mathrm{Hurban}} < Q_{\mathrm{Hrural}}$ in other cities, even those surrounded by relatively moist countryside. Since the strength of Q_{H} is the prime determinant of the depth of the mixed layer this possibility has potentially important implications for air quality in cities.

The storage, and hence thermal inertia, findings at SM in 1993 are derived from fluxes observed above roof-level and depend on spatially integrated properties at the local- or meso-scale. Appropriate urban–rural temperature differences for the same period are available from thermometers mounted at 6 m above roof at SM, and 6 m above ground, at the Plan Texcoco (PT) rural site (elevation 2250 m a.m.s.l.). The average hourly urban heat island (UHI) for the 1993 observation period and the warming/cooling rates for the two sites are given in Fig. 6. The most striking point is that the UHI is positive at all hours (a condition prevailing throughout the year; Jáuregui, 1997) and varies only between 1.0 and 4.6°C. There is a weak diurnal cycle, with highest values near sunrise and lowest values near sunset. Greater thermal inertia in the city compared with the countryside implies that the amplitude of the diurnal surface temperature wave is less in the city and its phase is delayed. In the 1993 case the daily amplitude at SM is about 1.6° less, but there is no lag. The warming/cooling rates at the two sites are surprisingly similar (Fig. 6) so the UHI is mostly due to a simple upward shift in the mean air temperature of the city. This is consistent with an environment dominated by sensible heat uses, especially at night, when storage release is very large and there is an almost continuous upward-directed convective heat flux.

Again it is difficult to make meaningful comparisons with earlier studies. The closest comparable work used thermometers placed 1.5 m above the roof of a ~ 12 m building at Tacubaya, and the same height above a ~ 5 m building at the International Airport (Fig. 1) for January, 1979 (see Fig. 7 in Jáuregui, 1986). The maximum UHI from this pair of sensors occurred at about the same time, and was about the same magnitude as that in 1993, but there was a negative (cool) UHI of about 1°C during the afternoon, in the 1979 set. Oke et al. (1992) offered the suggestion that this may be due to the Tacubaya area acting as an oasis – irrigation is practised and evaporation is a significant part of the energy balance. But it is also probable that the thermal climate of both locations were affected by the buildings themselves so caution is advised.

5. Conclusion

Energy balance measurements near the centre of Mexico City in the dry season show an environment dominated by sensible heat, and in particular one which stores large amounts of heat in the building fabric by day, and releases it again at night. The magnitude of daytime heat storage uptake seems to be sufficient to dampen the convective heat flux to the point where it uses no larger fraction of the daytime net radiation than is found at less heavily developed and moister urban sites. The nocturnal release of heat stored in the urban fabric is big enough to support a weak convective sensible heat flux throughout the night (see also Casadio et al., 1996). Evaporation is so weak at all times that despite the relatively small daytime convective heat flux, the Bowen ratio is large.

This site represents a relatively extreme environment: it is dry, made of dense materials and has a large active surface area. It was expected that these characteristics provided an opportunity to extend relations found over less intensely developed urban sites. This proved not to be the case. It appears that the competing effects of surface characteristics such as water availability, active surface area and thermal properties of the materials interact in a complex manner that will take time to unravel.

6. Dedication and Acknowledgements

This paper is dedicated to the memory of Günter Zeuner who took the first energy balance observations in a tropical city at Tacubaya.

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