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# Comparison of Modelled and 'Measured' Heat Storage in Suburban Terrain

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**Abstract**

Energy balance data including several days of directly-measured sensible and latent heat fluxes from a suburban area are presented. Results confirm the magnitude and general form of heat storage by cities as suggested by previous, but less comprehensive, studies. For the first time they also permit comparison between the predictions from storage heat flux models with the 'true' residual of the energy balance. In comparison with the OHM urban heat storage model the observed flux reaches an earlier daytime peak, and exhibits a more pronounced diurnal hysteresis.

**Zusammenfassung**

**Vergleich berechneter und 'gemessener' Speicherwärmeflüsse in vorstädtischem Gebiet**

Der Energiehaushalt eines Gebietes mit vorstädtischem Charakter, erfaßt mit mehrtägigen direkten Messungen der sensiblen und latenten Wärmeflüsse, wird vorgestellt. Die Resultate bestätigen die Ergebnisse früherer, unvollständiger Studien bezüglich der absoluten Werte und des Tagesgangs des Bodenwärmeflusses (gespeicherte Bodenwärme). Diese Studie erlaubt den ersten Vergleich berechneter und gemessener (als Differenz der Energiebilanz) Speicherwärmeflüsse. Verglichen mit dem OHM Stadtbodenwärmeflußmodell erreichen die gemessenen Energieflüsse ein früheres Tagesmaximum und weisen eine ausgeprägte Tageshysterese auf.

## 1 Introduction

The determination of the heat storage change by cities has been a topic of attention and controversy for the past few years. Unlike the case of spatially-homogeneous rural surfaces the evaluation of this flux is exceedingly difficult for urbanized terrain. This is because the active surface of a city consists of a three-dimensional, patchwork quilt-like system of individual surfaces many of which have widely divergent physical properties (e.g. thermal conductivity, heat capacity, etc.).

The amount and temporal dynamics of heat storage by cities are important characteristics in urban meteorology. First, because the greater thermal inertia of urban areas is usually mooted to be one of the central reasons underlying the existence of the heat island phenomenon. And second, because it is often necessary to have knowledge of this relatively large term in the energy balance when evaluating the turbulent fluxes of heat and moisture.

In the past, three methods have been employed to obtain values of the rate of heat uptake and release by urban systems. First, one can attempt to measure the flux of heat into and out of each individual surface type found in the city and combine them with an appropriate weighting scheme. If this is to be comprehensive it requires an immense sampling effort. There are a few examples of this approach, usually for a restricted subset of common surfaces (Yap, 1973; Taesler, 1978; Doll et al., 1985; Kerschgens and Hacker, 1985; Kerschgens and Drauschke, 1986; and Kerschgens and Kraus, 1990).

Second, if all other terms are measured, the storage heat flux can be obtained as the residual of the energy balance:

$$\Delta Q_S = Q^* + Q_F - Q_H - Q_E - \Delta Q_A \qquad (1)$$

where $Q^*$ is the net-all wave radiation flux density; $Q_F$ the anthropogenic heat flux density; $Q_H$, $Q_E$ are the turbulent sensible and latent heat flux densities, respectively; and $\Delta Q_A$ is the net horizontal heat advection. Here, $\Delta Q_S$ is the net uptake or release of energy from the urban system extending from above roof-level to a depth in the ground where net heat exchange over the period of study is negligible, and the remaining energy balance components are the respective fluxes through the top of the same volume (Oke, 1988). A potential problem when evaluating heat storage by way of the residual approach is that $\Delta Q_S$ becomes the sink for all errors contained in the other terms, including possible advective effects.

Determination of $\Delta Q_S$ from (1) also requires reliable turbulent flux measurements. Oke et al. (1989) recommend eddy correlation as the most reliable approach, followed by Bowen ratio-energy balance methods. Whilst it is quite common to measure the sensible heat flux density using the eddy correlation technique similar measurements of the latent heat flux density in the city are rare (one short-term study by Ching et al., 1983). Thus reliable closure of the urban energy balance is still awaited. In several observation programmes the turbulent heat fluxes have been evaluated using gradient Bowen ratio measurements. Both fluxes were evaluated by Kalanda et al. (1980), Oke and McCaughey (1983), Kerschgens and Hacker (1985), Oke and Cleugh (1987), Kerschgens and Kraus (1990), and Grimmond and Oke (1991), and evaporation by using the gradient Bowen ratio in combination with eddy correlation values of $Q_H$ by e.g., Oke and Cleugh, 1987; Grimmond et al., 1991; and Grimmond, 1992. However, the determination of the gradient Bowen ratio, based on measurements of vertical differences of temperature and humidity, assumes equality of the eddy diffusivities for heat and moisture. This prerequisite cannot be expected and is not observed in the urban atmosphere (Roth, 1993; Roth and Oke, 1993). It follows that (1) only produces reliable results if both sensible and latent heat fluxes are measured directly. This study presents the first full set of data including (a) the direct evaluation of $Q_E$ and (b) the simultaneous direct measurement of both $Q_H$ and $Q_E$ for an urban area.

Third, a modelling approach has also been used. The most promising method seems to be to parameterize $\Delta Q_S$ in terms of the primary forcing function, the net radiation, and a description of the surface. Grimmond et al. (1991) formulate the following objective hysteresis model (OHM):

$$\Delta Q_{SP} = C_1(Q^* + Q_F) + C_2\frac{\partial(Q^* + Q_F)}{\partial t} + C_3 \quad (2)$$

where

$$\partial(Q^* + Q_F)/\partial t = 0.5\,[(Q^* + Q_F)_{t+1} - (Q^* + Q_F)_{t-1}]$$

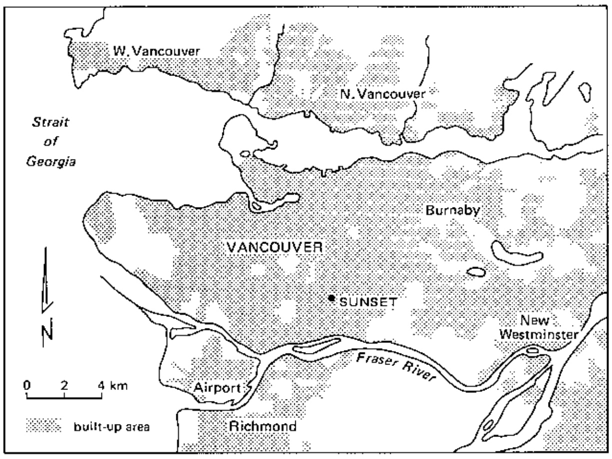

**Figure 1** Location of the observation site 'Sunset' and its regional setting in the Greater Vancouver Metropolitan Area.

and the subscript P stands for paramterized and t is time. Determination of the empirical coefficients involves a detailed description of the surface. Using data from Gimmond (1988) $C_1 = 0.38$, $C_2 = 0.27$ hr and $C_3 = -29.3\ \mathrm{W\,m^{-2}}$ at the present site. The second term in (2) is the hysteresis loop departure from the linear relation. For hours when $Q^* + Q_F < 0$ the coefficients are 0.98, 0.004 hr and 2.5 $\mathrm{W\,m^{-2}}$ for $C_1$, $C_2$ and $C_3$, respectively (Grimmond, 1988).

The first objective of the present study is to 'measure' the storage flux as the residual in Eq. (1) using directly measured radiant and turbulent (both sensible and latent) heat fluxes. The second aim is to evaluate the performance of the OHM heat storage model (Eq. (2)) by comparing its output against these 'measured' values.

## 2 Experimental

The suburban study area (called 'Sunset') is located in south Vancouver, B. C., Canada (Figure 1). the 1–2 story residential houses surrounding the site have a mean height of 8.5 m. Within a 2 km radius circle centered on the site about 43 % of the active area (which is approximately 1.5 times the plan area) is greenspace, 13 % is roof, 11 % is paved and 33 % is walls (or canyon) (Grimmond et al., 1991).

The instruments were mounted on a 30 m micrometeorological tower. The net radiation $Q^*$ was measured with a pyrradiometer (Swissteco, Model S-1) at an effective height of $z' = 19$ m (22.5 m above ground and allowing 3.5 m for the zero-plane displacement height). Typical measurement errors for net pyrradiometers are 3–4 % (Latimer, 1972). At the same height a one-dimensional sonic anemometer and fine-wire thermocouple, SAT (Campbell Scientific, Model CA27T) measured the vertical velocity and temperature fluctuations used to compute $Q_H$. A krypton hygrometer, KH (Campbell Scientific, model KH20) sensed the humidity fluctuations, and together with the vertical velocity from the SAT, provided the data to calculate $Q_E$. The signals used in the eddy correlation analysis were low-pass filtered with a cut-off frequency of 10 Hz, sampled at 5 Hz and averaged over three 20 min periods to give a one hour average.

The measurement of the latent heat flux using the KH is affected by the presence of atmospheric oxygen. Because of the strong sensitivity of the krypton line to oxygen this flux is likely to be underestimated. In the present study the data were corrected for this effect using the procedure of Tanner and Green (1989). In addition a vapour flux correction (due to density effects because of the vapour transport by a small vertical wind) was applied (Webb et al., 1980). Of the two corrections the oxygen correction is generally more important; together they increase the latent heat flux by 30 to 60 %. The largest corrections are necessary during hours with large sensible heat fluxes because both correction terms are directly dependent on the magnitude of $Q_H$.

Additional error sources in the measurement of the turbulent fluxes using fast response sensors can arise from sensor-induced flow distortion and spatial averaging. Massman et al. (1990) show that a three-dimensional sonic anemometer is subject to shadowing effects (caused by blocking of the flow by the wind-sensing transducers) which results in an underestimation of the vertical wind speed by up to 16 %. This subsequently affects the computation of $Q_H$ and $Q_E$ by the same amount. Since the one-dimensional SAT used here is much less bulky, the analogous correction would also be much smaller. In fact the w statistics from the SAT sensor were compared with those from a three-dimensional sonic anemometer which was mounted within 1 m at the same height and whose signals were fully corrected for flow distortion and shadowing. Agreement between the two was very good. Flow distortion does not necessarily result in underestimation of fluxes. The SAT-KH sensor combination was designed to be vertically-symmetric about its horizontal mid-plane to minimize crosstalk from the horizontal flux, following recommendations by Wyngaard (1988). This may result in flow-blockage which amplifies the vertical wind velocity (Wyngaard, 1988). However, due to the absence of appropriate wind tunnel data no quantitative error estimates are possible.

The underestimation of fluxes due to spatial averaging was assessed using the respective spectral transfer functions; in the case of (1) vertical wind for averaging over the path length (Moore, 1986), (2) humidity for averaging over the volume between the sensor and detector (Massman et al., 1990) and (3) latent heat flux for the lateral distance between the wind and humidity sensors (Moore, 1986). (No such correction is necessary for sensible heat since the location of the temperature sensor is very close to the SAT vertical wind path). Using the relevant dimensions for (1) 0.1 m, (2) spacing = 8 mm, diameter = 7.7 mm and (3) 0.12 m, it can be shown that signal degradation only occurs at frequencies ($f = nz'/U > 1$, where n is natural frequency and U is mean wind speed) above which the cospectra contain less than 10 % of the total energy (Roth and Oke, 1993). This result is consistent with Wyngaard (1988) who shows that a sensor separation equal to the path length does not cause additional flux loss. The result is also aided by the relatively large effective sensor height used here ($z' = 19$ m).

From the above it is concluded that $Q_H$ can be measured to a satisfactory degree of accuracy. The largest uncertainty lies in the corrections used for $Q_E$. In particular, the absorption coefficient for oxygen is not well known (B. Tanner, 1990; personal communication).

Further consideration has to be given to the determination of the urban energy balance. It is important to place the sensors well above the roughness elements (but still within the surface layer) to ensure that observations are representative of the local scale (Oke et al., 1989). Based on analyses of (co)spectral and turbulence statistics data of wind, temperature and humidity from the present site (Roth et al., 1989; Roth, 1993; and Roth and Oke, 1993), it is concluded that the observation height employed is probably sufficient for the sensors to measure the integrated effects of the surfaces comprising the surrounding suburban land use. This is especially true when considering that the temporal averages used are linked to a spatial average (Schmid et al., 1991). Finally, if a (spatially) internally-consistent energy budget is to result, the surface source areas influencing the separate measurements of the terms in (1) must coincide. This was achieved using the scheme discussed in detail in Schmid et al. (1991).

The approximate size of the anthropogenic heat flux density can be assessed using the methods detailed in Grimmond (1992). Based on her analysis for the same site for early summer, the day was subdivided into two periods with the following values: 11 W m$^{-2}$ (0600–2300 LAT) and 7 W m$^{-2}$ (2300 – 0600 LAT). The horizontal advection term in Eq. (1) is difficult to estimate, but based on Steyn's (1985) analysis of data from the same tower, it is considered small enough to be neglected.

The SAT and KH fast response sensors were part of an extensive turbulence research programme (Roth, 1993; Roth and Oke, 1993). As a result they were subject to frequent inspections and only operated during specific meteorological conditions. As a consequence, the observations obtained during 7 days starting on July 6, 1989 do sometimes not include the full diurnal cycle of the energy balance components. The main daytime average weather characteristics during the measurement period are summarized in Table 1.

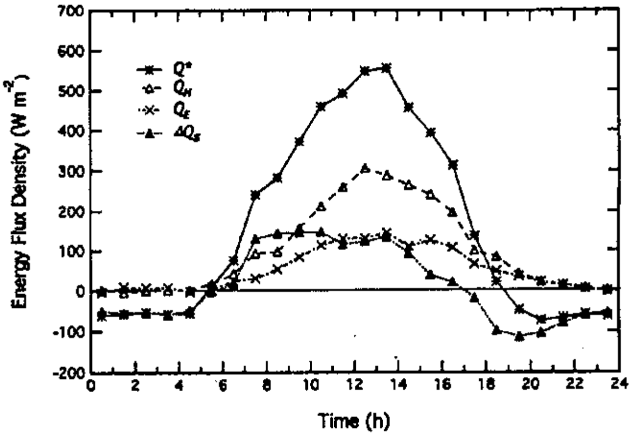

**Figure 2** Ensemble average energy balance at the Sunset suburban site in Vancouver, B. C. for portions of 7 days in July 1989. Note – $\Delta Q_S$ is the residual in Eq. (1), $Q_F$ values are too small to plot and $\Delta Q_A$ has been neglected.

## 3 Energy Balance Partitioning

The diurnal variation of the hourly ensemble averages of the energy balance components is given in Figure 2. Observations from individual days were of similar nature with respect to the trend and magnitudes of the averaged fluxes, but they are marked by more variability. Unlike the measurements by e.g., Cleugh and Oke (1986) and Grimmond (1992) the peak in Q* is observed somewhat later than usual. This may be due to the small sample size which includes a variety of cloud conditions (Table 1). Similar to previous studies of suburban sites in temperate climates the net radiative input is mainly dissipated as sensible heat ($Q_H + \Delta Q_S$). The latent heat flux peaks in the early afternoon and similar to $Q_H$ remains large and positive until close to midnight (Figure 2). Whereas the 'tail' in the curve of the sensible heat flux is often observed, the $Q_E$ tail is a less characteristic feature of suburban sites (e.g. it is not present in the results from Cleugh and Oke, 1986 or Grimmond, 1992). However, comparison with previous studies is difficult because Figure 2 includes the first directly measured latent heat fluxes. In the other studies $Q_E$ was estimated using a residual approach with modelled $\Delta Q_S$ (e.g. Cleugh and Oke, 1986) or the Bowen ratio-energy balance method (e.g. Grimmond, 1992). The $Q_E$ tail may be a result of the large energy release from heat storage (thus providing energy for evapotranspiration) which is augmented by the still unstable atmosphere. A similar process has been suggested by Kalanda et al. (1980) to explain the $Q_H$ tail.

After midnight the storage heat flux supplies all of the heat in response to the net radiative deficit. For a few hours after sunrise $\Delta Q_S$ becomes the most important sink for the radiative input. This may be

**Table 1** Dates and daytime average weather characteristics during the measurement period in July 1989.

| Date (July) | T (°C) | $\bar{q}$ (g m$^{-3}$) | U (m s$^{-1}$) | $\bar{\varphi}$ (degrees) | Cloud cover |
|---|---|---|---|---|---|
| 6 | 18–21 | 8.0– 9.0 | 3.0–4.0 | 240–290 | some Sc |
| 7 | 16–22 | 8.3–11.0 | 1.5–4.0 | 100–230 | dense Sc |
| 11 | 18–22 | 9.8–11.-0 | 2.0–4.7 | 220–270 | clear |
| 12 | 19–28 | 10.0–11.7 | 1.5–8.0 | 240–300 | Cu/Ac |
| 13 | 19–21 | 10.6–11.0 | 3.0–3.6 | 160–190 | clear |
| 14 | 17–21 | 9.5–11.2 | 1.2–3.0 | 100–210 | clear w/Cu |
| 15 | 16–18 | 8.3– 9.0 | 4.0–6.5 | 140–160 | Sc |

T = temperature, $\bar{q}$ = absolute humidity, U = wind speed, $\bar{\varphi}$ = wind direction. Sc = stratocumulus, Cu = cumulus, Ac = altocumulus.

due to the favourable angle of incidence of vertical walls with respect to the sun at a time when the turbulent boundary layer is still relatively shallow. $\Delta Q_S$ peaks 3–4 hours before $Q^*$ and declines through the afternoon and becomes a source of heat for the system about 2 hours before $Q^*$ reverses sign. In the evening $\Delta Q_S$ becomes the major source of heat which seems to support turbulent fluxes directed up into the atmosphere until midnight.

Because of the temporal differences between the storage heat flux and the net radiation, it is interesting to study the behaviour of the ratio $\lambda = \Delta Q_S/Q^*$ through the diurnal cycle. The present observations are compared with data from the 'Sunset (1978)' study (Oke and Cleugh, 1987) in Figure 3a. In the latter $\Delta Q_S$ is also obtained as the energy budget residual, however, $Q_E$ is derived using the gradient Bowen ratio in combination with eddy correlation values of $Q_H$. The present daytime results differ and show a higher ratio in the morning followed by a steady decrease until late afternoon. The large heat storage release, occurring just after the $Q^*$ sign reversal in the evening, results in a large positive peak in $\lambda$, which is particularly pronounced in the present data. Later in the night the radiative loss is almost completely supplied from the storage heat reservoir ($\lambda \approx 1$). The ratios during the transition periods are unstable but energetically inconsequential. The same is generally true for the data plotted in Figures 3b and c.

Although the focus of the present paper is on the storage heat flux, it is also interesting to investigate the diurnal pattern of other ratios involving energy balance components. The nature of the asymmetry in $Q_H$ is displayed in Figure 3b which shows the diurnal variation of $\chi = Q_H/Q^*$. This is a ratio of two important energy fluxes and is relevant to air pollution dispersion modelling. $Q_H$ is a controlling parameter for the evolution of the planetary boundary layer height which determines the mixing volume available for the dispersion of pollutants. Note that both energy components are directly measured in all studies plotted in Figure 3b. Similar to previous observations $\chi$ increases from the morning towards the evening. This can be attributed to the progressive decrease in the resistance of the urban boundary layer to sensible heat transfer. Because the comparisons include data from different times of year, and therefore daylength, the ends of the curves will not necessarily match (same is true for Figure 3c).

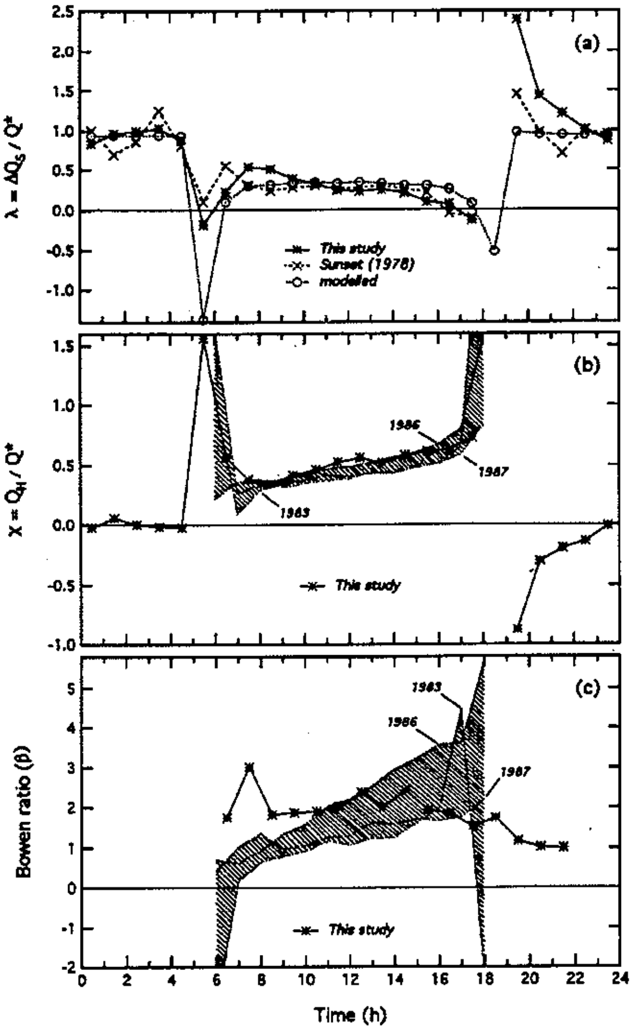

**Figure 3** Diurnal variation of the ensemble average ratios (computed as the ratio of the sums of the respective fluxes). (a) $\lambda = \Delta Q_S/Q^*$, (b) $\chi = Q_H/Q^*$ and (c) $\beta = Q_H/Q_E$ from the present and previous studies at the Sunset suburban site. The hatched areas in (b) and (c) give ranges of previously measured summer time values at the Sunset site (individual years 1983, 1986 and 1987 are indicated by dotted lines and taken from Cleugh and Oke, 1986, Cleugh, 1990 and Grimmond, 1992, respectively).

The average diurnal variation of the Bowen ratio $\beta$ for the present and previous studies is shown in Figure 3c. The difference in years, sensors and methods used to obtain $Q_E$ suggests that the results from the different studies should be compared with caution. $Q_E$ is derived as the energy budget residual and using a linear model for $\Delta Q_S$ in 1983. In 1986 and 1987 it follows as the energy budget residual using OHM and from the Bowen ratio-energy balance approach respectively. The data in Figure 3c illustrate the range of conditions that can be observed at this suburban site.

## 4 'Measured' vs Modelled Storage

The storage heat flux in Figure 2 is the first of its kind for an urban surface. This presents the opportunity to test the validity of $\Delta Q_{SP}$ estimates calculated using OHM (Eq. (2)). Values of both $\Delta Q_S$ and $\Delta Q_{SP}$ for the ensemble day are given in Figure 4a. They differ in three ways: 1) in the morning $\Delta Q_S$ is larger and reaches an earlier peak than $\Delta Q_{SP}$; 2) during midday and in the afternoon $\Delta Q_S$ is smaller than predicted by the model; and 3) a marked dip in $\Delta Q_S$ (large heat release from storage) just after the evening transition period is not represented in $\Delta Q_{SP}$.

Figure 4b further exemplifies the conclusion that OHM estimates adequately represent the mean heat sharing between $\Delta Q_{SP}$ and Q* (i.e. the slope) but are relatively poor at tracking the diurnal hysteresis effect (i.e. the quasi-elliptical loop). Clearly the time lags produced by the thermal inertia of the real system are larger than those given by the model. This also shows up in the modelled values of the ratio λ (Figure 3a) which fail to mimic the diurnal partitioning.

A word of caution is also appropriate. Although the 'measured' heat storage in the present study represents the most extensive data sets of its kind, it still cannot be regarded as fully representative of summertime conditions at the Sunset sit. The set is not large enough to allow filtering by cloud cover which introduces sources of variability and the important morning transition period is only represented by a few samples. Nevertheless the present measurements strongly suggest OHM does not fully predict several temporal features associated with the relatively strong hysteresis effect in the 'measured' data. Similar differences have been observed or deduced in previous studies. Namely, Grimmond et al. (1991) infer that (1) the phase in $\Delta Q_{SP}$ may be delayed by about one hour and (2) $\Delta Q_{SP}$ underestimates the storage release just after sunset. Grimmond et al. (1991) reach their first conclusion by comparing $\Delta Q_{SP}$ with two other models, one of which obtains the storage heat flux from a combination of appropriately weighted heat storage fluxes through two typical surfaces, a paved parking lot and a lawn (Kerschgens and Hacker, 1985) and the other from the sum of the heat content changes of all components of the urban system (Kerschgens and Kraus, 1990). The data necessary to evaluate these two models were gathered by their originators in Bonn, FRG during parts of two days. Compared to $\Delta Q_{SP}$ these two models find that the peak heat storage input is larger and observed about two house earlier. In the evening the negative peak in all three models occurs at around the same time but $\Delta Q_{SP}$ is again smaller.

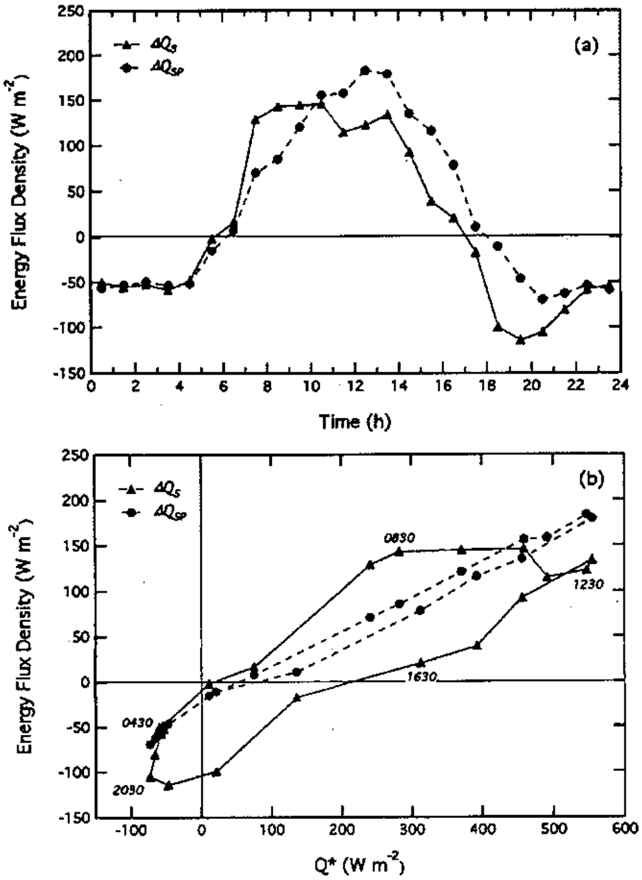

**Figure 4** (a) Ensemble average values of 'measured' $\Delta Q_S$ from Eq. (1) and modelled $\Delta Q_{SP}$ from OHM (Eq. (2)), and (b) the same storage data plotted as hysteresis loops between heat storage and net radiation.

A major advantage of OHM is that it provides an objective means of modelling heat storage patterns of a very complex system in terms of an energy flux and simple surface descriptors both of which are relatively simple to obtain. This is achieved by combining independent data sets involving simultaneous measurements of storage heat flux and net radiation for a range of surface materials encountered in the urban environment. One of the limitations of this approach, however, results from the sparse data available to represent the individual urban surface types. Grimmond et al. (1991) point out that their combined regression coefficients for the roof tops are based on only two studies which lead to disquietingly different coefficients. In particular $C_2$, which accounts for the hysteresis effect

(Eq. (2)), is not well defined. Therefore the value used in the current model may be in error.

The results from the present study also suggest the possibility that the geometry of the three-dimensional urban surface plays an important role in the timing of the heat storage uptake and release, i.e. that the model neglects the fact that some of the surfaces are in a preferential position with respect to the incident radiation at certain times of the day and therefore misses some of the heat storage uptake and release. Grimmond et al. (1991) were concerned that the model neglects the east-west aligned walls since the canyon parameterization (based on data from Nunez, 1974) is only for a north-south canyon. However, the recent results of Yoshida et al. (1991) suggest similarly small hysteresis for an east-west canyon. Therefore, whilst errors in the coefficients for roofs and canyons potentially can have a large influence (note their large active surface area at the 'Sunset' site) it is not possible to pinpoint the main source of discrepancy until there are better estimates of the coefficients and deeper understanding of the relationships and how to properly model temporally varying influences.

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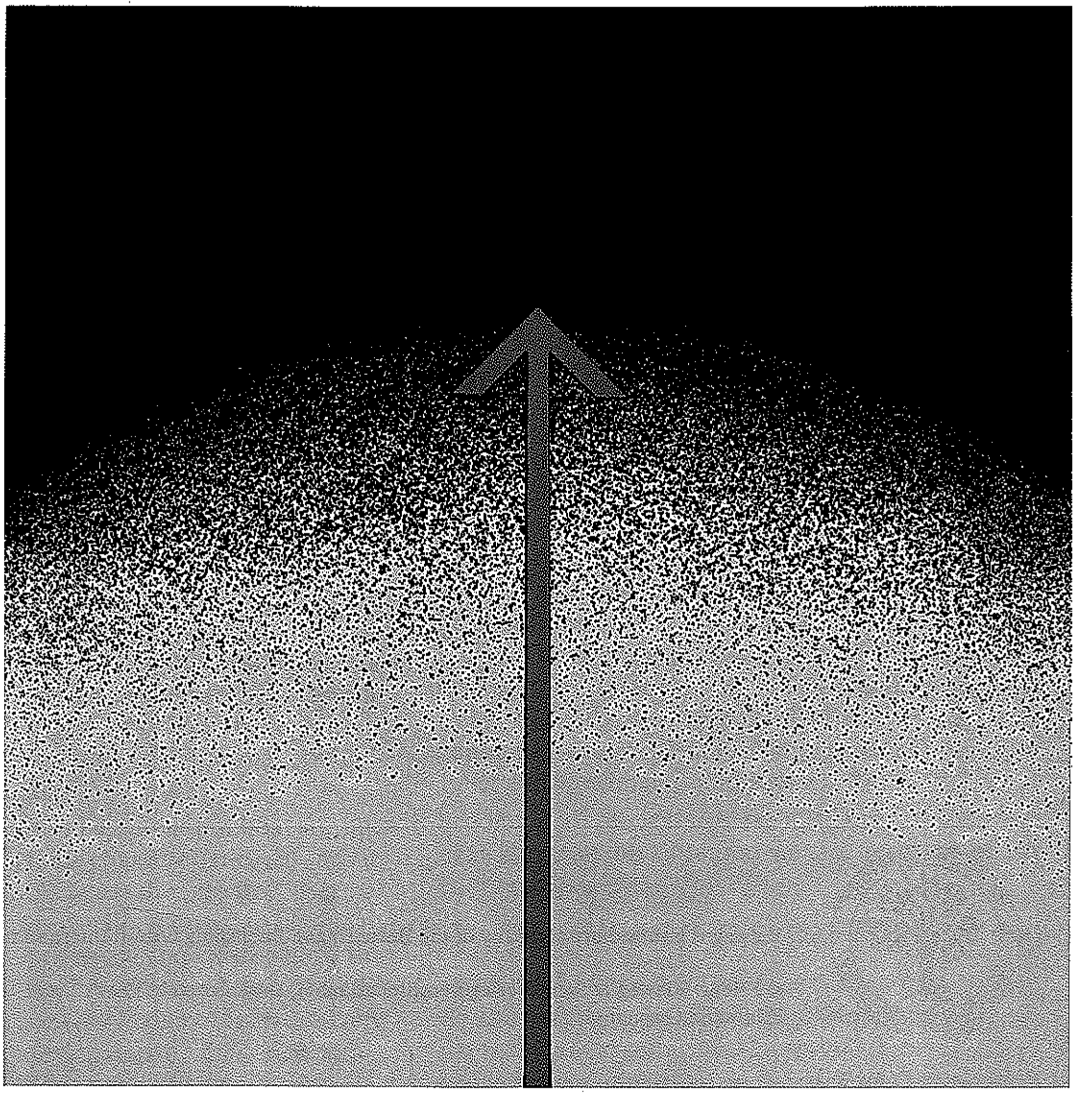

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