SPATIAL VARIABILITY OF ENERGY FLUXES IN SUBURBAN TERRAIN

H.P. SCHMID[1], H.A. CLEUGH[2], C.S.B. GRIMMOND[3] and T.R. OKE

Atmospheric Science Programme, Department of Geography, The University of British Columbia, Vancouver, B.C., Canada, V6T 1W5

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Abstract. Energy fluxes over an area of "homogeneous" suburban residential land-use in Vancouver, B.C., Canada are shown to vary by up to 25–40% within horizontal scales on the order of 10^2–10^3 m. Previously, variability of this magnitude has been expected to occur only at larger scales, between land-use zones or as urban-rural differences. In view of these findings, it is recognized that microadvective interaction between surface types at small scales may be important and can affect the energy balance even at larger scales.The present study discusses the small-scale spatial variability of energy fluxes and shows that it varies greatly for each term in the surface energy balance.

Net radiation shows a relatively conservative behaviour (via albedo-surface temperature feedback) with little spatial variability. The turbulent fluxes (measured by eddy correlation at 28 m height), on the other hand, show a link between their temporal and spatial variability as the result of a temporally shifting source area which contains varying combinations of surface cover (using the dynamical source area concept of Schmid and Oke, 1990). As a result, part of the measured temporal variation is attributable to spatial differences in surface cover. Anthropogenic heat flux and storage heat flux (both modelled using a high resolution surface data-base) exhibit temporally varying spatial distributions. Their spatial pattern, however, is governed by nested scales of urban morphology (blocks, streets, properties, etc.). These differences in the source of variability between each component flux suggest a difficulty in the interpretation of the energy balance over urban areas, unless each term is spatially-averaged over the principal morphological units occurring in the area.

1. Introduction

1.1. Objectives

Over an urban or suburban surface, with its nested structure of morphological scales and its wide range of surface types within a small area, common notions on "how to do micrometeorology" (e.g., Panofsky, 1973) collapse: in many cases a height range well above the roughness elements but low enough to ensure homogeneous fetch is simply non-existent. It may also be argued that a statistical concept of "surface roughness" or the idea of homogeneous fetch in such areas is invalid and needs to be re-examined on a fundamental level.

However, this paper is not as ambitious as that. It simply recognizes the need for detailed information about the energy fluxes and the energy balance over a type of surface which is (micrometeorologically speaking) "inadequate". Its aims

[1]Present affiliation: Dept. of Geography, Swiss Federal Institute of Technology, Winterthurestr. 190, CH-8057 Zürich, Switzerland.
[2]Present affiliation: School of Earth Sciences, Macquarie University, North Ryde, NSW 2109, Australia.
[3]Present affiliation: Climate and Meteorology Program, Dept. of Geography, Kirkwood Hall, Indiana University, Bloomington, IND 47405, USA.

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are to discuss the difficulties of measuring or modelling the surface energy balance over a suburban area. It seeks to provide some guidance with respect to the placement of instruments, the spatial resolution requirements of modelled fluxes, and the handling of energy balance data over complex areas. One recurring problem in the study of energy transfer processes over complex surfaces is the lack of a comprehensive theory. One is therefore often forced to refer to homogeneous surface-layer theory in order to analyse the data. Obviously, conclusions drawn from such hybrid methods are fraught with uncertainty.

The present work examines the magnitude of small-scale spatial variability of surface energy balance components within a residential suburban area in Vancouver, B.C., Canada. Here, "small-scale" refers to horizontal lengths of the order of 10^1–10^3 m and vertical scales that are limited to the turbulent surface layer, as in the micro-α scale of Orlanski (1975). It seeks to illustrate the relation between changes in surface composition and the spatial variability of surface energy balance components at such small scales. The local surface conditions affect the partitioning of available energy at scales where dispersion around buildings is important and may thus introduce local deviations of mean transport characteristics. The work shows that the positioning of instruments (both in the horizontal and the vertical) can significantly affect the validity of flux measurements: for turbulent flux measurements the degree of "spatial averaging" achieved by the flow is strongly dependent on height, as well as on the turbulence characteristics (i.e., the mixing or what is loosely termed the "averaging power") of the flow.

Such knowledge is important if surface energy balance observations from a single point are used to represent the areal average of a spatially complex region, such as a suburban area. Some guidance is provided on the spatial resolution required for the detailed study of sub-grid scale variability of larger scale models over suburban areas and on the magnitude of variability to be expected at such scales. Errors in the surface energy balance due to spatial misrepresentation have a direct effect on the performance of boundary-layer and mesoscale dispersion models over urban terrain.

In order to evaluate spatial variations in the energy balance, a detailed description of the surface in the study area is needed. This may be used to evaluate the degree of spatial averaging required to obtain spatially representative fluxes.

Finally, the relationship between the temporal and spatial variability of measured and modelled surface energy fluxes is discussed, with a focus on practical implications for field and modelling studies.

1.2. Principles

Energy exchanges between the surface and the atmosphere govern the evolution of the planetary boundary layer (PBL) and thereby affect its depth and thermodynamic behaviour, the surface temperature and humidity, the dynamics of local air flow and, indirectly, the concentration of pollutants. The necessity for continuity allows an accounting of all energy inputs and outputs in the form of an energy balance equation. The balance equation of an extensive urbanized area is conveniently defined (e.g., Oke, 1988) by a volume containing buildings, vegetation and other roughness elements, the air within the urban canopy-layer (UCL) and the soil down to a depth where vertical exchanges of heat and water may be considered negligible. The surface energy balance equation can be written:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \,. \tag{1}$$

Each term is a flux density (units of $W \cdot m^{-2}$): Q^* is the net all-wave radiation, Q_F the anthropogenic heat, Q_H the sensible heat, Q_E the latent heat, ΔQ_S the net sensible heat storage change and ΔQ_A the net heat advection.

Estimates of surface energy balances of urban or suburban sites are starting to appear (for a review, see Oke, 1988). Values for each term are obtained by measurement, modelling, parameterization or as a residual to close the balance. As written in (1), the energy balance equation is applicable to any control volume, irrespective of homogeneity. In practice, however, the direct evaluation of the advective term over a complex surface is often not feasible. While the study of "micro-advection" (and especially its feedback to mean turbulence at small scales) is a long-term aim of the authors, it is not considered in detail here. However, it is recognized that horizontal variations of vertical turbulent energy fluxes in the presence of a mean flow must induce advection. The importance of micro-advection may thus be inferred from the analysis of the magnitude of this spatial variability.

The temporal variation and the relative magnitude of each balance component is dependent on the magnitude of the energy forcing, usually Q^* and Q_F, and its partitioning at the "surface". The definition of this active surface, where the energy partitioning takes place, is one of the fundamental problems of energy balance studies in urban areas. The diverse size, shape, composition and arrangement of the urban canopy elements make it difficult to define and assign values to descriptors of the thermal, geometric, moisture and other characteristics of the urban "surface", or even to find a surface datum for meteorological purposes (Oke, 1988). This is a serious problem because the *ensemble* of surface characteristics affects the energy partitioning and therefore knowledge of the surface character is instrumental to an understanding of the surface energy balance and its components. Since both the availability and the partitioning of energy may be affected by changing surface conditions, the spatial variability of the energy balance is related to the variability of the surface composition.

Because of the spatial complexity of urban terrain, it is necessary to consider a hierarchy of nested systems and scales (Oke, 1984). Figure 1 shows an idealized arrangement of the daytime boundary-layer structure over a city, where the PBL is commonly equated with the convectively-driven mixed layer and a comparatively shallow surface layer. At the largest scale depicted, the urban surface modifies the lowest layers of the atmosphere, which are (ideally) adjusted to upwind rural surface conditions before their impingement on the city. If the urban area is

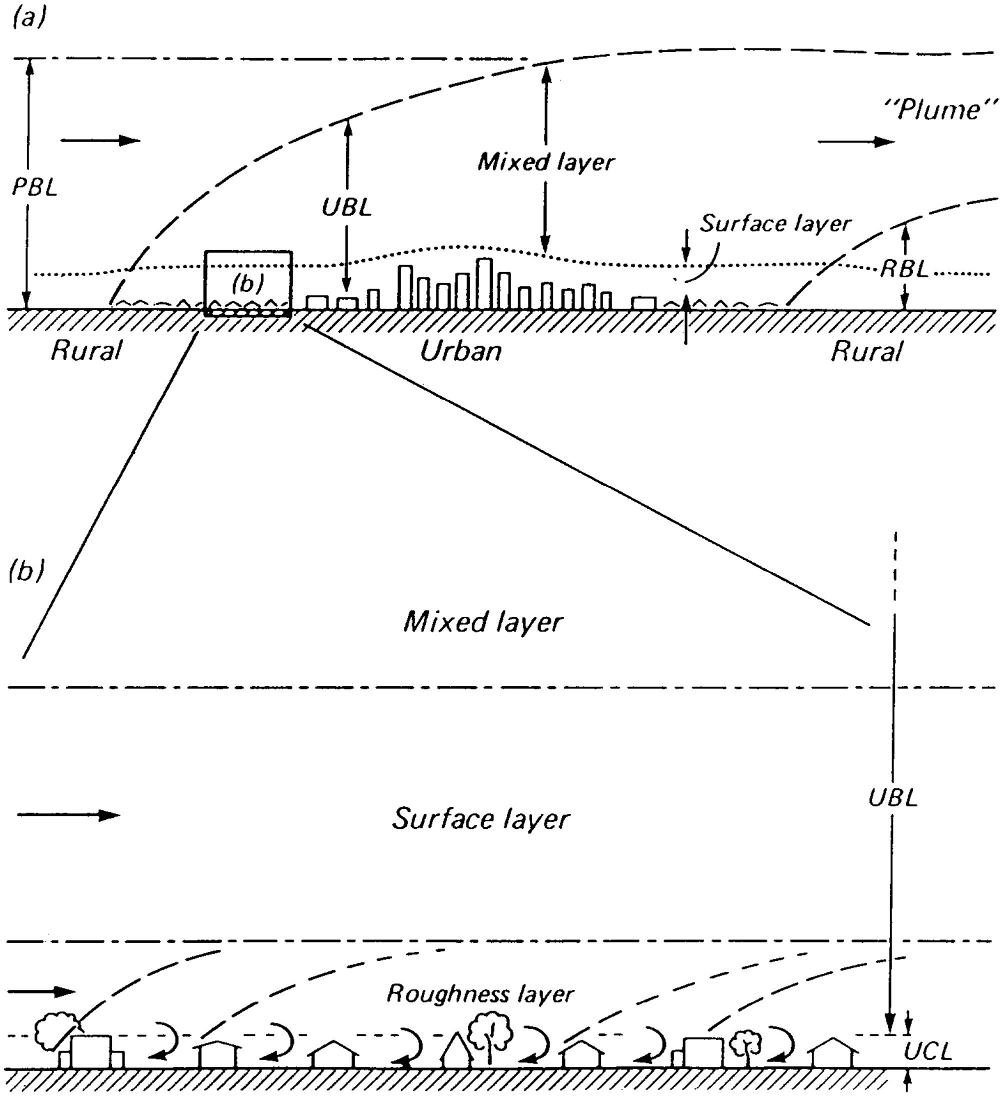

Fig. 1. Conceptual arrangement of boundary-layer structure over a city; (a) at the meso-scale ($\sim 10^1$ km); (b) at the local scale ($\sim 10^{-1}$ km) (after Oke, 1984).

extensive enough, the growing urban boundary layer (UBL) eventually includes the entire depth of the PBL. Similarly, a rural boundary layer (RBL) develops again at the downwind leading edge of the urban/rural transition.

Within urban areas, Auer (1978) identified several different land-use types and the variability of fluxes at this scale was a focus of part of the US EPA's Regional Air Pollution Study (RAPS) in St.Louis (e.g., Ching *et al.*, 1983, 1984). Carlson *et al.* (1981) estimated the distribution of surface energy balance components using a combination of satellite-derived surface temperature (at a resolution of about

$6 \cdot 10^2$ m) and a one-dimensional boundary-layer model. Both sets of studies show spatial variations of fluxes related to elements of urban morphology. Briggs (1988) argues that the horizontal scale of changed surface character should exceed $X \cong 2$, to result in a substantial response of turbulence conditions in the entire mixed layer, where $X = (x/U)w^*/z_i$ is the dimensionless distance in convective scaling (x is the streamwise distance in m; U the mixed layer wind speed in $m \cdot s^{-1}$; w^* the mixed-layer scaling velocity in $m \cdot s^{-1}$ and z_i the mixed-layer height in m). In typical mid-latitude summer conditions, this translates to a fetch of about 5–10 km.

In the present work, spatial variability at a smaller scale, within a land-use zone (such as considered by Smith *et al.* (1985) for a forest area), is of interest. The lower portion of Figure 1 is a schematic of the dominant atmospheric and surface components of a suburban surface that need to be considered. In the upper portion, termed the inertial sublayer (using this term less strictly than Tennekes (1973)), vertical profiles of wind, temperature and humidity do not depend on external scale lengths such as the characteristic dimensions of the surface geometry. This is also often referred to as the "constant flux layer", because over homogeneous surfaces, (turbulent) vertical fluxes vary by only about 10%, both in the horizontal and vertical directions (Dyer and Hicks, 1972).

However, it is often questionable whether an inertial sublayer actually exists over complex surfaces. The height range of validity of turbulent surface-layer theory is given by the asymptotic matching of two limiting expressions, $z \cdot f/u_* \to 0$ and $z/z_0 \to \infty$ (where z is the height, z_0 the roughness length, f the Coriolis parameter and u_* the surface friction velocity). For most practical applications, this translates into the requirement that turbulence measurements be taken at levels z_s, satisfying $100 \cdot z_0 < z_s < 100$ m (e.g., Tennekes, 1973). Over the very rough surfaces encountered in (sub-) urban areas (the roughness length of the present study area is estimated as $z_0 \approx 0.5$ m), this layer of validity is very thin or even non-existent. In addition, practical and operational constraints (e.g, maximum permissible tower height) in urban areas often limit sensor heights to $z_s \ll 100 \cdot z_0$.

Thus, in the lower portion of the surface layer, the flow is influenced by individual surface elements and is three-dimensional (Raupach and Thom, 1981). At this level, transport may be dominated by stationary sources and sinks representing local mean fluxes of heat. Thus, point measurements (such as obtained by eddy correlation) may not be representative of (ensemble-) mean surface-layer fluxes (Smith *et al.*, 1985). The finding of increased evaporation (over the level of local equilibrium) from an irrigated suburban lawn suggests that micro-advection effects are important in this layer (Oke, 1979), which has been given several names, including turbulent wake layer, transition layer or roughness layer. The term transition layer refers to the self-induced spatial averaging process of turbulent transfer in this layer: turbulent mixing results in progressive horizontal averaging with increasing height. The spatial variability is in transition between the surface, where it is greatest, and a height in the atmosphere where the horizontal inhomogeneities disappear completely. Ideally, the upper limit of this transition or roughness layer is the lower boundary of the inertial sublayer (Garratt, 1978). Therefore the degree of spatial variability which can be resolved by instruments (and thus the spatial representativeness of their measurements) depends on their height within the transition layer.

2. The Study Area and the Surface Data Base

Observations for this study were conducted at several sites in the "Sunset" suburban area in Vancouver, B.C., Canada (Figure 2). At the centre of the study area there is a 30 m meteorological tower ("Sunset" tower) located on the property of an electrical power substation. The topography of the area surrounding the tower is limited to low, smooth undulations and exhibits a slight southwestward slope towards the Fraser River.

In order to analyse the spatial variability of surface energy balance components and to relate them to the variable terrain character, a detailed surface database has been compiled by Grimmond (1988). The requirements of the database were that the individual grid squares of information would allow the influence of small differences in surface character to be identified, but not so small that the effort required to gather the necessary information was unrealistic. These requirements were deemed met using $100 \times 100\ m^2$ squares, and data were collected for a 5 km radius circle centred on the Sunset tower (i.e., approximately 8000 squares).

In the final database, each gridpoint is represented by a one-dimensional array containing 25 variables in 10 groups. These groups contain coded information about the position of the gridpoint, the number and total area of single family dwellings, apartments, apartments above commercial units, commercial buildings, industrial structures, institutional buildings (schools, churches etc.) and parks, the length of back alleys, minor and major roads, the number of inhabitants per dwelling and the total population in each gridsquare. Principal data sources for this inventory included land use maps, aerial photographs and city bylaws. The database was compared with a detailed surface description conducted earlier by Grimmond (1983) for a 21 ha area in the same suburb and the surface characteristics were found to agree closely. The population density was also in good agreement with that for individual census tracts.

With the use of the database, it is possible to produce maps of surface types contained within each grid square. Figures 3a,b show the plan area of paved areas and total vegetation cover respectively in several classes within each grid square (1 square = $10^4\ m^2$).

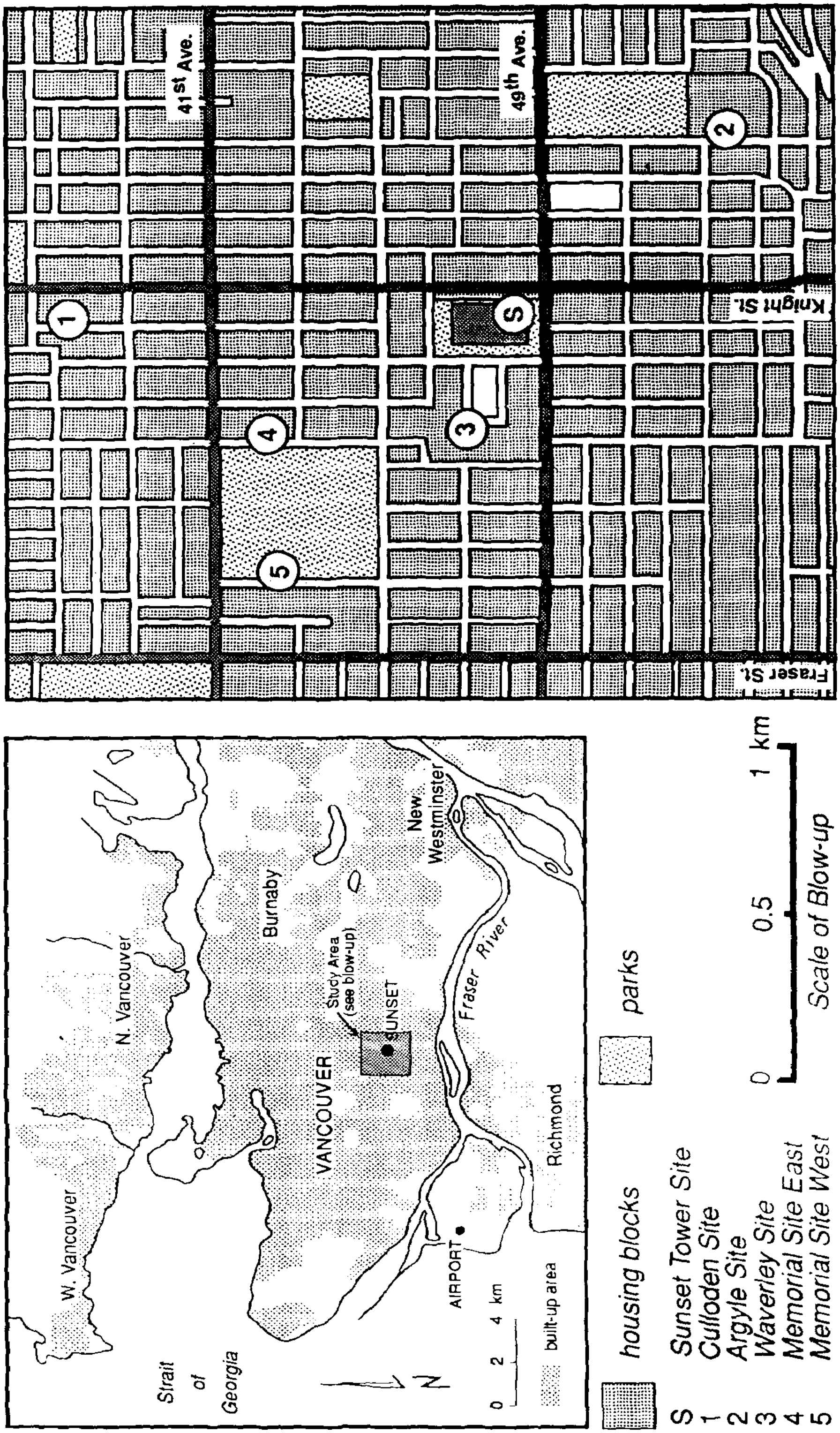

Fig. 2. Plan of the study area (with six observation sites) and its regional setting in the Greater Vancouver Metropolitan Area.

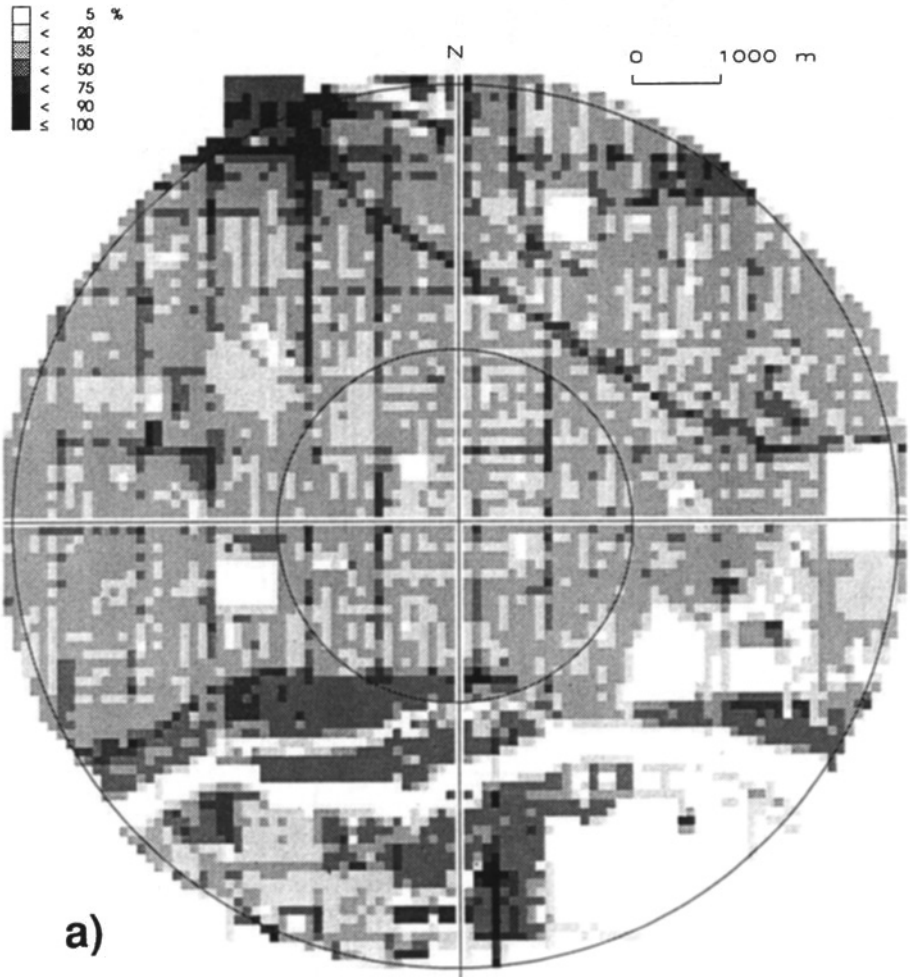

Fig. 3(a).

3. Determination of Energy Balance Component

3.1. Measured surface fluxes

(i) Source Areas

During the direct measurement of a surface energy flux, the sensing instrument is primarily influenced by a specific portion of the surface, termed the "source area" by Schmid and Oke (1990). This source area may be interpreted in analogy to the "field of view" of the instrument. The contributions of individual surface elements within the zone of influence are combined to produce a composite influence of the source area, reflected in the measured signal. Therefore even a point measurement involves a spatial average to some degree. In this study, it is of prime importance

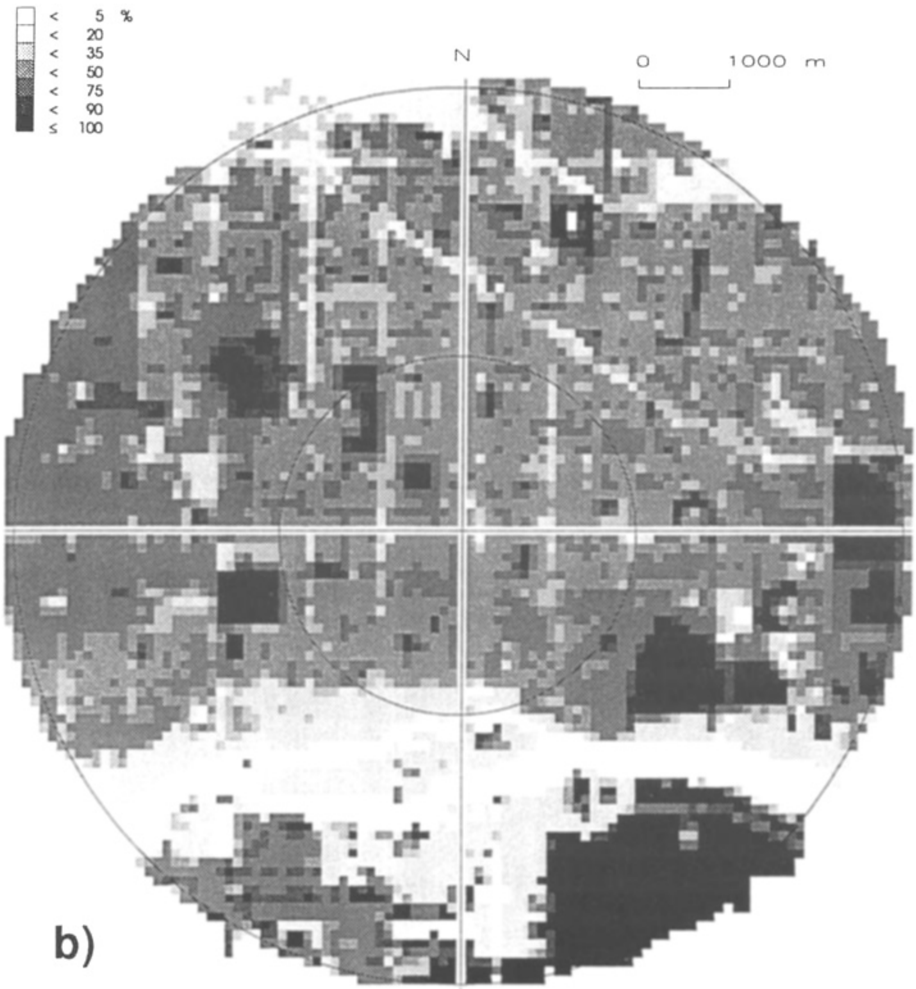

Fig. 3. Maps of surface type from the data base on a hectare grid, centered on the Sunset site. The inner circle has a radius of 2 km. (a) paved surface; (b) total vegetation (in % of the entire grid-cell).

to identify the source areas of flux measurements in order to estimate the degree of spatial averaging inherent in them.

The problem of the "field of view" of an inverted flat-plate radiometer (or the lower surface of a net-radiometer) is addressed by Reifsnyder (1967). If it is oriented parallel to a level ground surface, it is exposed to radiation from the entire surface, stretching to infinity in all directions. Obviously, the portion of the ground immediately beneath the radiometer provides the bulk of the radiation influence. Thus, Reifsnyder defines the view factor (F) for a circular surface disc of radius r, relative to a differential area (dA) directly above its centre (i.e., the receptor plate of the radiometer), as the ratio of radiation received from the disc to the amount received from the remaining annulus surrounding the disc and stretching to infinity. Reifsnyder shows that a graphical interpretation of the view factor leads intuitively to a simple mathematical expression for the radiative exchange between two surfaces that obey Lambert's cosine law and are separated by a transparent medium. The view factor, F, is then found as

$$F = \frac{r^2}{r^2 + z_s^2} . \tag{2}$$

For any F, the ratio of the sensor height to the radius of the F-source area is then given by:

$$\frac{r}{z_s} = \left(\frac{1}{F} - 1\right)^{-1/2} . \tag{3}$$

A useful rule-of-thumb resulting from this simple relation is that half of the radiative surface influence originates from an area with a radius equal to the sensor height.

In the case of turbulent transport of sensible or latent heat, the determination of a surface source area is more complex. The temporally averaged surface-"field of view" of a temperature or humidity sensor is determined by turbulent diffusion and is constantly changing both its size and position, depending on wind direction and speed and other characteristics of the flow. A solution to this problem has been presented by Schmid and Oke (1990) in a small perturbation model, following an original suggestion by Pasquill (1972).

The total surface effect experienced by the sensor is determined by the weighted contributions of all sources upwind. Schmid and Oke (1990) show that the mathematical form of the source weight function for a sensor at height z_s is precisely that contained in the concentration distribution in a hypothetical plane at height z_s, resulting from a continuous point source on the ground. Analogous to the view factor of radiative source areas, an effect fraction, P, may be defined as the portion of the total effect experienced by the sensor that originates from within the source area of level P. The upwind, downwind and lateral dimensions of the approximately elliptical source areas are a fairly sensitive function of sensor height, and are further affected by roughness, stability and the lateral wind fluctuations. For unstable conditions, these dimensions, the maximum source location (Figure 4) and the size of the source area containing half of the total effect are approximated by the following set of equations (Schmid and Oke, 1990):

$$\psi(z_s/L, p) = (1 - p \cdot z_s/L)^{1/4} - 1 \tag{4a}$$

$$x_m \cong 1.7 \cdot z_s^{1.03} \cdot [\ln(z_s/z_0) - \psi(z_s/L, 76)] \cdot (1 - z_s/L)^{-1/2} \tag{4b}$$

$$e_{0.5} \cong 7.7 \cdot z_s^{0.96} \cdot [\ln(0.23 \cdot z_s/z_0) - \psi(z_s/L, 30)] \cdot [\ln(-L)]^{1/2} \tag{4c}$$

$$d_{0.5} \cong 0.24 \cdot z_s \cdot [6 + \ln(z_s/z_0)]^{1/2} \cdot [\ln(-L)]^{4/5} \cdot \sigma_v/u_* \tag{4d}$$

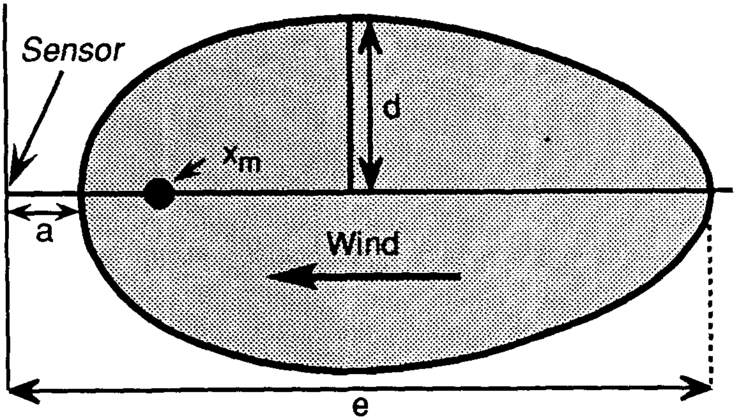

Fig. 4. Dimensions of a turbulent source area isopleth. x_m: maximum source location (upwind distance of the surface element with the maximal influence on a given sensor); a: downwind edge, e: upwind edge and d: lateral half-dimension of the source area.

$$a_{0.5} \cong 0.335 \cdot x_m \tag{4e}$$

$$Ar_{0.5} \cong 0.47 \cdot \pi \cdot (e - a) \cdot d\,, \tag{4f}$$

where (4a) is an auxiliary expression and needs to be evaluated with the appropriate 'p' for equations (4b) and (4c). Symbols and units used are z_s for the sensor height, L the Obukhov length, z_0 the roughness length, x_m the distance from the sensor to the maximum source location and $e_{0.5}$, $a_{0.5}$ and $d_{0.5}$ the upwind, downwind and lateral dimensions of the $P = 0.5$ source area, respectively (all in units of m), $Ar_{0.5}$ the respective surface area (in m^2), σ_v the standard deviation of the lateral wind fluctuations and u_* the friction velocity (both in $m \cdot s^{-1}$). The validity ranges of input parameters, for which Eqs. (4a–f) were evaluated, are: $2\,m \leq z_s \leq 64\,m$; 0.005 m; $0.005\,m \leq z_0 \leq 0.8\,m$; $5\,m \leq (-L) \leq 5000\,m$; $1.0 \leq \sigma_v/u_* \leq 6.0$. Within these ranges, any combination of values should satisfy $20z_0 \leq (-L)$ and $20z_0 \leq z_s$. For application of the source area model in stable conditions, see Grimmond (1988).

Due to the dynamical behaviour of the source area of turbulent fluxes, the surface influence experienced by the sensor is constantly changing in time. Thus the temporal variations of turbulent exchange processes contain a hidden spatial variability component, in contrast to the variability of net radiation where the source areas are fixed. The resulting incongruity in the behaviour of radiant and turbulent exchange variations may have significant consequences for the evaluation of internally consistent energy balances over inhomogeneous surfaces. This phenomenon and its implications will be discussed elsewhere.

(ii) Measurement of Net Radiation and Sensible Heat Flux

In the summer of 1986, net radiation was measured at 25 m on the Sunset tower and at 28 m at four other sites (Culloden, Argyle, Waverley and Memorial East,

Figure 2) using a mobile telescopic tower. This gave 0.95 view factor source area radii of 109 m at the Sunset tower and 122 m at the mobile sites ($z_s/r = 0.23$). Each of the mobile sites was operated concurrently with the Sunset site for a period of 3 days between YD 86/212 and 86/238. Swissteco (Model S1) net pyranometers were used to obtain 30 min averages at all sites.

The view factor analysis of the Sunset site indicates a ratio of the percentages of vegetated to built areas of (32/68). Here, "built" areas include buildings, pavement and gravel surfaces. Although detailed view factor analyses for the mobile sites are not available, the ratio of vegetated to built areas for these sites can be estimated from the surface data base, using the four grid-cells nearest to each location. Despite the crudeness of this method, it compares well with the view factor analysis of the Sunset site. The ratios of vegetated (%) to built (%) areas as estimated from the data base vary from 0.54 to 5.7 (see Table III). The Sunset site is the only one with a vegetated area fraction clearly below 50%. It is close to a major road intersection with a neighbourhood commercial centre, a school-yard and a power sub-station (both gravel). The high vegetative portion of both Memorial sites (East and West) is explained by their locations on either side of a park (Figure 2).

Concurrently with the net radiation measurements, sensible heat flux measurements were taken using two similar eddy-correlation systems (Campbell Scientific sonic anemometer/thermometer, Model CA-27T). One was mounted at 28 m on the Sunset meteorological tower, while the other was exposed at the same height on the mobile telescopic mast. Sensible heat flux measurements were gathered at the same sites as net radiation and at Memorial West as an additional site (Figure 2). Temperature and vertical velocity were sampled at a frequency of 10 Hz, and the cross-correlation was evaluated every 15 min and averaged to give hourly values of sensible heat flux.

The Sunset tower served as the main site and all meteorological data necessary for the source area calculations were collected there. Daytime winds in the region are commonly governed by a westerly sea-breeze (Steyn and Faulkner, 1986), so the Culloden, Argyle and Waverley sites were chosen to be aligned across this wind direction (Figure 2). Culloden and Argyle are separated from the Sunset tower by a distance in the order of 1 km, whereas Waverley is only about 400 m distant. At Memorial, an East and a West site were selected to lie just downwind and upwind respectively of a large park (approximately 300 m in width) during sea-breeze flow. These were chosen to examine the influence of this major inhomogeneity, in an otherwise residential area, on the sensible heat flux. These two sites are separated by approximately 350 m and lie 1 km (Memorial West) and 780 m (Memorial East) away from the Sunset tower.

3.2. Methods to Determine the Anthropogenic and Storage Heat Fluxes

It is not possible to measure the anthropogenic heat flux (Q_F) or storage heat flux (ΔQ_S). Q_F was estimated using the method outlined in Grimmond (1988). In this

TABLE I

Surface parameters used to determine anthropogenic heat flux and storage heat flux

(a) Anthropogenic Heat Flux	
• Number of vehicles by road type (major or minor road)	
• Length of road within the contributing area by road type	
• Number of electricity consumers by premise class type (house, school, etc.)	
• Number of gas users by premise class type	
• Number of people	
• Number of animals	
(b) Storage Heat Flux	
• Proportion of	-2D greenspace
	-3D walls
	-3D roof
	-2D impervious
	[Note that the sum of these 4 adds up to 1 (or 100%)]

method Q_F is calculated in three parts: heat from vehicles, stationary sources (mainly buildings) and human metabolism. Each requires the grid-specific information from the database listed in Table I(a) together with algorithms and coefficients relating fuel consumption to heat release, metabolic rates, etc.

The daytime storage heat flux was calculated using an objective hysteresis approach. This uses the grid data in Table I(b) together with a parameterization scheme to relate heat storage and net radiation based on such relationships from a variety of suburban surface types.

The degree of spatial or temporal variability of these fluxes is constrained not only by the types of surfaces present, but also by the grid-size and total domain and by the input algorithm, respectively. It can thus be set to suit the spatial and temporal resolution of the study.

5. Results

5.1. Net Radiation

The aggregate net radiation results indicate relatively little difference between the "mobile" sites and the fixed point measurement (Figure 5 and Table II). The overall root-mean-square difference (RMSD) of $24.1\ \mathrm{W \cdot m^{-2}}$ is approximately twice that due to instrument error alone (determined by a calibration run), i.e., $12\ \mathrm{W \cdot m^{-2}}$ can be attributed to the effects of spatial variability. Most of this difference is non-systematic (in the sense of Willmott, 1981): for all sites, the slope of the regression line is close to unity and the intercept is very small. These statistics demonstrate that the spatial variability of the net radiation areally averaged at 25–30 m over suburban land is small.

The observations comprise a range of cloud-cover and land-use; thus the result can be analysed in terms of both cloudiness and location. The only days which experienced significant cloud-cover were YD 86/222 and 86/223, which coincide

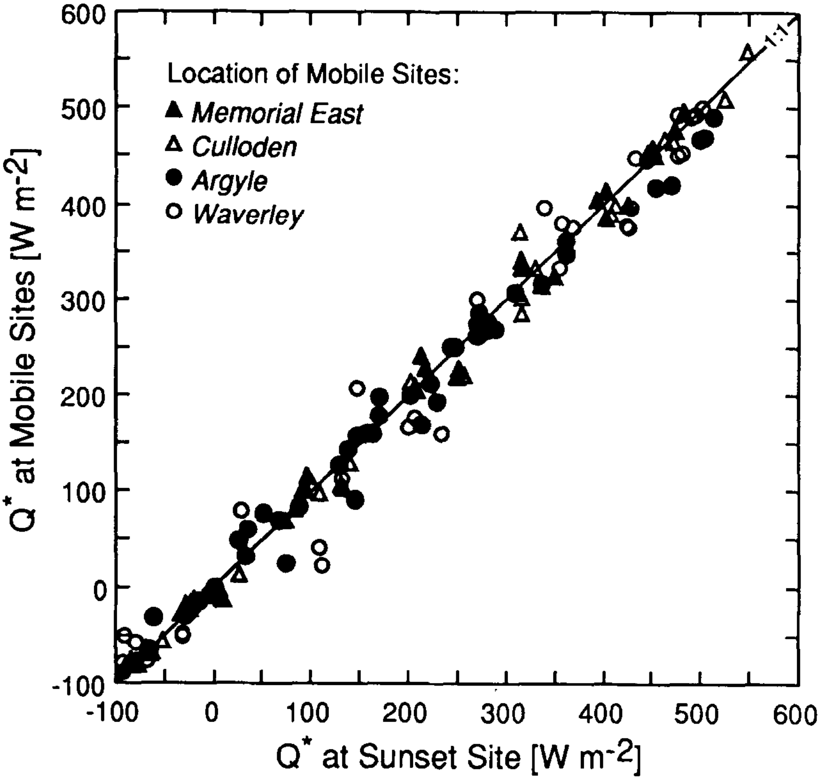

Fig. 5. Synchronous observations of hourly net radiation at the Sunset site and the composite of four mobile sites.

TABLE II

Summary statistics for the net radiation measurements

Mobile site	Mobile mean $[W \cdot m^{-2}]$	Sunset mean $[W \cdot m^{-2}]$	Difference of means abs. %[a]	RMSD $[W \cdot m^{-2}]$	RMSD %[a]
Culloden	189.22	191.36	1.1	15.25	8
Argyle	176.71	182.49	3.2	21.74	12
Waverley	232.36	243.29	4.6	37.35	15
Memorial East	188.60	190.73	1.1	16.09	8
All sites	195.87	201.25	2.7	24.41	12

[a]*Note*: % are calculated relative to $1/2(\text{Mobile}_{\text{mean}} + \text{Sunset}_{\text{mean}})$.

with the measurements at the Argyle site. Comparison of net radiation between Argyle and the Sunset site illustrates a greater degree of scatter (RMSD = $21.7\ W \cdot m^{-2}$) than for the other sites (except the Waverley site, see below). It seems that the presence of cloud actually had the greatest impact upon the *slope* of the regression line, thus introducing a systematic difference between the Argyle and Sunset values. On YD 86/221 and 86/222, this difference is positive in the morning. In the afternoon of YD 86/222 and 86/223, the effect is reversed. However, even in conditions of a variable input in insolation, it is encouraging that the differences between sites is so limited.

The greatest scatter between the mobile and fixed sites is for Waverley, even though this site is in relatively close proximity to the Sunset tower. However, since the absolute net radiation levels are much higher during this period, the relative difference of the means is still only 4.6%. In agreement with the other sites, the relative RMSD is much larger than the relative difference of the means, emphasizing the random nature of the deviations. The scatter in the hourly values may be caused by local and transitory reflection and shading effects which are smoothed out in the averages over approximately three days. Even though the Sunset means are consistently higher than the Mobile means, their differences are of the same order as the instrument error.

In summary, these observations demonstrate the conservative nature of the net radiative flux. Although a wide range of surface materials can be found in the area, the spatial variability of net all-wave radiation is reduced by a negative feedback loop between the long-wave and the short-wave portions of the spectrum via the albedo, and the radiation temperature of each surface element. This effect is more prominent in long-term averages, where local and transitory shading and reflection effects cancel.

These results are entirely consistent with previous studies of net radiation variability in cities. Aircraft observations by White *et al.* (1978) indicate relatively small differences between land-use zones across St. Louis while a number of fixed site comparisons show only small intra-urban and even urban-rural differences (see Oke, 1988 for a review). The present study extends these findings to even smaller scales and emphasizes the conservative nature of net radiation.

5.2. Turbulent Sensible Heat Flux

A comparison of the Q_H values measured at the mobile sites versus the concurrent data from the Sunset Tower shows an increase in variability with increase in the magnitude of the flux (Figure 6). This effect is absent in a direct instrument comparison during a field-calibration period, where the two sensors were both mounted on the Sunset tower, separated by a distance of only 0.15 m. In this configuration, for flux values greater than $50\,W \cdot m^{-2}$, the RMSD between the sensors varies only slightly around $14.5\,W \cdot m^{-2}$. This is illustrated by the different patterns of scatter of the two datasets in Figure 6. Thus the increase in variability with the magnitude of Q_H during the inter-site comparison period is not due to instrument uncertainty or the larger absolute values, but may be attributed to the character of the sites themselves and their influence on the energy partitioning. It is suspected that the relative proportion of vegetated and built surfaces is of prime importance. This explanation is supported by the finding that the area surrounding the Sunset site is relatively dry (i.e., it has a lower ratio of vegetated to built surfaces, see Table III) compared to the other sites.

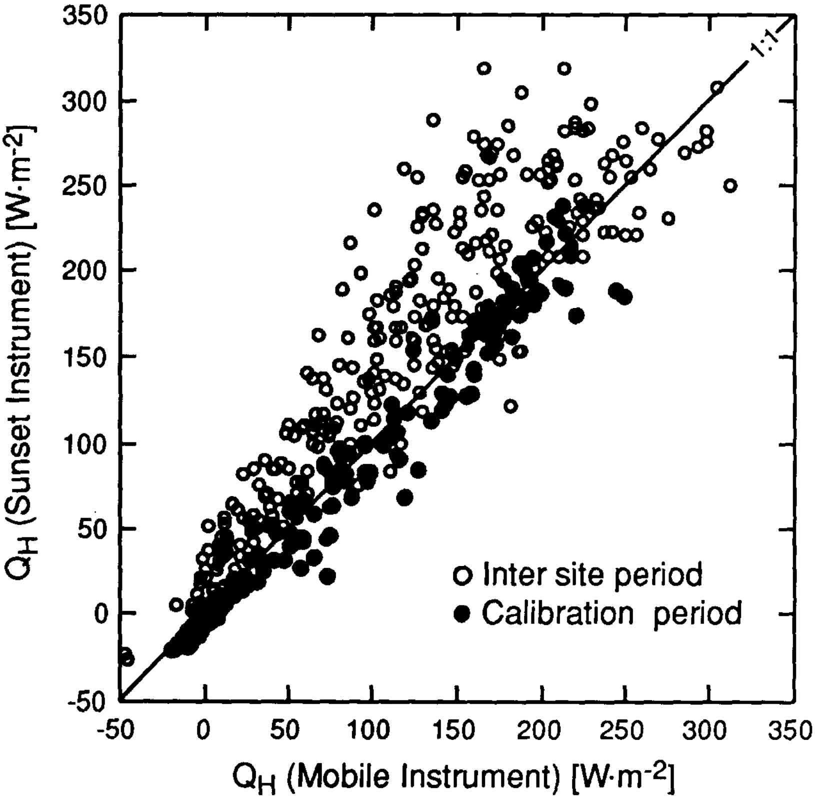

Fig. 6. Synchronous observations of hourly sensible heat flux at the Sunset site and the composite of five mobile sites (empty circles); comparison of the two instrument sets used (filled circles).

TABLE III

Site information and summary statistics for the sensible heat flux measurements

Site	Ratio veg./built [%/%]	Number of data	Mobile mean [W · m^{-2}]	Sunset mean [W · m^{-2}]	Difference of means abs. %[a]	RMSD [W · m^{-2}]	RMSD %[a]
Sunset	35/65						
Culloden	45/55	116	80.9	91.6	12.4	26.4	30.6
Argyle	55/45	60	95.6	145.2	41.2	58.2	48.3
Waverley	65/35	65	124.2	155.1	22.1	47.5	34.1
Memorial East	80/20	45	109.0	157.6	36.5	66.8	50.1
Memorial West	85/15	63	107.2	134.4	22.5	41.1	34.1
All sites except Memorial East	57/43	304	98.2	124.2	23.4	42.0	37.8
All sites	61/39	349	99.6	128.5	25.3	45.9	40.3

[a]*Note*: Percentages are calculated relative to 1/2($Mobile_{mean}$ + $Sunset_{mean}$).

The summary Q_H statistics for each Sunset/mobile site pair are given in Table III. Given the location of the Memorial East site (in the lee of a 300 m wide park), the inter-site differences versus the Sunset values are large, as expected. For this reason, this site is not included in Figure 6. In contrast, the intersite differences at Memorial West (to the windward of the park) are considerably smaller. These differences are believed to show the tendency of the irrigated park to shift the local Bowen ratio towards evapotranspiration, resulting in an advectively reduced Q_H to the lee of the park.

Some of the large differences between the Argyle and the Sunset values may be due to the partly cloudy conditions that might have had a larger effect at Argyle than Sunset, as noted in the net radiation results. The mean values at Culloden are smallest because this is the only site where data were recorded at night (when Q_H is very small or slightly negative). A comparison of Tables II and III shows clearly that the variability of sensible heat flux is nearly four times larger than that for net radiation.

If it is the influence of the local site characteristics that governs the energy *partitioning*, there should be a more or less time-consistent Q_H deviation between sites (although irrigation schemes might introduce a certain temporal variability). On the contrary, however, the results show that at any specific site, the Q_H difference to the Sunset values is not constant in time, but varies at irregular intervals (not shown). Although part of this may be due to the spatial variability of insolation during periods of broken cloud-cover or because of large thermals that affect one site but not the other, most of this effect should disappear over an averaging period of one hour, and another explanation has to be found. As described above, the adoption of a dynamic source area concept for turbulent transfer demonstrates that the effective site influence for a point measurement changes not only in space, but also in time. Thus, "the flow" may perform a strong spatial average at one time (when the source area is large) but not at another time (when the source area is small). The following example of the daytime evolution of the area enclosing 50% of the sources affecting the Sunset sensor (thereafter the 0.5 level) shows that the surface character of the source area can change drastically over the course of a day.

Figure 7 shows the 0.5-level source areas for 5 hrly averaging periods on YD 86/231, as obtained from Eqs. (4a-f). During the day, the wind direction (and thus the orientation of the source areas) veered gradually from the southeast to a west-northwesterly direction, consistent with the characteristic sea-breeze regime of this coastal location. About two and a half hours after sunrise, at 8:00 LAT, convective activity was already well developed (with an Obukhov length $L = -61$ m, determined at the Sunset tower), and the source area was relatively small with the maximum source location close to the sensor (89 m), located over a neighbourhood commercial centre surrounding a busy intersection with its considerable anthropogenic heat output (see next section). Because of the small size of the source area, individual surface elements close to the maximum source

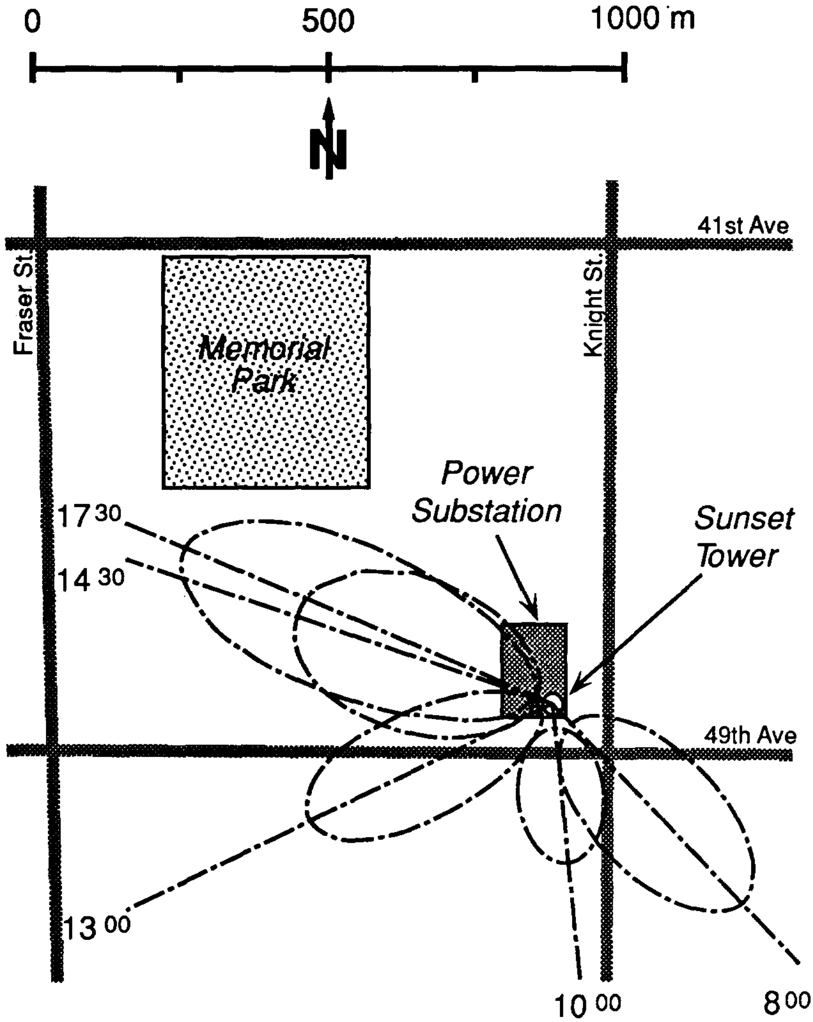

Fig. 7. The evolution of the turbulent source area during YD 86/231 for the Sunset tower site. The alignment of the 0.5-level isopleths varies with wind direction, and their dimensions are dependent on atmospheric stability and lateral turbulence intensity. The variable thermal properties within the source area over time provide a link between the temporal and spatial variability of turbulent sensible heat flux.

location are very important, so that the thermal behaviour of this intersection is expected to have a considerable effect on the measured heat flux. However, it should be noted that the source area is a probabilistic concept, indicating a 50% probability that the surface elements inside this 50%-level source area affect the thermal conditions at the sensor. Thus, it can be misleading to try and interpret a specific combination of source area and flux data.

Two hours later, the convective activity almost reached its peak ($L = -20$ m), the source area is even smaller and almost circular and veered to the south, so that the maximum source location moved about 100 m west, away from the large intersection and the commercial centre and towards the adjacent residential housing with its large proportion of vegetation. A different source area influence, due to the changed thermal behaviour compared to two hours before, is therefore to be expected.

By 13:00 LAT, the wind direction veered to the west-southwest, the maximum source location lay in a small park and the main part of the source area contained single family housing. The dry and hot surface of the substation on which the tower was located was only touched by the source area on its periphery.

At both 14:30 and 17:30 LAT, the wind direction was from the west-northwest. The differences between the two periods are interesting. At 14:30 LAT convection was on the decline but still strong ($L = -63$ m). The maximum source location was well inside the substation, at a distance of 90 m from the tower. A strong influence of the hot and dry substation surface is thus suggested (and also apparent in the data; not shown here). Three hours later conditions changed: convection was much weaker ($L = -264$ m), the source area was larger and the maximum source was, located 40 m further upwind. With the larger source area, the measured flux consisted of a better spatial average and thus the measured spatial variability was reduced. At the same time, the maximum source location of the Sunset tower was sufficiently far away that the influence of the substation was reduced.

These five examples illustrate the relationship between temporal and spatial variability of the source areas of turbulent fluxes over complex terrain. It shows that in the middle of the day, when instability and the magnitude of fluxes are large, the Sunset source area is frequently situated over dry and hot surface elements. In contrast, similar source area calculations for the 'mobile' sites (not shown here) indicate much less variability in source area composition and generally a higher proportion of vegetation cover as found from the surface data-base above. This difference in the average thermal environment between the Sunset and the composite of the mobile sites is reflected in lower overall mean Q_H values at the latter (over a 2–3 day period), as shown in Table III and also by different mean daily variations of Q_H (Figure 8). The differences between the Sunset and the composite mobile sites are plotted on an expanded scale in the lower half of Figure 8. This curve is very similar in shape but reduced in magnitude to that of suburban-rural differences reported by Cleugh and Oke (1986, their Figure 6). As in the suburban-rural case, the peak of the difference curve lags about two hours behind the peak of the flux values. An explanation for this effect is offered by Cleugh and Oke (1986): the extra sensible heat at the Sunset site is mostly channelled into storage in the morning, and into the atmosphere in the afternoon.

The finding that sensible heat flux measurements at a height of almost 30 m and with horizontal scales of less than 10^3 m in a suburban area show a variability which is almost comparable in magnitude to suburban-rural differences at a much larger scale ($>10^4$ m; Ching *et al.*, 1983) is somewhat surprising, since Ching *et al.*

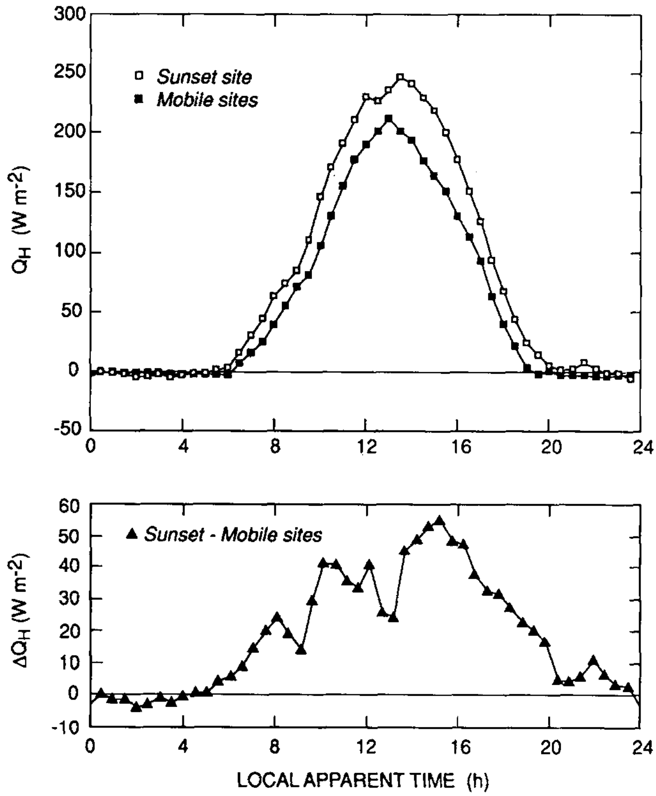

Fig. 8. Comparison of the mean daily variations of turbulent sensible heat flux between the Sunset site and the composite mobile sites. The differences between the two (ΔQ_H) is plotted in the lower part on an expanded scale.

(1983) suggest that measurements at that height should be representative of a fetch of 4–5 km (their Figure 3). However, in view of the dynamical source area arguments and the findings of the present study, it seems that more local effects can be important.

The fetch analysis of Ching *et al.* (1983) is based on convective boundary-layer scaling and thus emphasizes the variability induced by large thermals. Since convective thermals are usually not stationary, but have a characteristic time scale, an adequate averaging time which includes a statistically significant number of the major heat flux-bearing eddies, ensures conditional stationarity of the measurements with respect to variability at the boundary-layer scale. The corresponding fetch is then defined as the horizontal scale of this significant number of eddies. However, as they point out, variability due to a small-scale heat source distribution at the surface is not taken into account by this method.

In contrast, source area estimates are based on surface-layer theory alone and do not take into account the large-eddy structure of a convective boundary layer. They are intended to estimate the influence that small-scale variability of the surface has on a heat flux measurement. Obviously, it seems that source area estimates (with an adequate averaging time) are valid over a surface which is homogeneous at the land-use scale (4–5 km) but is variable at the local scale (less than 1 km), and that the fetch estimates of Ching *et al.* (1983) are useful to evaluate variability at the land-use scale, over areas that are homogeneous at the local scale.

The role of the self-induced spatial averaging of turbulent transport may be examined by analyzing the measured variability of sensible heat flux versus the size of the source area: if the "averaging power" of the flow is large, the source area is also large and the remaining spatial variability is expected to be reduced. In the following, the flux differences between the Sunset site and the mobile sites (ΔQ_H) are compared to the corresponding sizes of the 0.5–level source area, calculated for the Sunset site and the time of the measurements. Thus, the degree of scatter of these differences should be reduced with increasing source area.

One measure of the degree of scatter (or the spread) of the inter-site differences is available from a method described by Chambers *et al.* (1983). For a set of points (x_i, y_i), they estimate the spread of the y_i versus x as the median absolute deviation from a locally weighted non-parametric regression curve through the set of points (LOWESS, see Cleveland, 1979). In the present analysis, the resulting curve is a graphical representation of the degree to which the ΔQ_H-values vary around their local median value as a function of their respective source area sizes.

This method is applied to the sensible heat flux variability (ΔQ_H spread) between the Sunset and the mobile data for both the inter-site period and the calibration period (Figure 9). While the curve for the inter-site period shows a marked reduction of spatial variability towards larger source areas, an overall trend is virtually absent in the calibration period. In view of the theoretical arguments above, this latter result comes as no surprise: during the calibration period, the two sensors are mounted side by side and are thus affected by the same source area. However, the dependence of the measurable spatial variability on the size of the source area during the inter-site period is clearly demonstrated by the upper curve in Figure 9. When the source area is small, the individual measurements may not be representative of the dominant morphological scales of the urban surface and are subject to considerable spatial variability. Larger source areas correspond to flow conditions with a more "efficient spatial averaging power". Thus, the flux measurements are representative of a large area, leaving less room for variation.

5.3. Anthropogenic heat flux

Using the database, it is possible to calculate the size of the Q_F flux for each grid square for any hour for which the data are available; in this case, any hour between YD 87/22 and 87/179. Figure 10 is a map of Q_F for 9:00 LAT on YD 87/22. Q_F varies from zero over the Fraser river and some farm land in Richmond (see Figure 2), to approximately 80 $W \cdot m^{-2}$, where two major roads and high density

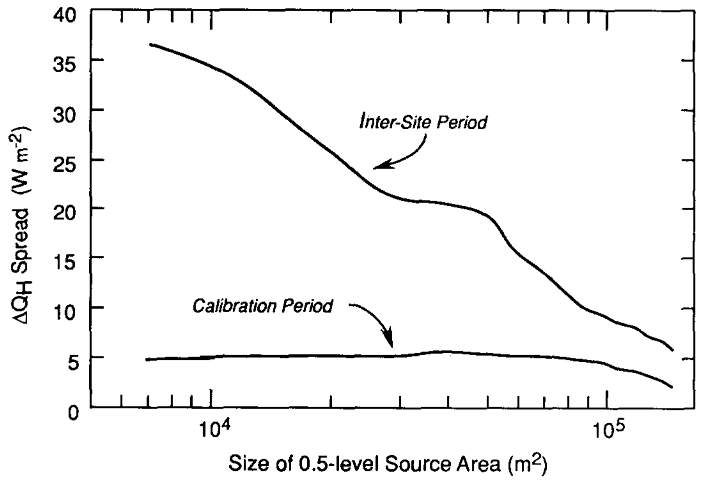

Fig. 9. Dependence of the spatial variability of sensible heat flux (ΔQ_H Spread) on the size of the source area. With increasing source area the measurements of sensible heat flux are representative of a larger area and their spatial variability is reduced. This effect is absent when two instruments mounted on the same tower are compared during a calibration period.

housing are present in one square. Comparison of this map with that of major roads reveals the importance of the heat produced by combustion of vehicle fuels in suburban terrain because the general grid nature of the streets is evident in the Q_F map. The temporal variability of the spatial Q_F distribution is related to diurnal, weekly and annual patterns of human activities and can be complex. In general, Q_F due to fuel combustion of vehicles and industrial activity exhibits a distinct diurnal and weekly pattern with little spatial variation (i.e., the spatial structure of Q_F variations is similar at all times but may have a temporal variation in amplitude) (Grimmond, 1988). The same can be said for heat sources due to space heating, except that here also a distinct annual pattern can be expected.

5.4. Storage heat flux

Similar to Q_F, the storage heat flux density for each grid volume for any hour or any energy conditions may be calculated, using the surface database and a hysteresis effect method.

Figures 11a, b are maps of the ΔQ_S ensemble (YD 87/22–87/179) distribution at 8:00 LAT when $(Q^* + Q_F) = 30\ \mathrm{W \cdot m^{-2}}$, $d(Q^* + Q_F)/dt = 107\ \mathrm{W \cdot m^{-2}\,h^{-1}}$ and 12:00 LAT when $(Q^* + Q_F) = 550\ \mathrm{W \cdot m^{-2}}$, $d(Q^* + Q_F)/dt = 55\ \mathrm{W \cdot m^{-2}\,h^{-1}}$. The net range and magnitude of ΔQ_S in the two examples are quite different: in the morning (8:00 LAT), it varied from -9 to $+29 \cdot \mathrm{W\,m^{-2}}$ and at noon (12:00 LAT) from 151 to $292\ \mathrm{W \cdot m^{-2}}$. At the earlier time, parks have the highest rate of storage, but the spatial ΔQ_S distribution was quite flat, the principal variations occurring at large scales (Figure 11a). In contrast, at midday the road pattern was most evident and the small scale spatial variability of ΔQ_S was en-

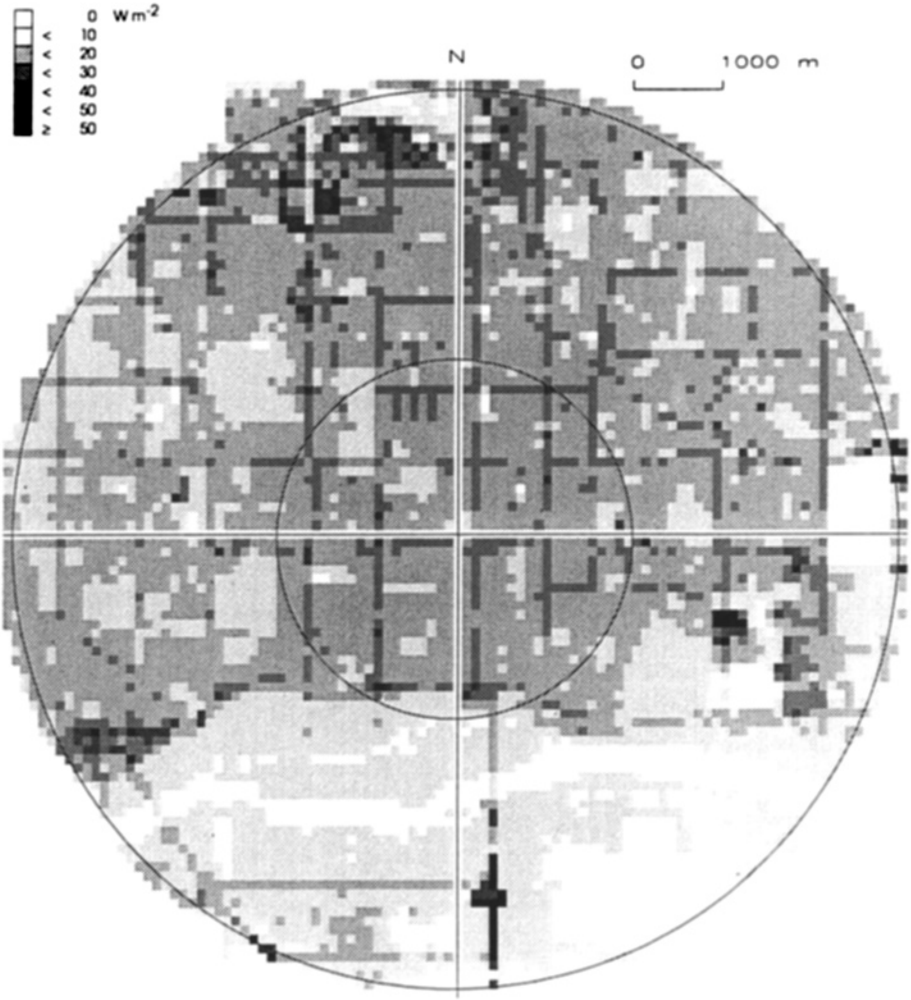

Fig. 10. Map of anthropogenic heat flux for 9:00 L.A.T. on YD 87/22. Hectare grid centered on the Sunset site. The inner circle has a radius of 2 km.

hanced (Figure 11b). Note that in Figure 11a, b the grid squares which have the largest flux were not the same at both times (parks in the morning, roads at noon), although those with the smallest fluxes were similar (residential areas). This reflects the different Q^* vs ΔQ_S responses (hysteresis effect) of different surfaces.

5.5. Speculations on the spatial variability of the turbulent latent heat flux

In this study, the latent heat flux is treated as a residual of the energy budget equation and no direct information on its spatial variability is available. However, an estimate can be made, firstly, by examining the results of other studies where the measured or modelled spatial variability of Q_E at a larger scale is available,

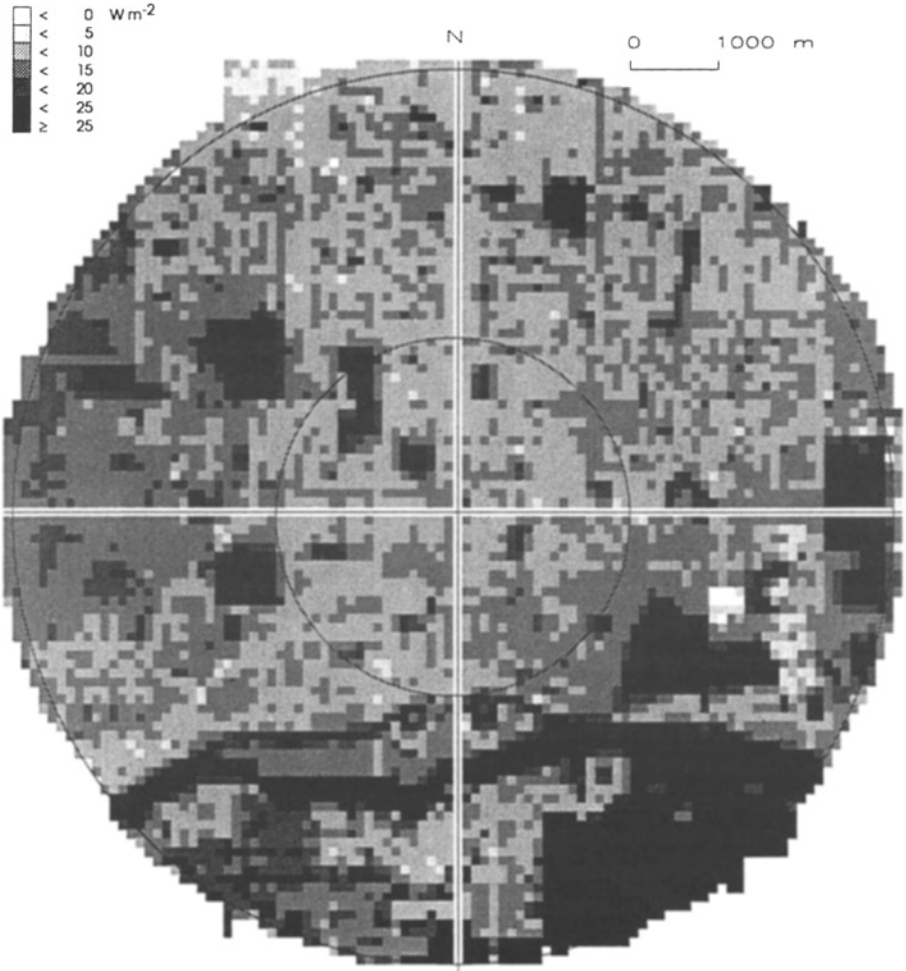

Fig. 11(a).

and secondly, by recognizing that the source area concept used for Q_H can also be applied to Q_E.

Ching *et al.* (1984) present data of sensible and latent heat flux from aircraft measurements at a height of 150 m over St.Louis and the surrounding region. The minimum scale resolved by this study allows estimates of the variability between land-use zones, but only to a limited degree within the same zone. The influence of land-use on the partitioning of enthalpy between Q_H and Q_E, rather than directly on the individual fluxes is demonstrated quite clearly by their results. Thus, the Bowen ratio varies much more than the sum of Q_H and Q_E. This observation supports the notion that the Q_H- and the Q_E-variabilities are comparable in character and amplitude, although Ching *et al.* (1984) note that the spatial complexities of Q_E are rather larger than those of Q_H. Carlson *et al.* (1981)

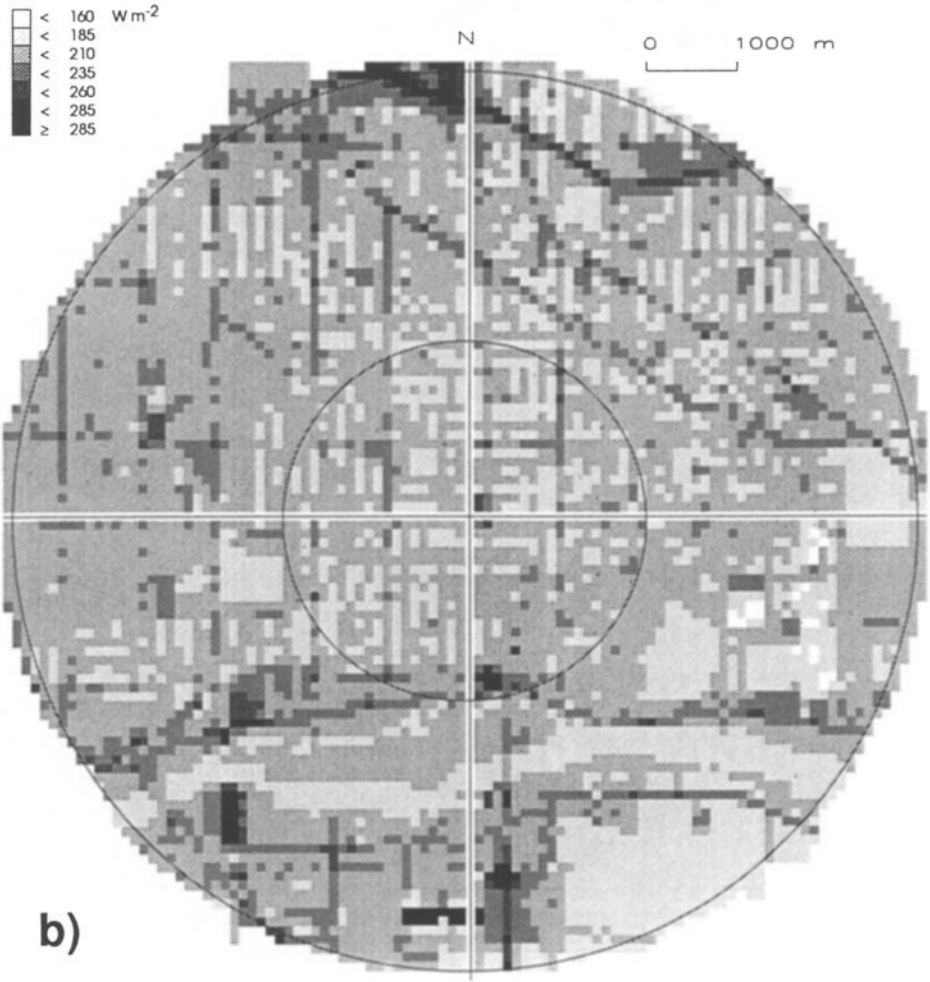

Fig. 11. Map of storage heat flux; (a) 8:00 L.A.T.; (b) 12:00 L.A.T. (ensemble of all days modelled). Hectare grid centered on the Sunset site. The inner circle has a radius of 2 km.

used a one-dimensional boundary layer model and satellite data to estimate the distribution of energy balance components over St.Louis and Los Angeles at a scale of about $6 \cdot 10^2$ m. However, at that scale there were no direct measurements available for comparison. Their model results for St.Louis show similar patterns but reversed gradients for the Q_H and the Q_E distributions, as confirmed by Ching *et al.* (1984) for the larger scales.

This empirical evidence suggests that the measurable spatial variability of Q_E is dependent on the source areas of the sensors and thus is immediately associated with the temporal variability, as was found for the sensible heat flux. It is suspected that in the presence of a mix of impervious and vegetated surfaces, the discrete nature of the vegetation distribution and temporally variable irrigation patterns may induce a stronger variability in Q_E than in Q_H.

6. Conclusions

The spatial variations of some surface energy flux terms at the smallest scales of urban morphology (e.g., at tens to hundreds of metres) are comparable in magnitude to urban-rural differences. It has been shown that this may be the case even in an area that is considered to be homogeneous at the land-use scale (e.g., several kilometres). This finding should be considered, when areal averages of values for the surface energy balance are needed. Specifically, it is suggested that micro-advective effects are important at scales that are commonly sub-grid to most flow and diffusion models over suburban areas.

The magnitude and spatial structure of flux variations are different for the individual energy balance components. Anthropogenic heat flux and net heat storage change must exhibit patterns that closely follow the structure of the surface morphology and variations may range over several orders of magnitude. Variations of daytime turbulent sensible heat flux of up to 40% at scales of 10^2–10^3 m and at a height of 28 m have been found in the present study. The least spatially sensitive term of the surface energy balance is found to be the net radiation. Although the inherent spatial average in the direct measurement of net radiation ("view factor" source area) normally includes a smaller domain than the turbulent diffusion source area for the same height, the spatial variability of net radiation was found to be about four times smaller than that for turbulent sensible heat flux. This conservative behaviour of net radiation is attributed to a negative feedback between the long- and short-wave portions of the radiation budget.

Direct measurement of the turbulent fluxes includes a built-in spatial average to a certain degree, but this may be insufficient if the source area is small. Measured spatial variability of sensible heat flux shows a pronounced tendency to increase if source areas are small. Thus, the resolvable spatial variability of turbulent fluxes depends on measurement height, surface roughness, thermal stability and lateral wind fluctuations.

A further complication arises from recognition that turbulent source areas are not stationary in time, in contrast to the radiation, storage and combustion heat source areas. Thus, for example, the domain of spatial averaging of an eddy correlation measurement is constantly changing and the temporal variability of the flux measurement is linked to its spatial variability, whereas the averaging domains for the other balance terms remain unchanged. Therefore, care should be taken that each term is evaluated as an appropriate spatial average, in order to obtain values that are consistent with a spatially representative energy balance. If a single estimate for anthropogenic heat production (or a measurement of ground heat flux) is compared with measured net radiation and turbulent fluxes, the energy balance should not be expected to close. If this principle is neglected, and one term is treated as a residual, the compounded errors may be large.

In the case of turbulent fluxes, it is concluded that the requirements for measurements to be representative of a suburban area may be defined by two limiting factors: on the one hand, influences from other land-use areas (i.e., from scales larger than the suburban scale) can be excluded by satisfying the fetch conditions suggested by Ching *et al.* (1983); on the other hand, small-scale surface inhomogeneities (i.e., at a scale smaller than the suburban scale) can be effectively averaged by ensuring that the turbulent source area is large enough to include the dominant units of suburban morphology.

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References

Auer, A.: 1978, 'Correlation of Land Use and Cover With Meteorological Anomalies', *J. Appl. Meteorol.* **17**, 636–643.

Briggs, G. A.: 1988, 'Surface Inhomogeneity Effects on Convective Diffusion', *Boundary-Layer Meteorol.* **45**, 117–136.

Carlson, T. N., Dodd, K. J., Benjamin, S. G., and Cooper, J. N.: 1981, 'Satellite Estimation of the Surface Energy Balance, Moisture Availability and Thermal Inertia', *J. Appl. Meteorol.* **20**, 67–91.

Chambers, J. M., Cleveland, W. S., Kleiner, B. and Tukey, P. A.: 1983, *Graphical Methods for Data Analysis*, Duxbury Press, Boston, Wadsworth Statistics/Probabilitiy Series, 395 pp.

Ching, J. K. S., Clarke, J. F., and Godowitch, J. M.: 1983, 'Modulation of Heat Flux by Different Scales of Advection in an Urban Environment', *Boundary-Layer Meteorol.* **25**, 171–191 .

Ching, J. K. S., Godowitch, J. M., Clarke, J. F., and Auer, A. H.: 1984, 'Urban Scale Variations of Turbulence Parameters and Fluxes', *Proc. of AMS Specialty Conf. on Air Quality Modeling of the Nonhomogeneous, Nonstationary Urban Boundary Layer*, Baltimore, MD., AMS, Boston, MA.

Cleugh, H. A. and Oke, T. R.: 1986, 'Suburban-Rural Energy Balance Comparisons in Summer for Vancouver B.C.', *Boundary-Layer Meteorol.* **36**, 351–369.

Cleveland, W. S.: 1979, 'Robust Locally Weighted Regression and Smoothing Scatterplots', *J. Amer. Statist. Assoc.* **74**, 829–836.

Dyer, A. J. and Hicks, B. B.: 1972, 'The Spacial Variability of Eddy Fluxes in the Constant Flux Layer', *Quart. J. Roy. Meteorol. Soc.* **98**, 209–212.

Garratt, J. R.: 1978, 'Transfer Characteristics for a Heterogeneous Surface of Large Aerodynamic Roughness', *Quart. J. Roy. Meteorol. Soc.* **104**, 491–502.

Grimmond, C. S. B.: 1983, 'The Suburban Water Balance: Daily, Monthly and Annual Results from Vancouver, B.C.', M.Sc. Thesis, The University of British Columbia, Vancouver, 172 pp.

Grimmond, C. S. B.: 1988, 'An Evaporation-Interception Model for Urban Areas', Ph. D. Thesis, The University of British Columbia, Vancouver, B.C., 206 pp.

Oke, T. R.: 1979, 'Advectively-Assisted Evapotranspiration from Irrigated Urban Vegetation', *Boundary-Layer Meteorol.* **17**, 167–173.

Oke, T. R.: 1984, 'Methods in Urban Climatology', in Kirchhofer, W., Ohmura, A., and Wanner, H. (eds.), *Applied Climatology, Proc. 25th Int. Congr. Appl. Geogr., Symp.* 18, Zürich, August **21**,1984, *Zürch. Geogr. Schr.* **14**, 19–29.

Oke, T. R.: 1988, 'The Urban Energy Balance', *Prog. Phys. Geogr.* **12**, 471–508.

Orlanski, I.: 1975, 'A Rational Subdivision of Scales for Atmospheric Processes', *Bull. Amer. Meteorol. Soc.* **56**, 527–530.

Panofsky, H. A.: 1973, 'Tower Micrometeorology', in Haugen, D. A. (ed.), *Workshop on Micrometeorology*, AMS, Boston, Mass., 151–176.

Pasquill, F.: 1972, 'Some Aspects of Boundary Layer Description', *Quart. J. Roy. Meteorol. Soc.* **98**, 469–494.

Raupach, M. R. and Thom, A. S.: 1981, 'Turbulence in and above Plant Canopies', *Ann. Rev. Fluid Mech.* **13**, 97–129.

Reifsnyder, W. E.: 1967, 'Radiation Geometry in the Measurement and Interpretation of Radiation Balance', *Agricultural Meteorol.* **4**, 255–265.

Schmid, H. P. and Oke, T. R.: 1990, 'A model to estimate the source area contributing to turbulent exchange in the surface layer over patchy terrain', *Quart. J. Roy. Meteorol. Soc.* **116**, 965–988.

Smith, M. O., Simpson, J. R., and Fritschen, L. J.: 1985, 'Spatial and Temporal Variation of Eddy Flux Measures of Heat and Momentum in the Roughness Sublayer Above a 30-m Douglas Fir Forest', in Hutchison, B. A. and Hicks, B. B., (Eds.), *The Forest-Atmosphere Interaction*, Reidel, Dordrecht, 563–582.

Steyn, D. G. and Faulkner, D. A.: 1986, 'The Climatology of Seabreezes in the Lower Fraser Valley, British Columbia', *Climatological Bull.* **20**, 21–39.

Tennekes, H.: 1973, 'The Logarithmic Wind-Profile', *J. Atmos. Sc.* **30**, 234–238.

White, J. M., Eaton, F. D., and Auer, A. H.: 1978, 'The Net Radiation Budget of the St.Louis Metropolitan Area', *J. Appl. Meteorol.* **17**, 593–599.

Willmott, C. J.: 1981, 'On the Validation of Models', *Phys. Geogr.* **2**, 184–194.