Suburban Energy Balance Estimates for Vancouver, B.C., Using the Bowen Ratio-Energy Balance Approach

B. D. KALANDA AND T. R. OKE

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

D. L. SPITTLEHOUSE

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

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ABSTRACT

The energy balance of a suburban site in Vancouver, B.C. in late summer is presented. The balance is obtained from direct measurements of net radiation, parameterized heat storage and turbulent fluxes determined according to the Bowen ratio-energy balance method with reversing psychrometers. An error analysis shows the turbulent fluxes are good to within 10–20% by day. Features of the suburban energy balance are found to be intermediate between those previously reported for urban and rural surfaces. Average daytime Bowen ratios are usually in the range 0.5–1.0 with some days as high as 2.5. The daytime sensible heat flux is in-phase with the net radiation. At night this flux is sometimes positive. Evapotranspiration is always an important term in the balance. The role of urban irrigation and microscale heat advection in maintaining evapotranspiration rates is discussed.

1. Introduction

Cities are one of the few remaining surfaces awaiting satisfactory energy balance analysis. This information is required to provide the energetic basis of urban climates and thereby an ability to construct realistic numerical models of urban atmospheric processes. Such models hold the potential for predicting the outcome of different land use/emission strategies on the atmospheric environment of urban areas. This could be of immense value in, among others, air quality and fuel consumption considerations.

Different scales of energy balance analysis will be required to adequately characterize the situation. On the microscale we may be interested in the conditions operating within the urban canopy layer (Oke, 1976) which exists beneath mean roof level in between the urban roughness elements (buildings and trees). Examples of such studies include those of Landsberg and Maisel (1972) and Oke (1979a) for individual surfaces and Nunez and Oke (1977) for urban canyon systems.

At the local or mesoscale we may be interested in the energy exchanges over areas of tens of square kilometers. Then, instead of individual surfaces or units, we need to know about the integrated response of the urban surface to external forcing functions (e.g., solar radiation, precipitation, wind) and their effect upon the urban boundary layer whose lower limit is the top of the urban canopy layer (e.g., the top of the box illustrated in Fig. 1). The energy balance of such an integrated urban surface is best represented in terms of the energy fluxes passing through the top of a representative soil-building-air volume such as that in Fig. 1 which extends to a depth where there is no net vertical heat exchange over the period of interest. Then if the volume is located in a large enough area of uniform urban land-use so that advective influences can be neglected, the balance becomes

$$Q^* = Q_H + Q_E + \Delta Q_S, \qquad (1)$$

where Q^* is the net all-wave radiative heat flux density; Q_H, Q_E are the turbulent transports of sensible and latent heat flux density, respectively; and ΔQ_S is the net heat storage change in the volume expressed as an equivalent vertical flux through unit surface area of its top. This formulation ignores the presence of any anthropogenic heat sources within the volume. For completeness such a term may be added to the left-hand side of (1). Attempts to measure or otherwise evaluate the terms in (1) usually rely on instrumentation mounted on roof-top masts, tall towers or aircraft. Examples include the studies of Oke *et al.* (1972), Yap and Oke (1974a), Dabberdt

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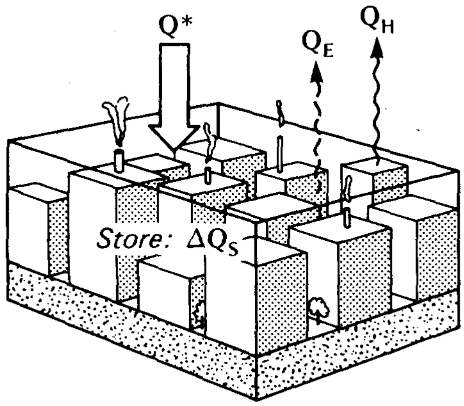

FIG. 1. Schematic depiction of the fluxes involved in the energy balance of an urban soil-building-air volume. Note that heat fluxes due to horizontal advection and anthropogenic heat production have been neglected (after Oke, 1978).

and Davis (1978), Ching *et al.* (1978),[1] Oke (1978)[2] and Coppin (1979). The latter three studies all used eddy correlation instrumentation mounted on tall towers to assess the turbulent components, but only one (Oke, 1978) has attempted to close the complete balance.

This paper is concerned with an evaluation of the energy balance of a uniform suburban surface during the late summer in Vancouver, B.C. The turbulent fluxes were evaluated using the Bowen ratio-energy balance method (Section 2). Since this approach has not been fully tested in the urban boundary layer its merits are evaluated (Section 3) before the experimental results are presented (Sections 4 and 5).

2. Experimental site and instrumentation

The observation site (hereinafter referred to as the Sunset site) was located in a suburban area of south Vancouver, B.C. (49°13′N, 123°4′W, Fig. 2a). The terrain is generally flat in the vicinity of the site and single-family (1–2 story) housing is the predominant land-use to at least 2 km in all directions (Fig. 2b). In the circle of 2 km radius centered on the site 64% of the area was covered with greenspace (mainly lawns, parks and a cemetery), 14% with houses, 11% with commercial and institutional buildings (mainly shops and schools) and the remaining 11% with paved surfaces. Many modern cities (especially in North America) have the bulk of their land-use in a similar format (e.g., Marotz and Coiner, 1973). The surface albedo of the area is 0.12–0.14 (Steyn and Oke, 1979) and based on geometric considerations (Kutzbach, 1961[3]; Lettau, 1969; Counihan, 1971) the surface roughness length is between 0.5 and 1 m, and the zero-plane displacement is ~3.5 m. The study was conducted in the period mid-August to mid-October 1977.

The suburban energy balance terms of (1), schematized in Fig. 1, were evaluated as follows. Net all-wave radiation (Q^*) was monitored with a net pyrradiometer (Swissteco, Model S1) mounted at 12 m above mean roof level on a 30 m free-standing tower. The sensor was purged with dry air by a recirculating system (Stevens and Wright, 1977) and its output was recorded on a data logger (Doric Scientific, Model 210).

The flux of energy due to heat storage change in the volume (ΔQ_S) was parameterized in terms of the net all-wave radiation according to the scheme outlined in full by Oke *et al.* (1979). The method relies upon a series of equations relating these two fluxes for a variety of urban materials and surfaces. These are then weighted according to the fraction of each surface type in the landscape. For the Sunset site the parameterization is

$$\text{Day:}\quad \Delta Q_S = 0.25(Q^* - 27), \tag{2}$$

$$\text{Night:}\quad \Delta Q_S = 0.67Q^*, \tag{3}$$

which yields values in watts per square meter. The error in an estimate of ΔQ_S is arbitrarily, but probably conservatively, set at $\pm 0.05Q^*$.

The turbulent fluxes (Q_H, Q_E) were determined using the Bowen ratio-energy balance method. The Bowen ratio (β) is defined as $\beta = (Q_H/Q_E)$. Assuming similarity of the eddy diffusivities for heat and water vapor this simplifies to

$$\beta = \gamma\overline{\Delta\theta}/\overline{\Delta e}, \tag{4}$$

where γ is the psychrometric constant, $\overline{\Delta\theta}$ the mean potential air temperature difference between two measurement heights and $\overline{\Delta e}$ the mean atmospheric vapor pressure difference, corrected for the natural decrease in pressure with height, over the same height interval. Substitution of (4) into (1) and rearranging gives

$$Q_H = (Q^* - \Delta Q_S)/(\beta^{-1} + 1), \tag{5a}$$

$$Q_E = (Q^* - \Delta Q_S)/(1 + \beta). \tag{5b}$$

The assumption of similarity has been shown to be valid in the unstable and near-neutral cases for a variety of surfaces.

Some advantages of the method are the durability

[1] Ching, J. K. S., J. F. Clarke and J. M. Godowitch, 1978: The variability of the heat flux and mixed layer depth over St. Louis, Missouri. *Proc. WMO Symp. Boundary Layer Physics, Application to Specific Problems & Air Pollution*. WMO No. 510, 71–78.

[2] Oke, T. R., 1978: Surface heat fluxes and the urban boundary layer Proc. WMO Symp. Boundary Layer Physics, Applied to Specific Problems of Air Pollution. WMO No. 510, 63–69.

[3] Kutzbach, J., 1961: Wind tunnel determination of the roughness length as a function of the fetch and roughness. Annual Report, Dept. of Meteorology, University of Wisconsin, Madison, 71–113.

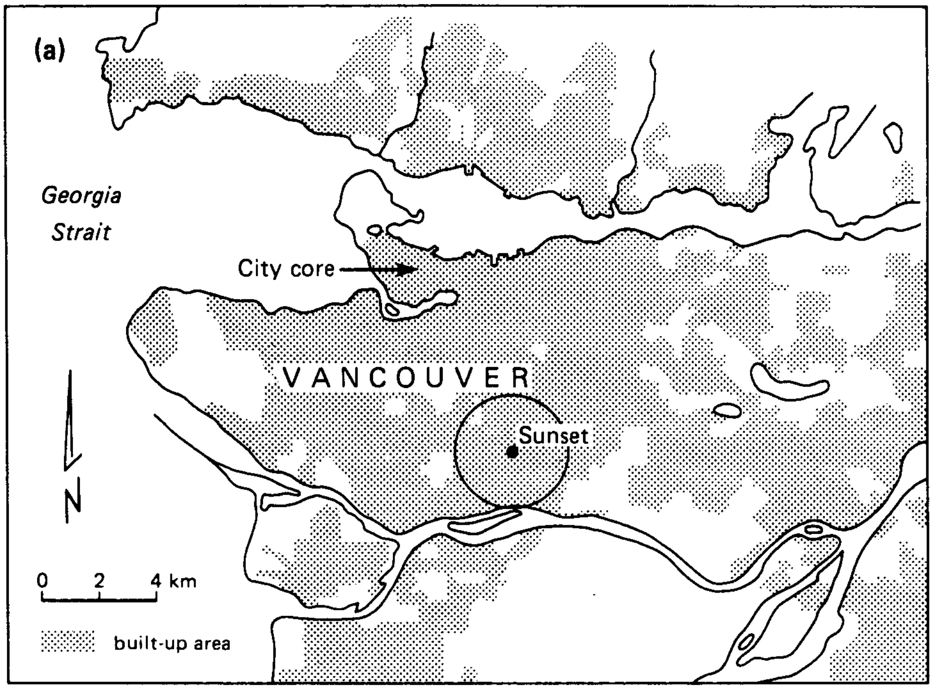

FIG. 2a. Location of the Sunset suburban site. Circle around the Sunset site has a radius of 2 km.

of the measurement system, the ability to run for extended periods (days) without maintenance and the measurement of turbulent energy partitioning even if the available energy ($Q^* - \Delta Q_S$) is in error or not available.

The temperature and humidity differences necessary to evaluate (4) were measured at a mean height of 10.5 m above mean roof-level, over a 4 m vertical separation by a reversing differential psychrometer system (Fig. 3) similar to that described by Black and McNaughton (1971). The system consists of two vertically-separated wet- and dry-bulb psychrometers (aspirated at ~3.5 m s^{-1}), a reversing motor assembly and a data logger-control unit to integrate and record the signals and to control the operation logic. The reversing mechanism interchanges the position of the sensing heads every 15 min. Following reversal the sensors are allowed to equilibrate for 5 min, then their signals are integrated for 10 min before the next reversal. Combining the data from two consecutive 15 min periods effectively eliminates any systematic errors between thermometer pairs.

The system used in this investigation differed slightly from that referenced above:

- Silicon (Fairchild FD300) rather than germanium diodes were used because of their linear output from at least 240–370 K, high sensitivity

FIG. 2b. Photograph of Sunset suburban site taken from the tower looking toward the west.

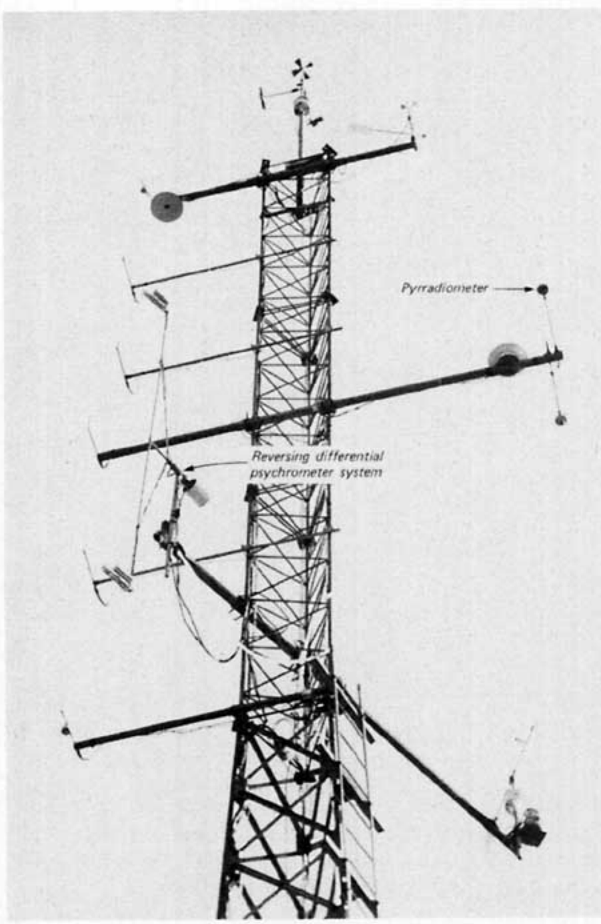

FIG. 3. The reversing differential psychrometer system mounted on the tower.

(~2 mV K^{-1}), low cost and easy availability. Each diode pair was calibrated and matched to ±0.1%.

• The use of the smaller silicon diodes allowed the use of a smaller internal diameter for the sensor housing (20.9 mm ID) and reduced the power requirements for adequate aspiration. Furthermore, by using acrylic tubing (schedule 40 PVC irrigation tubing, 250 mm in length, 2.9 mm wall thickness) a lighter yet still durable sensing housing was realized. To reduce solar heating the acrylic tubes were wrapped in a 7 mm thick layer of closed cell foam rubber and an outer layer of highly reflective tape (aluminized Mylar). A boiled sock shoelace was used as a wick to supply water from a large reservoir covered with aluminized Mylar tape and mounted parallel to the housing. The power supply for the diodes was located in the data logger-control unit. In this unit the differential output of the wet-bulb pair and the dry-bulb pair was continually monitored by dual-ramping integrators (Tang *et al.*, 1976). Integrator sensitivity was 1000 counts $(mV\ h)^{-1}$ and the combined calibration and stability error of these integrators was ±0.3%.

• The 4 m vertical separation between sensing heads was used in anticipation of small vertical temperature differences. These were expected due to the enhanced mixing induced by the rough suburban surface and the need to place the sensors well above the urban canopy.

Anthropogenic heat releases occurred within the volume but were not evaluated separately because they are already included in some of the measured fluxes. For example, the heat lost via chimney stacks will be included in the turbulent sensible and latent heat fluxes, that seeping out through the building fabric to the exterior will alter the surface temperature and therefore the long-wave portion of the net radiation budget and the surface-to-air gradient supporting the sensible heat flux. However, anthropogenic contributions to storage are not evaluated because the equations used in the parameterization do not include this term, indeed, it could be argued that because net radiation will probably be diminished by the increased longwave loss the parameterized storage value will be affected in the wrong direction. The exact size of this error is not known but is expected to be small (<25 W m^{-2}) in the summer in Vancouver (Yap, 1973).

Advective heat fluxes at the site were assumed to be negligible. This assumption is based on the following grounds:

• Great care was exercised in the choice of the tower site to ensure that the surrounding suburban land-use was as extensive and spatially homogeneous as possible. A minimum suburban fetch of 2 km existed, and in the southwest–northwest quadrant from which most daytime winds occur, it is considerably greater (at least 8 km) (Fig. 2a). Analysis of the internal composition (greenspace, houses, etc.) of each of 16 land-use sectors in the circle of 2 km radius based at the tower showed remarkably little deviation from the mean values given at the start of this section. Surveys of the spatial variability of the air temperature in the vicinity of the site showed slack horizontal gradients at this location within the heat island.

• The heights of observation for Bowen ratio measurements (8.5 and 12.5 m above mean roof level) were chosen to be high enough to minimize local surface wake effects but low enough to ensure their placement inside the suburban internal boundary layer. The lowest sensors were ~20 roughness lengths above the zero-plane displacement level and this combined with the characteristically large turbulence intensities encountered over suburban terrain should ensure effective mixing of individual canopy layer plumes in all but very light wind conditions. Using the roughness length for the site and a minimum fetch of 2 km the depth of the suburban internal boundary layer should be in excess of 40 m in adiabatic conditions and greater in unstable conditions (Munro and Oke, 1975).

- Analyses by Kalanda (1979) and Steyn (1980) show no dependence of heat fluxes on wind direction at the site.
- Based on the urban and suburban work of Yap and Oke (1974a) and Coppin (1979) a 1 h averaging period was adopted. This rather long period takes advantage of the natural variability of wind direction and the lateral mixing it produces.

3. Evaluation of methodology

The Bowen ratio-energy balance method of determining the turbulent heat fluxes has never been fully evaluated in the urban boundary layer. If confidence is to be placed in the flux estimates it is imperative that an error analysis be undertaken because there is reason to expect that the crucial vertical wet- and dry-bulb temperature differences are likely to be small. The experience of this study confirmed that at approximately 10 m above roof level these differences were <0.05 K m^{-1}. This situation places very stringent requirements on the measurement system if unacceptably large errors are to be avoided.

The error analysis follows those of Cook and Rabinowicz (1963), Fuchs and Tanner (1970) and Bailey (1977). The probable error (δY_{prob}) of a given result Y from a combination of measurements ($x_1, x_2, \ldots, x_n$) having associated errors ($\delta x_1, \delta x_2, \ldots, \delta x_n$) is

$$\delta Y_{\text{prob}} = \left[\left(\frac{\delta Y}{\delta x_1}\delta x_1\right)^2 + \left(\frac{\delta Y}{\delta x_2}\delta x_2\right)^2 + \cdots + \left(\frac{\delta Y}{\delta x_n}\delta x_n\right)^2\right]^{1/2}.$$

Equations of this form were constructed using all available evidence concerning the size of error sources contributing to measurements of: the absolute values and the vertical differences of wet- and dry-bulb temperature; the Bowen ratio; the net allwave radiation (and the heat storage derived from Q^*); and the sensible and latent heat flux densities. Full details of the values used are given in Kalanda (1979).

An example of the computed probable errors $\delta\beta$, δQ_H and δQ_E at a wet-bulb temperature of 288 K is given in Table 1.

The full analysis showed that for $\beta > 0$ the errors $\delta\beta$, δQ_E and δQ_H decrease as the wet-bulb temperature increases (i.e., $\overline{\Delta e}$ increasing) and that they increase rapidly as the magnitude of the temperature differences become smaller. Over the suburban area the wet-bulb difference was usually smaller than the dry-bulb difference and therefore was the most significant term contributing to errors. These findings have obvious implications regarding the viability of this method in hotter/drier/rougher environments than encountered in this study. The error in the hourly turbulent flux estimates in the suburban area were typically 10–20% by day (β typically <3.0), and 25% or more at night. Such values are slightly larger than found over crops (e.g., Davies and Allen, 1973; Bailey, 1977), but about the same as those for a forest (McNaughton and Black, 1973; Spittlehouse and Black, 1980) and were considered acceptable for the purposes of this study. The errors are reduced to <10% for daytime or 24 h energy totals. To aid interpretation of the results error bars are added to all graphs where appropriate.

TABLE 1. Errors in the Bowen ratio, and the latent and sensible heat flux densities given measurements of the vertical wet- and dry-bulb temperature differences over a vertical separation of 4 m. The analysis is based on probable errors of ±0.004 K and ±1 Pa in the measurement of differential temperature and vapour pressure respectively, and applies to the case of a wet-bulb temperature of 288 K, a net radiation of 200 W m^{-2} and a heat storage of 43 W m^{-2}.

ΔT (K)	ΔT_w (K)	β	$\pm\delta\beta$ (%)	Q_E (W m^{-2})	$\pm\delta Q_E$ (%)	Q_H (W m^{-2})	$\pm\delta Q_H$ (%)
−0.400	−0.421	0.50	6	105	10	53	10
−0.400	−0.286	1.00	8	79	10	79	10
−0.400	−0.218	2.00	12	52	12	105	10
−0.400	−0.195	3.00	17	39	15	117	10
−0.200	−0.196	0.50	6	105	10	53	10
−0.200	−0.135	1.00	10	79	10	79	10
−0.200	−0.105	2.00	17	52	14	105	11
−0.200	−0.095	3.00	23	39	20	117	11
−0.160	−0.151	0.50	8	105	10	53	11
−0.160	−0.105	1.00	11	79	11	79	11
−0.160	−0.083	2.00	20	52	16	105	11
−0.160	−0.075	3.00	28	39	23	117	12
−0.120	−0.106	0.50	10	105	10	53	11
−0.120	−0.075	1.00	15	79	12	79	12
−0.120	−0.060	2.00	27	52	20	105	13
−0.120	−0.055	3.00	38	39	30	117	13
−0.080	−0.061	0.50	16	105	11	53	14
−0.080	−0.045	1.00	27	79	16	79	16
−0.080	−0.038	2.00	48	52	33	105	18
−0.080	−0.035	3.00	70	39	53	117	20
−0.060	−0.038	0.50	30	105	14	53	22
−0.060	−0.030	1.00	50	79	27	79	27
−0.060	−0.026	2.00	91	52	61	105	32
−0.060	−0.025	3.00	133	39	190	117	74

4. Suburban energy balance

Interest in the suburban energy balance centers on the turbulent terms especially the partitioning of heat into sensible and latent forms and the magnitude, sign and temporal variation of these fluxes. This does not mean that the net radiation and heat storage terms are unimportant because, of course, they represent the net available energy in the system to support the turbulent fluxes. Rather it reflects the fact that we know somewhat more about the

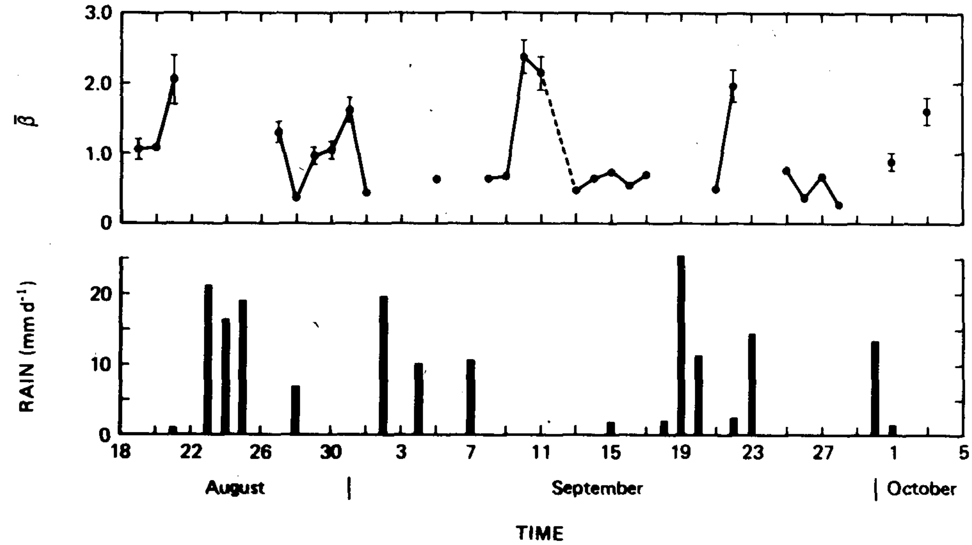

FIG. 4. Daily values of mean daytime Bowen ratio $\bar{\beta}$ and precipitation during the experimental period. Probable errors are shown by vertical bars.

radiation budget over urban areas and that it appears that despite the certainty that all of the component short- and longwave radiative fluxes are altered by the presence of an urban atmosphere and surface, the final outcome is not very different from that found over rural surfaces (for a summary of evidence see Oke, 1974, 1979b). In the case of the heat storage the picture is clouded by the need to resort to parameterization (Section 2) and the limitations this imposes on its interpretation (Oke *et al.*, 1979).

Several distinctive features of the turbulent energy fluxes in urban areas were discovered by Yap and Oke (1974a) and have since been largely corroborated by Ching *et al.* (1978). They include the following:

1) Periods of relatively high variability in the hourly turbulent fluxes in the midday period and also from day to day.

2) Asymmetry in the diurnal pattern of the sensible heat flux. Whilst the peaks in Q_H and Q^* are in-phase with each other the afternoon decline in Q_H is often less rapid than its increase in the morning. This produces a "tail" to the curve in the afternoon and evening.

3) The occurrence of positive Q_H values (i.e., away from the surface at night, especially between sunset and midnight).

4) The magnitude of the latent heat flux is larger than anticipated. Here we examine the Sunset suburban results for evidence of similar characteristics.

a. General features

The general pattern of turbulent energy partitioning throughout the study period (mid-August to early October 1977) is shown in Fig. 4. It includes values of the mean daytime Bowen ratio ($\bar{\beta}$), calculated from daytime totals of Q_H and Q_E, on days with at least 6 h of data when Q^* was positive. Examples of the diurnal variation of hourly β values for the period 8–14 September 1977 are presented as part of Fig. 5a–5f. This period was selected because it includes almost the full range of conditions encountered in the study (Fig. 4) and also because it will later be shown to illustrate some interesting features related to suburban evapotranspiration (Section 5).

Probably the most important result which emerges from Fig. 4 is that suburban $\bar{\beta}$ values at this site and at this time of year are usually in the range 0.5–1.0 with occasional days reaching slightly in excess of 2.0. This situation even applies to the three days at the start of this study (19–21 August) which were preceded by about five weeks with <1 mm of precipitation. Thus even under mild drought conditions this suburban area is still channeling much of its energy into latent heat. These figures are in good agreement with those obtained using eddy correlation instruments at other suburban sites in Vancouver, Uppsala (Oke, 1978), and St. Louis (Ching *et al.*, 1978), but less than those reported by Coppin (1979, β = 1.3–6.2) for Adelaide during a very hot dry spell.

b. Temporal variability of fluxes

The form of the diurnal variation in β (Fig. 5) is fairly consistent from day to day. Nocturnal values are rather erratic and may be positive or negative, more usually the latter. In the daytime they are always positive with two peaks in the early morning and evening. The peaks are not very significant since they are found at the times of net minimum absolute energy in the system and are due to the very small vertical gradients of temperature and humidity found in the day/night transition periods. Also, notice that these peaks are subject to large errors, and that in general as β becomes larger so its hour-to-hour variability and the errors associated with its measurement increase. It is quite common to find that on a day where $\bar{\beta} \approx 2$ the hourly daytime values may reach as large as 6 (e.g., Fig. 5d), whereas if $\bar{\beta} < 1$ so is the great majority of the hourly values.

The relative lack of variability in the daytime turbulent fluxes at the Sunset site is not in agreement with the suburban results of Oke (1978)[2] or Coppin (1979). This could be due to a number of differences between these studies. The Sunset study 1) is the only one to employ the Bowen ratio-energy balance approach; the others used eddy correlation systems; 2) may possess more uniform land-use characteristics than the other sites, thus damping the variability produced by changes in wind direction; and 3) may have been conducted over the site with the greatest surface moisture availability, thus tending to produce a relative suppression of thermally induced convection and a smaller range of atmospheric instability. Coppin (1979) finds that the suburban sensible heat flux cospectrum at low frequencies has a trend toward greater energy as instability increases and convection becomes more organized.

It has been suggested that the daytime oscillations seen at other sites in Vancouver might be due to air mass changes associated with the passage of sea breeze fronts (Oke, 1978).[2] Obviously, since the fluxes do not exhibit these variations very clearly at Sunset that hypothesis can not be tested, but it should be mentioned that sea breeze fronts did pass the site (usually at about 1000–1200 PDT) yet little influence on the fluxes was seen. For example, fronts were in evidence at about 1100 PDT on 8 and 9 September (Figs. 5a and 5b) but any effects on the fluxes were almost imperceptible.

Although excessive hourly variability was not clearly observed the abrupt shifts in partitioning from day to day seen by urban sites was very evident. See, for example, the reversal of the roles of the sensible and latent fluxes between 9 and 10 September (Fig. 4, 5b and 5c). In the absence of major synoptic changes it is hard to see what underlies such events. Some thoughts regarding the possible role of surface water availability are outlined in Section 5.

c. *Asymmetry of daytime flux regimes*

For the most part the midday peaks in the hourly turbulent fluxes at Sunset occur in unison with that of the net radiation (Fig. 5). Moreover the turbulent fluxes seem to retain their relative role in the balance throughout any given day so that daytime $\bar{\beta}$ values are relatively constant and symmetric about midday. Thus only a few days show any indication of the tail in the curve of sensible heat flux which is frequently found at more heavily urbanized sites and in dry, desert-like environments where both the peak and the tail are shifted into the afternoon. Equally, there is almost no evidence of the situation found in the case of moist vegetation systems where the latent heat flux peaks in the afternoon followed by a tail of relatively high values in proportion to the net radiation (often $Q_E > Q^*$) (e.g., Ripley and Saugier, 1978; Yap and Oke, 1974b; McNaughton and Black, 1973). The explanation for the late peak in Q_H at dry sites is usually related to the diurnal variation of convective instability which peaks in mid-afternoon along with the surface temperature. The late peak in Q_E at moist sites is thought to be a response to the peak in the diurnal trend of atmospheric vapor pressure deficit which occurs at about the same time (Fig. 5).

The suburban environment is largely composed of surfaces lying at either end of the moisture spectrum: dry impervious construction materials and moist irrigated greenspace. Around the Sunset site, at times other than immediately after rainfall, 36% of the surface is in the former category and a similar area is in the latter (assuming at least one half of the greenspace is irrigated). Therefore we hypothesize that the symmetric and in-phase behavior of suburban fluxes may be the result of fortuitous offsetting between the balances of the two major surface covers. Given this argument the occurrence of a tail in Q_H at suburban sites might be anticipated if soil moisture becomes limited as in a drought. Such conditions fit the reports for Uppsala (Oke, 1978) and Adelaide (Coppin, 1979).

In case there is the suspicion that the diurnal patterns were masked by the use of a parameterized heat storage term in Eq. (5) it should be noted that had any asymmetry existed in one of the turbulent fluxes it would have appeared as a trend in the Bowen ratio and this was not the case despite the afternoon peak in vapor pressure deficit (Fig. 5).

d. *Nocturnal energy balances*

Caution must be exercised when interpreting the nocturnal energy balances because the turbulent terms are often small and the fluxes are dependent on the parameterization of the heat storage. Under these circumstances it may not even be possible to be certain about the sign of Q_H or Q_E, let alone estimate their magnitude.

Nevertheless, it seems fair to say that β is typically negative at the Sunset site at night, although exceptions exist (see Fig. 5). This implies that either Q_H or Q_E is positive (i.e., either there is a flux of sensible

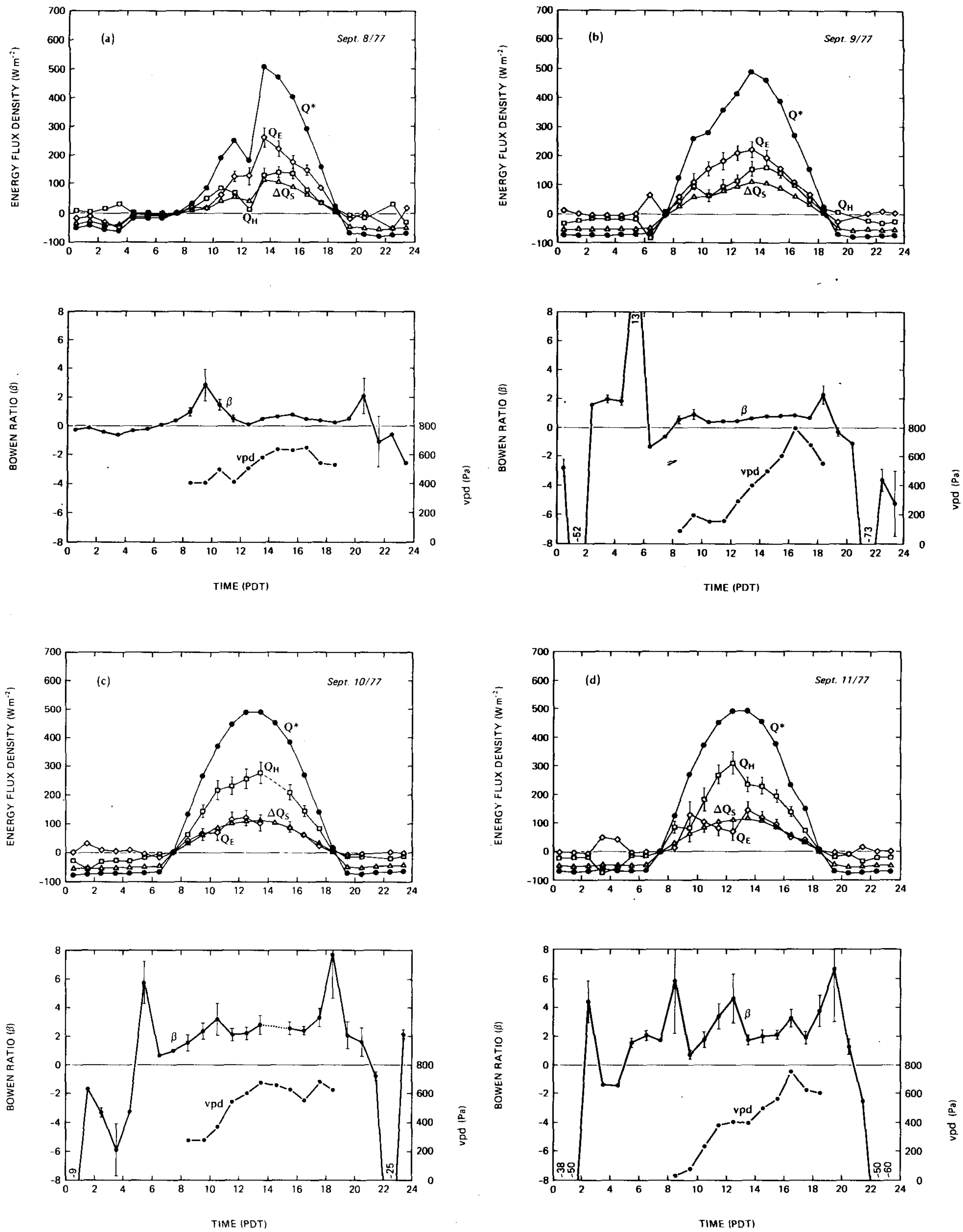

FIG. 5. Hourly variation of the energy balance components, Bowen ratio and vapor pressure deficit (vpd) at the Sunset suburban site during the drying period 8–14 September 1977. Vertical bars on the turbulent flux and Bowen ratio values are probable errors. Lack of a bar indicates the error is too small to be plotted.

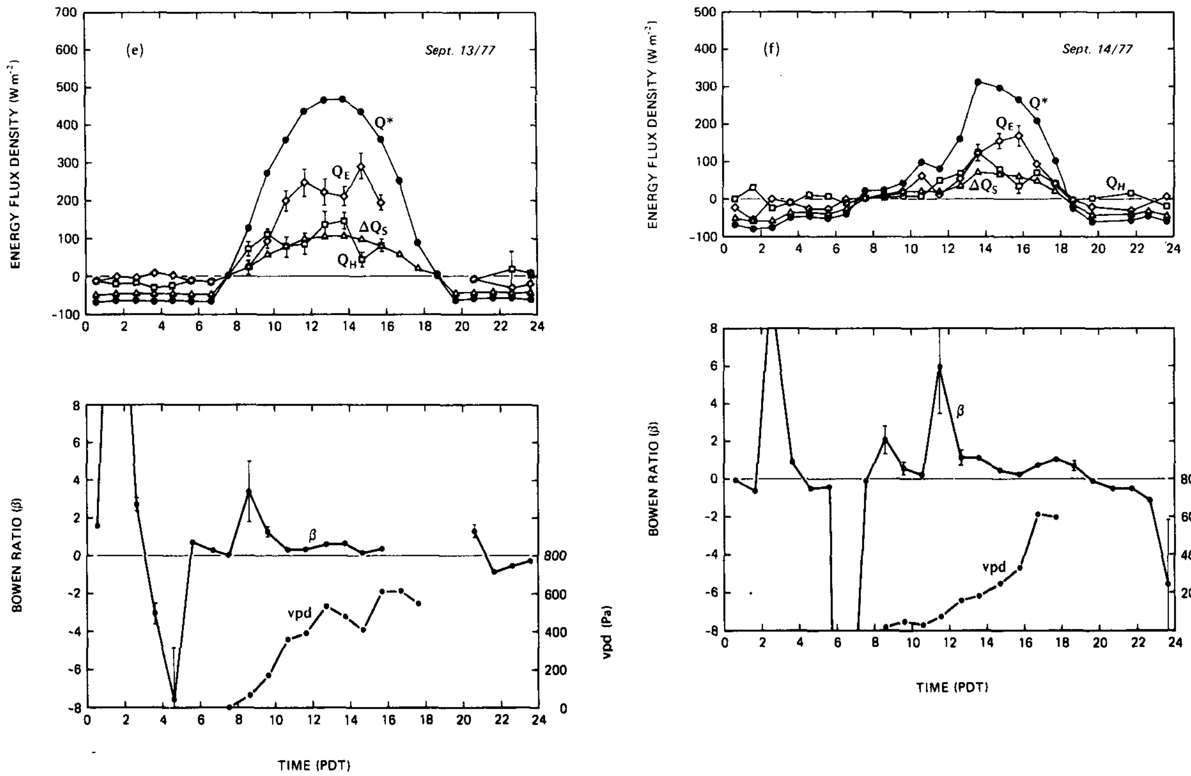

FIG. 5. (*Continued*)

heat from the surface to the air or evaporation is occurring). While the latter is a common feature of many environments, the former is almost unique to urban areas (Yap and Oke, 1974a). Both conditions were observed at the suburban site. Their frequency of occurrence was almost equal but we were unable to isolate the reasons underlying which mode was assumed. There is some association between the presence of cloud and positive Q_H as suggested by Coppin (1979), but exceptions exist.

These results are in general agreement with Oke (1978) and Coppin (1979) at other suburban sites. The suburbs would seem to represent an intermediate state between urban and rural conditions. The former exhibits positive Q_H at night on a majority of occasions and the latter almost never.

5. Evapotranspiration

Probably the most notable features of the suburban balance are the rather large magnitude of the energy involved in the water vapor flux (evapotranspiration) and the rather abrupt changes in the size of this term from day to day on some occasions despite the fact that it is fairly stable from hour to hour on any given day.

Fig. 6 provides further evidence that evapotranspiration can be large in the suburban environment. It shows the relation between the daytime totals of Q_E determined by the Bowen ratio-energy balance method, and the so-called "energy term" $[s/(s + \gamma)(Q^* - \Delta Q_S)$, where s is the slope of the saturation vapor pressure versus temperature curve and γ the psychrometric constant] of the familiar Penman combination model of evaporation (Monteith, 1964). The results for the majority of the days lie approximately about a slope of unity. The upper and lower limits to the scatter are at slopes of ~1.25 and 0.50, respectively. The data near the upper limit are for days immediately following rainfall when presumably even the impervious suburban surfaces are moist and thus energy, not water, is the limiting control on the loss of water to the air. The upper limit is similar to that found by a number of workers using either daytime or 24 h evaporation totals (e.g., Priestley and Taylor, 1972; Davies and Allen, 1973). The general tendency for the data to fall about a slope of unity conforms to the state of equilibrium evaporation which has been found to approximate conditions over a variety of extensive natural surfaces having a range of moisture availabilities (e.g., Denmead and McIlroy, 1970; Davies, 1972; Wilson and Rouse, 1972; Rouse and Stewart, 1972).

Eight of the 26 days lie below a slope of 0.75. At these times energy availability is not the primary

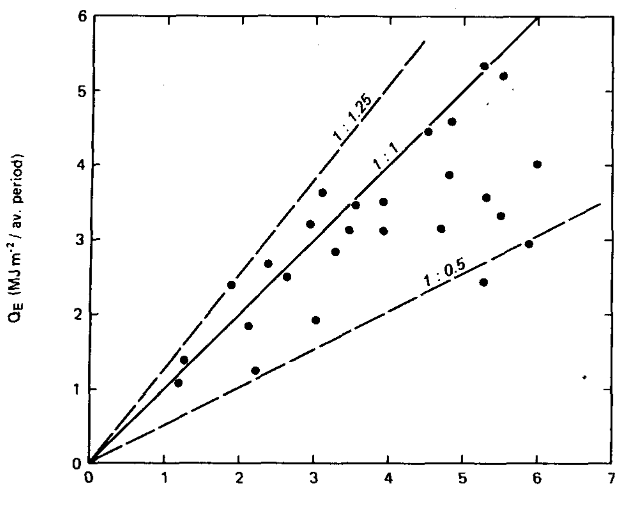

FIG. 6. The relation between daytime totals of evapotranspiration (Q_E) and the so-called energy term $s/(s + \gamma)(Q^* - \Delta Q_S)$ of the Penman combination model. Data are given for days having at least 6 h of daytime observations, expressed in MJ m^{-2} per total period of observation.

control governing Q_E and we might expect that water is limited. Such occurrences are to be expected as surfaces dry out. The unexpected result is that these days do not necessarily fall at the end of periods without rainfall. For example, the period 8–14 September shown in Fig. 5 can be considered to be a drying-period following a week in which ~40 mm of rainfall was recorded, including 11 mm from a thunderstorm on 7 September. On Days 1 and 2 of the drying period evapotranspiration was the dominant energy sink with Q_E proceeding at close to the 'equilibrium' rate on both an hourly and daytime total basis so that $\beta < 0.75$ (Fig. 4). This is followed by an abrupt drop in the role of Q_E in the balance on Days 3 and 4 ($\beta > 2$) which could be interpreted as a response to drying-out of some surfaces (especially the semi- or totally impervious ones). However, this is followed by an equally sudden return to equilibrium conditions and $\beta < 0.75$ for Days 6 and 7. Note that these conditions do not seem to change when rain falls on 15 and 17 September. A similar sequence also seems to apply during the drying period of 29 August to 1 September (Fig. 4).

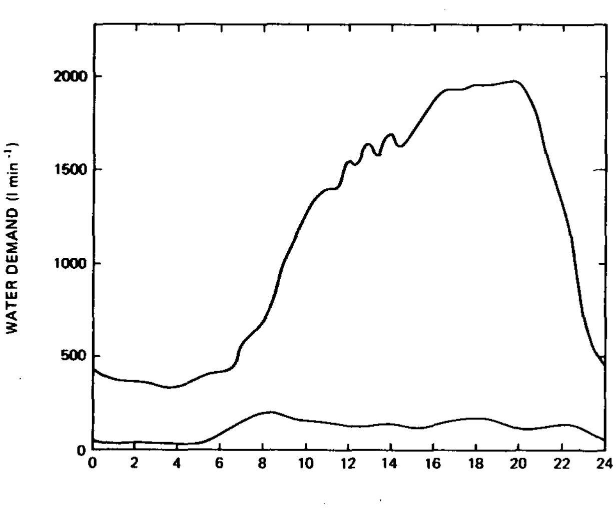

FIG. 7. Water demand hydrographs for a residential area (0.21 km^2) of Vancouver in 1971. Lower curve for a typical day in the fall, winter or spring; upper curve for a typical hot summer day. (Source: City of Vancouver Engineering Department.)

If we accept these suburban Q_E results as correct, and the error analysis indicates that we should, then a number of interesting questions pose themselves including:

- How can a surface composed of 36% built surfaces maintain near 'equilibrium' evapotranspiration rates 6 days after only moderate rain?
- What is the source of the moisture to support these rates of water loss?
- What mechanism underlies the return to high evapotranspiration after the environment appears to be drying out?

Since the experiment did not anticipate these findings it was not designed to answer these questions, but the following discussion is offered to aid their solution.

The primary question concerns the source of the water. In the absence of rain it must be postulated that human intervention in the water balance of cities is involved. One such source might be the release of water vapor as a by-product of fuel combustion, whose energetic equivalent we have neglected in drawing up Eq. (1). However, calculations of the *maximum* expected release of water vapor for a summer day in Vancouver show that this term is at least an order of magnitude less than the observed evapotranspiration (~1.63×10^{-6} kg m^{-2} s^{-1}, or an energetic equivalent of 4 W m^{-2}). The calculation was based on the New York study of Bornstein and Tam (1977)[4] and assumptions that the vapor releases are in proportion to the anthropogenic heat values of the two cities and that the strength of the maximum area source in New York is also an upper limit for Vancouver.

The other obvious source is the water supply piped into the city. This is made available to evapotranspiration through leakage underground from sewers and water mains tapped by deep-rooting trees, its

[4] Bornstein, R. D., and Y.-T. Tam, 1977: Anthropogenic moisture production and its effect on boundary-layer circulations over New York City. *Proc. Conf. Metropolitan Physics of the Environment,* USDA Forest Service General Tech. Rep. NE-25, NE Forest Expt. Stn., Upper Darby, PA, 36–52.

use in swimming pools and as a roof coolant, and its application to lawns, gardens, boulevards, golf courses and cemeteries by irrigation sprinkling. In the summer in Vancouver these latter uses produce a dramatic increase in residential water demand as illustrated in Fig. 7. These data are for a suburban area ~3 km from the Sunset tower. The large difference between the two curves is largely attributable to sprinkling. On that basis this amount of water distributed evenly over the 0.12 km^2 of lawns in the area corresponds to an application of ~10 mm of water per day or ~6 mm if expressed as an equivalent input over the entire residential area. Even allowing for half of this amount to be lost to the sewers as run-off this is enough water to support the observed evapotranspiration rates which do not exceed 3 mm day^{-1}. Therefore, it may be concluded that urban irrigation is at least capable of providing a source of sufficient magnitude.

Recently Oke (1979a) has shown that irrigated lawns in a suburban setting may act as "microoases." Since they are commonly surrounded by sources of sensible heat (heated pavement and buildings) these lawns may evapotranspire at rates in excess of their radiation budget on a daily basis. Thus their advectively assisted rate may in part compensate for the total lack of evaporation from built surfaces. In this manner it may be possible to at least partly explain how spatially averaged evapotranspiration rates can be maintained at levels approaching the equilibrium state.

An attempt was made to relate the temporal changes in $\bar{\beta}$ (Fig. 4) to residential water demand (irrigation). Unfortunately, the records are not available on a suitable time or space scale, so that no conclusions could be drawn. An hypothesis worthy of test is that the day-to-day variations in evapotranspiration during a drying period are due to a cycle of sprinkling habits based on the home-owner's perceived need for water. For example, for a period of up to, say, 4 days following rain, sprinkling may be deemed unnecessary and as soon as the impervious and non-irrigated surfaces begin to dry evapotranspiration may begin to drop in relative importance in the suburban energy balance. After this period sprinkling may be resumed on a regular basis and evapotranspiration may regain its former role.

6. Conclusions

This study of the energy balance of a suburban area in Vancouver has shown:

1) The Bowen ratio-energy balance approach with reversing psychrometers and a 4 m separation can be utilized in urban meteorology to provide turbulent flux estimates with errors of 10–20% by day (β typically <3.0) and 25% or more at night.

2) The suburban energy balance is different from and intermediate between those for urban and rural areas. Distinguishing features include: a march of sensible heat flux density that is in-phase with the net radiation regime; a mean daytime Bowen ratio value typically in the range 0.5 to 1.0 with some days as high as 2.5; hourly daytime Bowen ratios in the range 0.2 to 6.0; large day-to-day variability in energy partitioning on occasion; nocturnal sensible heat flux density values are usually negative but positive values also occur.

3) Suburban evapotranspiration is always an important, and sometimes the dominant, term in the energy balance. Hourly and daytime total evapotranspiration rates often approach or exceed the 'equilibrium' value. This may be made possible by the augmentation of evapotranspiration from irrigated greenspace by advected energy.

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