SUBURBAN-RURAL ENERGY BALANCE COMPARISONS IN SUMMER FOR VANCOUVER, B.C.

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(Received in final form 9 April, 1986)

Abstract. Simultaneous energy balance observations at a rural and a suburban site in Vancouver, B.C. during the summer of 1983 are presented. The study is a follow-up to that conducted in 1980. Many of the 1980 results were unexpected and the present study seeks to assess their representativeness. The net radiant, turbulent sensible, and rural soil heat flux densities were measured directly. The suburban heat storage was parameterized and the turbulent latent heat flux densities were resolved as residuals in the energy balances. The 1983 average diurnal energy partitioning for both sites was typical of those quoted in the literature, suggesting that the 1980 results represent an extreme case. Suburban-rural differences showed the suburban area to have a 4% increase in net radiation, a 51% increase in turbulent sensible heat, and a 46% decrease in turbulent latent heat flux density. The values of the average daytime Bowen ratio were 0.46 and 1.28 for the rural and suburban areas, respectively. The sensible heat flux density exhibited relatively large values in the late afternoon and remained directed upward on many summer evenings. Large day-to-day variability in the relative magnitude of the suburban turbulent fluxes may have been due to synoptic influences. In this environment, the turbulent surface and mixed layers are closely coupled because of the low aerodynamic resistance over the rough surface.

1. Introduction

Land surface and atmospheric alteration by urbanization leads to the development of distinct urban climates. Features such as the urban heat island, the urban centripetal air circulation, and the downwind enhancement of precipitation are well documented (e.g., Landsberg, 1981).

The challenge of modern urban climatology is to investigate the mechanisms underlying these urban climates and to relate them in a rational model of cause and effect. In short, a physical climatology of the urban atmosphere is sought.

In the case of thermal effects, it is the transfer, conversion and storage of heat in the urban system which is of interest, and the way in which these differ from their non-urban counterparts. The energy balance is used as a unifying framework within which these effects are studied.

The present paper uses differences between the surface energy budget components of suburban and rural sites as a measure of the impact of urban developent. Such an approach is known to be flawed, as shown by Lowry (1977). Nevertheless, it is a practical surrogate for the hard-to-attain 'true' measure which requires urban and pre-urban observations, at the same location, after stratification by weather type. The limitations of the present strategy have been fully discussed by Oke and McCaughey (1983) as part of a study (hereinafter referred to as OM) which is the direct precursor of the present one, having used the same sites. Here the rural site plays a dual role. It represents an idealized version of the type of environment surrounding urban areas; but

Boundary-Layer Meteorology **36** (1986) 351–369.

it also serves in the experimental sense as a 'control' site. It fills this latter role because the site characteristics (fetch, flatness, homogeneity, and surface composition) conform with most requirements for standard micrometeorological theory and measurement approaches to apply.

The relevant energy balance formulations for the two environments are as follows:

Rural 'control':

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

where Q^* is the net all-wave radiative flux density, Q_H and Q_E are the turbulent flux densities of sensible and latent heat, respectively, ΔQ_S and ΔQ_P are the net heat flux densities due to storage change in the soil and photosynthetic activity, respectively, and ΔQ_A is net heat advection.

Suburban:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_P + \Delta Q_A\,, \tag{2}$$

where Q_F is the anthropogenic heat flux density due to combustion. The suburban balance refers to that at the upper surface of a volume or 'box' which extends over the depth of the canopy (or building) layer (Oke, 1976). Within the layer beneath roof-top, heat, mass, and momentum transfer is highly variable in space and time, leading to microscale advection and wake or plume structures. By taking measurements well above the buildings, the effects of these localized features are diffused and the fluxes are considered to be representative of areally-averaged conditions for the land-use unit. By choosing sites with sufficient horizontal homogeneity, local or meso-scale advection (ΔQ_A in Equations (1) and (2)) can also be avoided. Further, given the characteristics of the two sites in this study, it is considered acceptable to ignore the ΔQ_P and Q_F components (see OM).

There are few studies of genuine urban-rural energy balance comparisons, as distinct from those using over-simplified urban surrogate surfaces such as concerete or parking lots which do not adequately represent the three-dimensional and very varied nature of the urban-atmosphere interface. The OM study evaluated the budgets of a rural and a suburban site in Greater Vancouver, B.C. during the summer using the Bowen ratio-energy balance approach to obtain the turbulent heat fluxes. The results challenged most pre-conceived ideas of urban-rural energy partitioning differences. With high radiant loading, evapotranspiration from the suburban site was consistently larger than from the rural one despite adequate water supply to the latter. It was postulated that this finding could be explained by small-scale 'oasis-type' advective effects as demonstrated by Oke (1979). The necessary conditions for this system are provided by anthropogenic control of suburban moisture availability through the practice of lawn and garden sprinkling during hot weather (Grimmond and Oke, 1986; Loudon and Oke, 1986). The wetting of localized patches in areas which include many totally dry surfaces (e.g., roads, buildings) creates a patchwork of contrasting surfaces. These are ideally arranged in terms of horizontal interaction so that the hot dry air from one surface provides additional energy to drive the evapotranspiration from the pervious surfaces. The weather during the OM study may have yielded optimum conditions for such microscale advection.

Ching *et al.* (1983), using eddy correlation techniques to measure the turbulent heat and mass transfers at several sites in St. Louis, Mo., found a more typical range for the energy partitioning. The daytime average Bowen ratio ($\beta = Q_H/Q_E$) was the largest at their most heavily urbanized site, intermediate at a suburban site and lowest in the rural area. Kerschgens and Hacker (1985) suggest a similar relation between β and urban development from a short field study in the Bonn, F.R.G. region.

The present study was undertaken as an extension to that of OM, thereby establishing the nature of suburban and rural energy balance differences over a greater range of surface and atmospheric states. The suburban results are also used to investigate the diurnal and inter-diurnal characteristics of energy partitioning in that environment.

2. Experimental

2.1. Site-descriptions

The sites (Figure 1) used in this study are identical to those of OM and are fully described therein. The suburban site has also been discussed by Kalanda *et al.* (1980) and Steyn (1980); therefore, only a summary will be given here.

The suburban site, called Sunset, is located in south Vancouver, B.C. (Figure 1). Observations are conducted from a 30 m tower situated in an extensive area of suburban

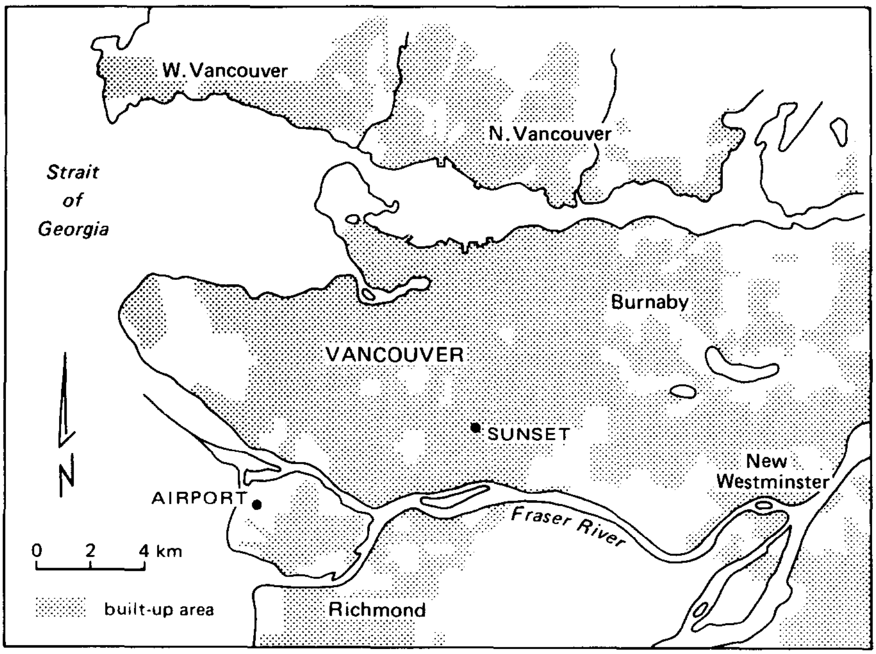

Fig. 1. Location of the observation sites: Airport (rural) and Sunset (suburban).

housing (1–2 storey detached dwellings with a mean height of 8.5 m). The surrounding area is 64% greenspace (lawns, gardens, parks, etc.) and 36% built-up (25% houses and other buildings, 11% paved). Features of special note include:

– Between 0.75–2 km NW of the site are a park and a cemetery both of which are sprinkled during dry weather.

– 100 m SE of the tower is a 20 m high school building.

– Scattered commercial and industrial buildings are located in areas 1–2 km from the site to the NE and S.

This spatial variability may be capable of creating some dependence of turbulent fluxes upon wind direction. However, both Kalanda (1979) and Steyn (1985) failed to discern such effects.

The tower site has an albedo of 0.12–0.14, a roughness length of 0.5 to 1 m and a zero-plane displacement length of approximately 3.5 m.

The rural station, called the Airport, is situated on the airfield of the Vancouver International Airport (Figure 1). It is a flat, managed grassland area located on part of the Fraser River delta and the soils are silts overlying a bed of sand (at 0.9 m depth). The water table is at the surface during the winter and drops to a depth of about 1 m by late summer. Surface water ponding in winter produces a mat of dead grass next to the soil surface. During the growing season, fresh stalks protrude through the mat and the grass is kept to a height of 0.15–0.20 m by regular mowing. The mat is important in the summer because it increases the albedo, insulates the soil to heat exchange and decreases both the infiltration of precipitation and the direct evaporation from the soil. The albedo of the site is about 0.20 and the roughness length is approximately 15–20 mm.

2.2. Instrumentation

The instrumentation that was central to the energy balance comparisons was identical at the two sites. Net radiation (Q^*) was monitored using a net pyrradiometer (Swissteco, Model S-1) mounted so as to view an appropriate surface area (rural 1 m; suburban 30 m height).

The sensible heat flux density (Q_H) was measured at both sites with a sonic anemometer-thermometer system, SAT (Campbell Scientific, Model CA 27) which utilizes the eddy correlation approach. In this system, the vertical velocity is sensed as a phase shift in sound waves and air temperature by a fine wire thermocouple (diameter 12.7 μm). The sampling frequency by the data logger (Campbell Scientific, Model CR 5) is 10 Hz (actually each input is a 0.1 s average of the signal) thereby defining the high-frequency cut-off. The microprocessor in the logger utilizes a sampling time of 5 min dictating the low-frequency limit of 3.33×10^{-3} Hz.

In the present study, the SAT's were required to obtain areally representative values of the two surfaces. This involves seeking appropriate compromises in the choice of averaging period and measurement height. If the averaging period, τ, or instrument height, z, are too small, then the spatial and temporal sampling scales will be inadequate to resolve the spatial and temporal scales of turbulence in the respective environment.

However, if τ is too long (greater than 2 h), the stationarity of the time series must be doubted. If z is too great, measurements will not represent the fully adjusted urban boundary layer, but will include advective effects.

Due to the presence of relatively tall roughness elements, and the great spatial variability of surface materials which characterizes suburban terrain, the choice of sensor height and averaging time is not a simple task. The selection of 20 m effective height (i.e., height above zero-plane displacement) for the turbulence measurements corresponds to the minimum height, suggested by Raupach *et al.* (1980), necessary to avoid the wake, or transition layer. Raupach *et al.*'s formulation is restricted to momentum fluxes, and was derived from wind tunnel studies. The work of Garratt (1980) deals with field measurements of both heat and momentum transfer. The range of heights suggested by these studies and others varies from 30 to 60 m; however, the tower employed in this study restricted the effective height to a maximum of 20 m. In addition, greater effective measurement heights might introduce advective errors.

Wyngaard (1973) addresses the problem of averaging time, using an equation developed by Lumley and Panofsky (1964). For the sunset site, his analysis yields τ between 80 and 130 min for a sensible heat flux measured during unstable conditions ($z/L = -1$), with 10% uncertainty. If this degree of uncertainty is relaxed to 15%, then τ lies between 36 and 60 min. In neutral stability, τ values should be about 67% greater.

In this study, τ was selected as 60 min for both the rural and suburban site, to conform with previous practice and to meet the criteria mentioned above. In addition, hourly averages match the standard meteorological observing times at the Airport site. The measurement height at the rural site was 1.8 m, thus avoiding advective influences from the adjacent runway.

Heat storage change (ΔQ_S) was evaluated differently at the two sites. In the rural case, three heat flux plates (Middleton Model CN3) connected in series were embedded in the soil at a depth of 10 mm and monitored on the data logger. At the suburban site, as in the OM study, the parameterization scheme suggested by Oke *et al.* (1981) was employed. It uses measurements of Q^* and the following equations:

$$\begin{aligned} &\text{Day} \quad (Q^* \geqslant 0)\text{: } \Delta Q_S = 0.25(Q^* - 27) \\ &\text{Night } (Q^* < 0)\text{: } \Delta Q_S = 0.67(Q^*) \quad (\text{W m}^{-2})\,. \end{aligned} \tag{3}$$

Given the assumptions already stated regarding neglect of Q_F, ΔQ_P, and ΔQ_A, it is evident that the latent heat flux density (Q_E) is found as a residual from Equations (1) and (2).

Supplementary observations at both sites included the following. Incoming solar radiation was obtained from the nearby Langara and Airport sites of the UBC Solar Monitoring Network (Hay, 1984). Measurements of reflected solar radiation were taken at the Airport and Sunset sites using pyranometers mounted at 1 and 20 m, respectively. Both sites were instrumented to record wind speed and direction, air temperature, relative humidity and precipitation. Near-surface soil moisture values were obtained by the gravimetric method from samples gathered twice per week. Three samples were collected at the rural site and six from the suburban area (each from an unirrigated site within a radius of 1.5 km from the tower).

2.3. Error considerations

The core of this paper is concerned with energy balance comparisons between the two environments. Of the four component terms, Q^*, Q_H, Q_E, and ΔQ_S, errors in the first two warrant special attention. Both are measured directly and by identical approaches at the two sites. The net radiation sensors were calibrated by comparison with a

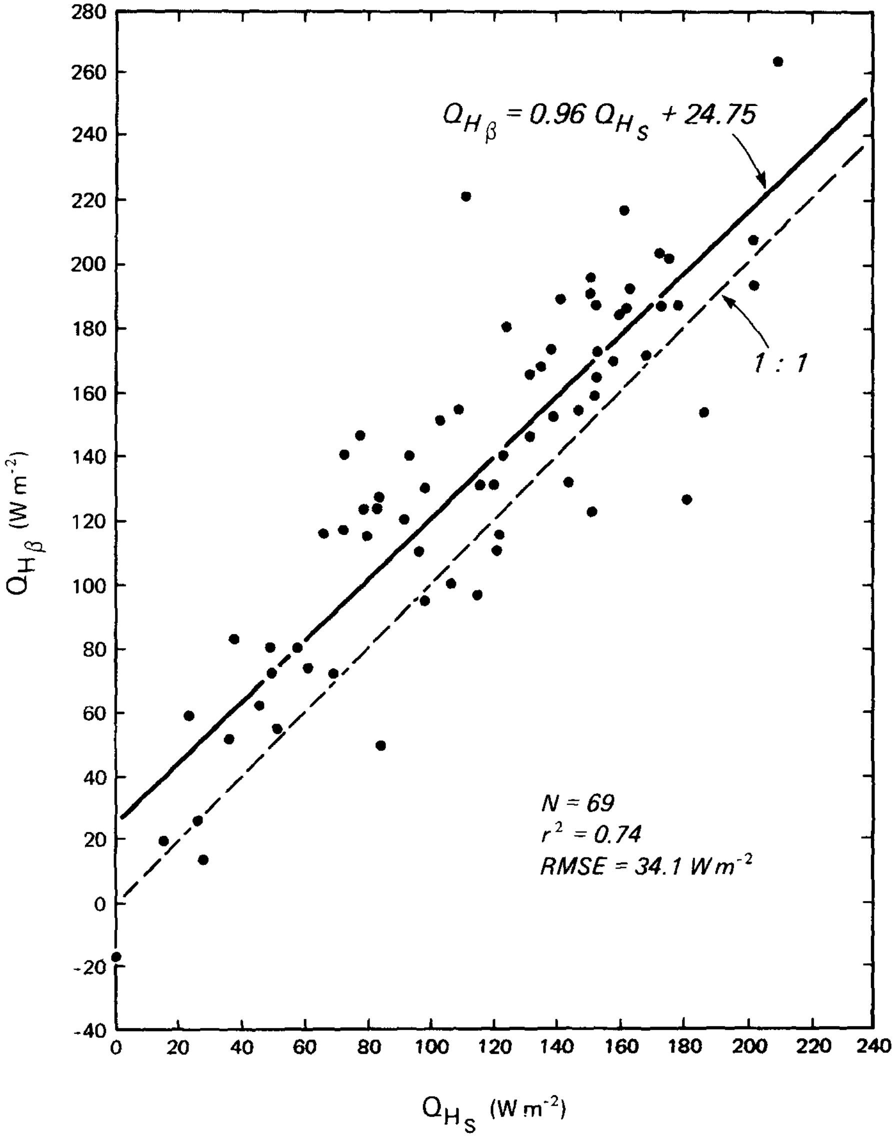

Fig. 2. Comparison between estimates of the turbulent sensible heat flux density at the rural site using the sonic anemometer-thermometer (Q_{H_s}) and Bowen ratio-energy balance (Q_{H_β}) approaches.

standard, immediately before the study by the National Radiation Laboratory (Atmospheric Environment Service). This should ensure their accuracy to within 3 to 4% (Latimer, 1972) and their inter-instrument difference should be even less.

No such standard calibration is available for the SAT system. The sensible heat flux from one of the SAT systems was compared with that determined by the Bowen ratio-energy balance method. The latter were obtained using a reversing psychrometer system similar to that used in the OM study, and the Q^* and ΔQ_S systems already noted for the rural site. The inter-comparison was conducted at that site by Hilts (1983, internal report). The results (Figure 2) show the SAT estimates to be 17% less in the mean, with a root-mean-square error of 34 W m^{-2}. Whilst this discrepancy is of some concern, it is not possible to attribute error to either of the two systems or approaches. It should also be noted that it is the relative differences between the two sites which are of interest; therefore, absolute errors will be of greater concern when evaluating Q_E, rather than during Q_H intercomparisons. Given the typical size of Q_H in the energy balances of the two sites, we estimate probable errors of approximately 6–10% of Q^*.

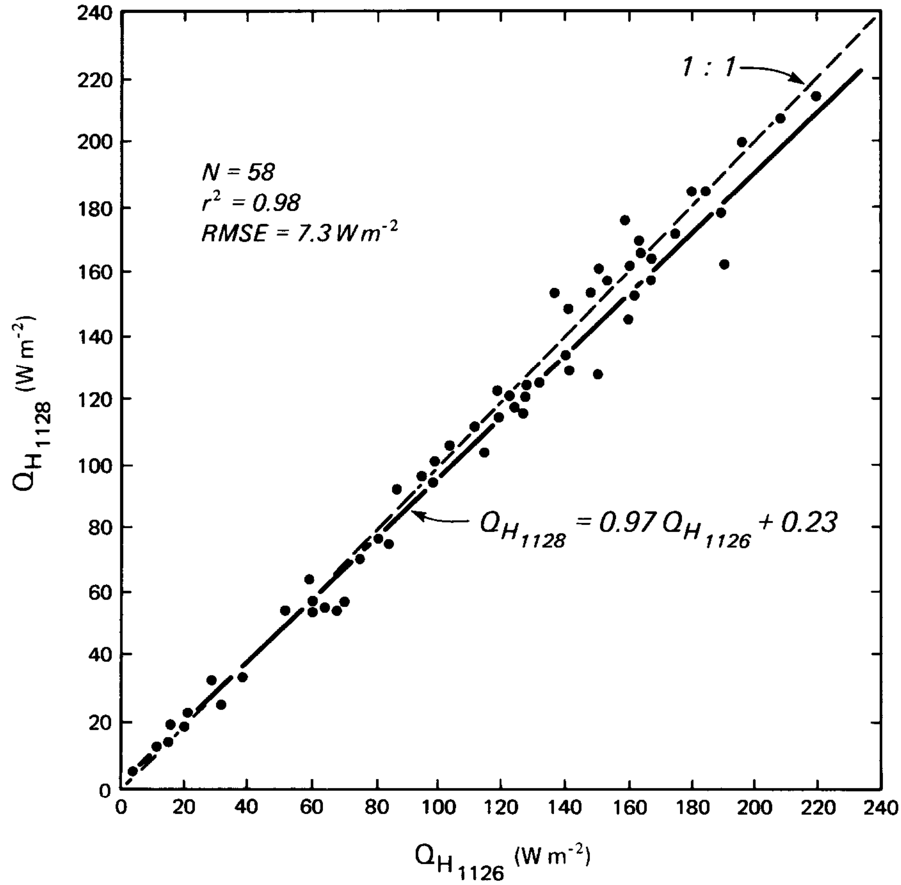

Fig. 3. Example comparison of the sensible heat flux density observations between a pair of SAT systems (numbered 1126 and 1128). Hourly average values at the rural site during June 1983.

The results of the more important comparison between the SAT systems (later to be installed at the two sites) are given in Figure 3. The inter-instrument variability is remarkably small considering that these are turbulent flux measurements. Three instruments were used during the course of the experiment and their combined differences were found to be less than 10% in the mean, with RMSE of less than 20 W m^{-2}.

These figures suggest that considerable confidence can be placed in the estimates of Q^* and Q_H, and especially in suburban-rural differences and ratios.

As will be shown, ΔQ_S at the rural site is a small term in the balance and it may be safely assumed that errors in its estimation are negligible (probably less than 1% of Q^*). Suburban storage, on the other hand, is difficult to assess. Based on considerations given by Oke *et al.* (1981) and Oke and Cleugh (1986), we suggest that maximum daytime ΔQ_S errors are of the order of 10% of Q^*. Errors in suburban-rural differences are likely to be of the same size.

Since the latent heat flux (Q_E) is found as a residual, it becomes a sink for errors accumulated in the assessment of the other terms. Using the estimates given in this section for errors in Q^*, Q_H, and ΔQ_S, we may anticipate Q_E values to be in error by a maximum of about 25% (15% of Q^*) at the rural site, and by up to 70% (25% of Q^*) at the suburban one. These are worst-case values assuming all errors are systematic and operate in the same direction. More typical errors may be about one half of these values. This simple error accounting obviously suggests caution in assessing the Q_E results at each site, and inter-site differences arising therefrom. Further, it should be noted that the suburban ΔQ_S parameterization scheme is a linear one and, therefore, is incapable of representing any phase differences in the diurnal variations of Q^* and ΔQ_S.

2.4. Observation period

Suburban-rural comparison measurements were conducted in the period July 18 to September 22, 1983. General climatological observations were recorded continuously throughout the period whereas the energy balance data were gathered on an intermittent basis. Precipitation, fog or heavy dew limited the energy balance measurements to a total of 30 complete days (daylight hours).

June 1983 was relatively cloudy and wet in Vancouver so that the soil moisture store was well stocked at the start of observations. Unsettled weather continued into July. Cyclonic weather systems deposited significant amounts of rainfall during July 11–14 and 25–28, yielding the wettest July on record. Despite this, these events were interspersed with periods of days with high radiation input. Observations during these days show the energy partitioning when water availability is essentially unlimited. The beginning of August was marked by a three-week interval of anti-cyclonic weather. This drying period was only broken by thundershowers on August 9 and a small frontal disturbance on August 11.

As with the year (1980) of the OM study, precipitation was much greater than normal in July (more than double), but much less in August (almost one half). Unlike 1980, when sunshine duration was close to normal, July values in 1983 were much lower and August values much greater.

The results from this study are representative of the local (or land-use) spatial scale. For the suburban site, this means that areal averages were contributed to by surfaces up to about 2 km from the tower. The discussion of results will be organized according to two temporal scales. First, the diurnal scale due to the forcing of the solar cycle, and second, a series of days spread over the summer period whose energy balance characteristics may have been affected by variations in water availability related to precipitation/drying cycles.

3. Diurnal Energy Balance Results

3.1. Summary Statistics

A summary of the average daytime energy balance components at the rural and suburban sites is given in Table I. It shows that the net radiation receipt at the suburban site is approximately 4% greater than at the rural one. These values agree with the corresponding 3% daytime increase found by OM. The explanation is provided by the data

TABLE I

Summary statistics of the suburban-rural energy balance comparison. All 1983 results are averages calculated using the same 30 days. Also included are the results from 1980 (OM) and the list of typical values given by Oke (1982)

	$\overline{Q^*}$[a] (W m^{-2})	$\overline{Q_H}$ (W m^{-2})	$\overline{Q_E}$ (W m^{-2})	$\Delta\overline{Q_S}$ (W m^{-2})	$\overline{A}$	$\overline{\alpha}$	$\overline{\beta}$	$\overline{\chi}$	$\overline{\phi}$
(a) Rural									
1983	283	86	187	12	0.20	1.09	0.46	0.30	0.66
1980 (OM)	267	106	157	4		0.99	0.67	0.39	0.59
Oke (1982)						1.05[b]	0.50	0.28	0.57
(b) Suburban									
1983	295	129	101	65	0.13	0.70	1.28	0.44	0.34
1980 (OM)	275	29	183	63		1.25	0.16	0.11	0.67
Oke (1982)						0.80	1.00	0.39	0.39
(c) Suburban/rural ratios[a]									
1983	1.04	1.51	0.54						
1980 (OM)	1.03	0.28	1.16						
Oke (1982)	1.00	1.39	0.68						

Notes:
$A = (K\uparrow/K\downarrow)$, albedo.
$\overline{\alpha} = (\overline{Q_E}/(\overline{s/s+\gamma}))\,(\overline{Q^*} - \overline{\Delta Q_S}))$. Priestley–Taylor parameter, where s is the slope of the saturation vapour pressure versus temperature curve and γ is the psychrometric constant.
$\overline{\beta} = (\overline{Q_H}/\overline{Q_E})$ Bowen ratio.
$\overline{\chi} = \overline{Q_H}/\overline{Q^*}$.
$\overline{\phi} = \overline{Q_E}/\overline{Q^*}$.
[a] Values of $\overline{\chi}$ and $\overline{\phi}$ assume equality of suburban and rural $\overline{Q^*}$.
[b] McNaughton and Jarvis (1983).

showing the suburban albedo to be considerably lower. The albedo value for the suburban site is consistent with previous estimates at Sunset (Steyn and Oke, 1980) and for similar sites (Oke, 1986). Other modifications to the surface radiation budget are likely to operate in the opposite direction: incoming short-wave is likely to exhibit a slight reduction in the city due to pollution, and net long-wave radiation should show an enhanced drain on the system due to the warmer surface.

The proportion of the radiant input going to storage in the two environments is apparently very different. The rural value is very low, probably due to the insulation effect of the layer of dead grass lodged in the stand. The suburban case is of course dictated by the coefficients in the parameterization equations and the net radiation. The suburban-rural difference is, therefore, as expected, and due to the method of estimation used, it is not open to further comment.

The 1983 results show that the sharing of energy between the turbulent sensible and latent heat transports is in general agreement with expectation, based on the typical values for rural and suburban sites given by Oke (1982) and listed in Table I. The rural data show the dominance of the latent heat exchange due to evapotranspiration with a daytime average Bowen ratio of approximately 0.5. Similarly the Priestley–Taylor parameter value is slightly in excess of unity, a condition referred to as equilibrium evaporation. It conforms with that for an extensive, moist low vegetation cover over a daytime (rather than daily) period. The latent and sensible heat fluxes in the suburban case are more equal. In 1983 the sensible heat is the larger, giving an average Bowen ratio of 1.28, with evapotranspiration proceeding at about 70% of the equilibrium rate. Given the similarity of the 1983 and the 'typical' results, it follows that the suburban/rural ratios are also in general agreement (Table I).

Reviewing the summary statistics, it becomes clear that the 1980 suburban data appear as an anomaly and cause the suburban/rural ratios for the same year to be in discord with the rest of the table. We shall return to this observation in Section 3.3.

3.2. Average Diurnal Variation

The diurnal variation of the energy balance components, averaged over the 30 summer days, is given in Figure 4. The rural results (Figure 4(a)) are typical for the most part, and confirm the appropriateness of this as a control site. The three most important fluxes exhibit a variation which is approximately symmetric about solar noon, and are all in phase. Soil heat storage change shows a slight lag (rather than its usual tendency to lead) vis-à-vis the other terms. This is minor and of little significance; it may be due to the very low thermal diffusivity of the grass mat already mentioned. This diurnal cycle of Q_H, Q_E, and Q^* is typical of vegetation covers that are radiatively controlled (McNaughton and Jarvis, 1983). The in-phase nature of Q_E may also be assisted by the suppression of the afternoon vapour pressure deficit due to the encroachment of maritime air as part of the daily sea breeze circulation at this site (Steyn and Oke, 1982).

The corresponding suburban results are given in Figure 4(b). Before detailed comment, it is necessary to make some cautionary statements. As mentioned in Section 2.3, the suburban parameterization of ΔQ_S forces a linear relation between storage and net

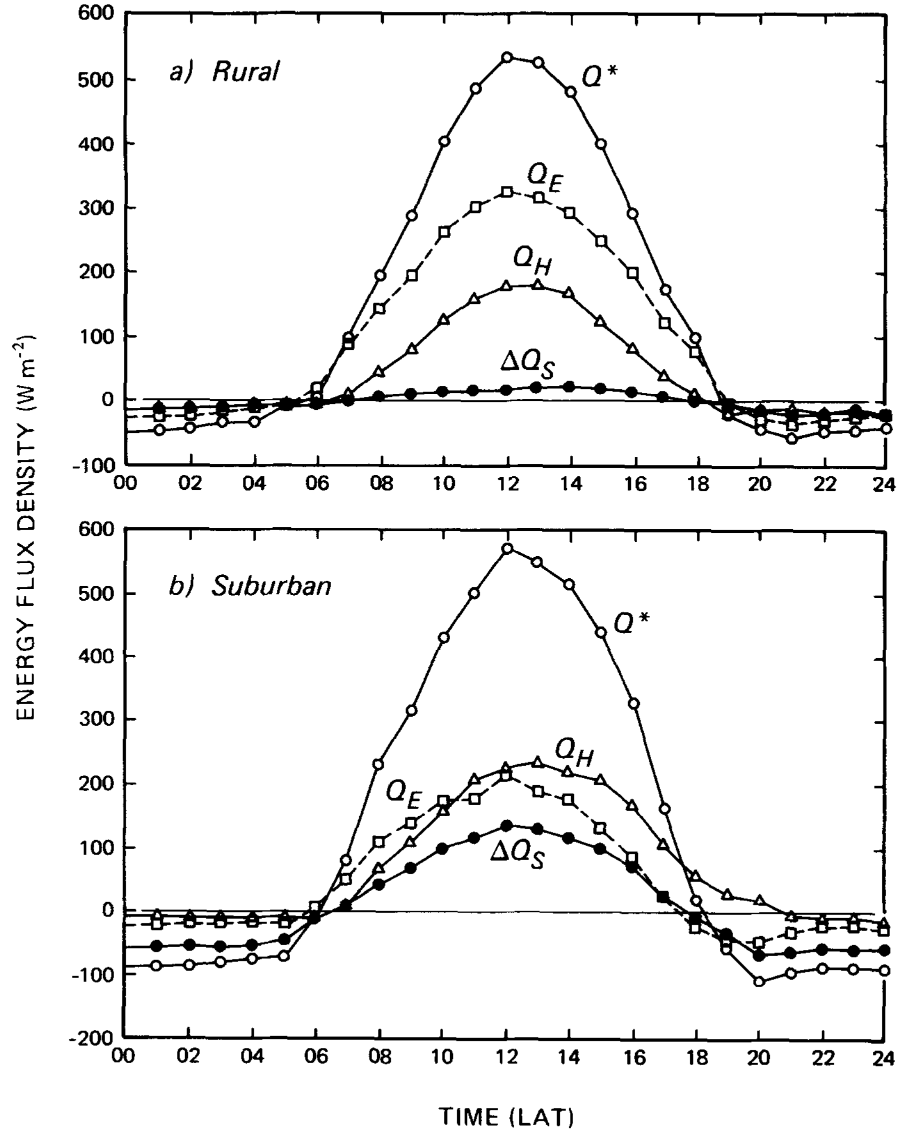

Fig. 4. Variation of average energy balance components for (a) the rural, and (b) the suburban sites in Vancouver for 30 summer days in 1983. Note that the number of samples for the night-time average values is less than the 30 days used for the daylight averages.

radiation. Whilst this provides a good fit to the mean of the empirical data used to derive the equation, it suppresses any systematic temporal trends that may have been present (e.g., cyclical loops as observed by Camuffo and Bernardi, 1982). However, in addition to affecting the calculated hourly values of ΔQ_S, any discrepancies influence Q_E because it is estimated as the residual of Equation (2). Failure to include real asymmetry in ΔQ_S will appear as an equal and inverse error in asymmetry of Q_E. The asymmetric diurnal pattern of Q_E in the data presented here arises from that in the measured Q_H values, but whether it has a physical basis cannot be stated unequivocally.

Recent estimates of ΔQ_S from the Sunset site (using data from experiments where all other components of the energy balance are measured) do show cyclical loops, but they do not cause values to deviate from the parameterization by more than about 50 W m^{-2} on average (Oke and Cleugh, 1986).

The foregoing creates difficulties because asymmetry of Q_H and Q_E is the most apparent feature in Figure 4(b). A reasonable physical explanation is suggested as follows. In the period 06 to 10 hr, the role of Q_E is dominant in dissipating the radiative surplus. It is hypothesized that this may arise from the evaporation of water freely available at the surface. Sources for this surface water include: firstly, the considerable quantities of intercepted water resulting from garden sprinkling, held by vegetation in addition to occurring on paved surfaces (sidewalks, driveways, etc.). A second potential source is the additional surface moisture contributed by dewfall. Loudon and Oke (1986) show that a large proportion of garden sprinkling in Vancouver occurs in the late afternoon and evening period when the drying potential is low. The low aerodynamic resistance offered by the relatively rough suburban landscape helps to create a potential for water loss similar to that in forests (Szeicz, 1974).

By mid-morning, the interception and dew-wetted sources of water become exhausted, and most further loss of water to the air is via transpiration which is subject to the additional resistance to transfer provided by stomatal regulation. Latent heat transfer remains a major channel for heat loss from suburbia but the sensible heat flux shed from the radiatively-warmed fabric becomes dominant.

In relative terms, Q_H becomes increasingly important in the late afternoon, and even remains as a heat sink (directed from the surface to the air) following the reversal of the net radiation. The reversal of Q_H may be delayed until 21 hr compared with 18 hr at the rural site. Both the phase-shift, and the retention of a positive Q_H term, are in agreement with the findings at more built-up sites in Vancouver (Yap and Oke, 1974); Uppsala, Sweden (Oke, 1978); and St. Louis, Mo. (Ching *et al.*, 1983). An hypothesis to explain this was proposed by Yap and Oke (1974). They suggest that the daytime heat storage may be released from some urban surfaces prior to the time of general sunset. This occurs in response to the extensive and abrupt shading experienced within the urban canopy at relatively low angles of solar elevation. As a corollary, this shading may also, in part, be responsible for the rather sluggish rise of Q_H in the morning, as noted earlier.

The nature of the asymmetry in Q_H at the suburban site is clearly displayed in Figure 5. It shows the diurnal variation of the ratio $\chi = Q_H/Q^*$. This is a very useful indicator of energy partitioning in this study because it involves the two energy balance components measured directly.

Figure 6 summarizes the results of this section by showing the energy flux density differences between the two environments for each component. It demonstrates a number of interesting points:

Throughout most of the daytime, the net radiation input is greater at the suburban site, but this can change rather abruptly in the late afternoon.

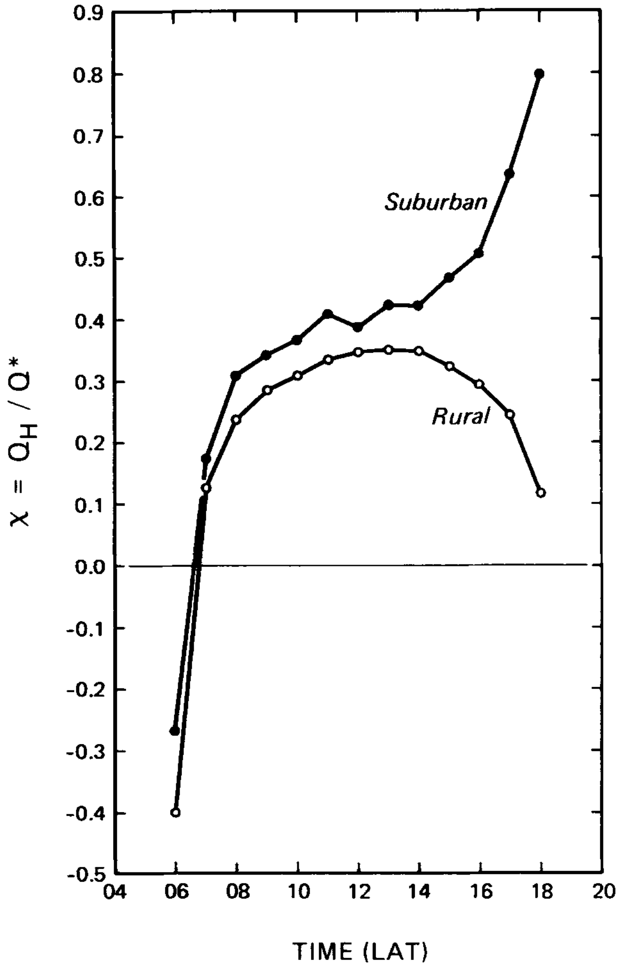

Fig. 5. Diurnal variation of the ratio χ ($= \overline{Q}_H/\overline{Q}^*$) at the two sites in Vancouver 1983. Data are hourly averages for 30 summer days.

At the suburban site, heat is preferentially channelled into sensible forms (Q_H or ΔQ_S) rather than to latent heat, in contrast to the rural area.

The extra sensible heat at the suburban site is mostly channelled into storage in the morning, and into the atmosphere in the afternoon and evening (see also Figure 6).

3.3. Day-to-day variations

Longer term variability in the energy balances of the two environments can be studied using the semi-continuous set of observations for the period July 30 to August 22, 1983. Just before this period, there had been 22 mm of precipitation; thereafter, the weather was dominated by anticyclonic conditions except for a frontal shower on August 2 and a thundershower on August 9, both of which provided less than 2 mm of rainfall. Soil moisture at both the rural and suburban (un-irrigated) sites decreased (Figure 7). Rural

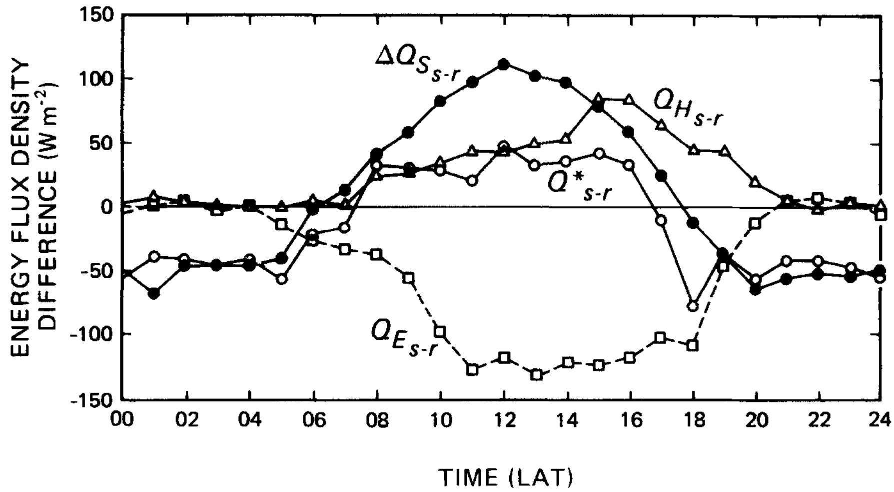

Fig. 6. Average suburban-rural energy flux density differences.

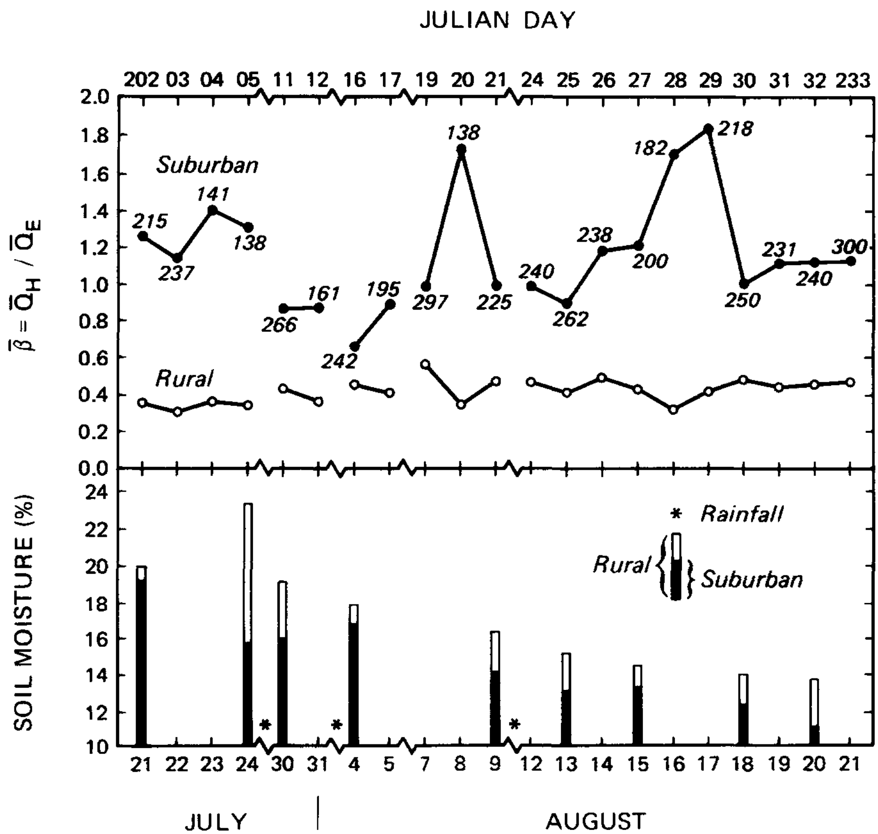

Fig. 7. Day-to-day variation of the average daily Bowen ratio ($\bar{\beta}$) at the Airport and Sunset sites together with the daily precipitation and occasional soil moisture values. Numbers on the Sunset graph are wind directions in degrees.

moisture was always the greater, probably because the deltaic site retains a relatively high water table. Suburban values do not fully represent water availability in that environment because they do not include either the irrigated greenspace (lawns, golf courses, etc.) or the impervious built areas (roads, buildings, etc.) each of which probably occupies about one third of the surface area.

Figure 7 shows the variation of the average daily Bowen ratio ($\bar{\beta} = \bar{Q}_H/\bar{Q}_E$) during this drying period. The rural results display a slight upward trend and very little day-to-day variability. This would seem consistent with the moisture availability. The suburban results show a slight upward trend beginning at Julian Day 211, and also some sharp peaks suggesting an abrupt change in either surface or atmospheric control on energy partitioning. This suburban variability has been noted before. Oke (1978) suggested that it may be due to synoptic control. Kalanda *et al.* (1980), Grimmond and Oke (1986), and Loudon and Oke (1986) demonstrate a close correlation between sprinkling habits and evapotranspiration, and OM (1983) suggest an hypothesis which links surface water availability with synoptic regimes (especially radiation) and 'oasis'-type advection.

In the present case, there is no information on the water supply but there does appear to be a linkage with aspects of the synoptic weather, especially wind direction. The peaks in Figure 7 were assoicated with weather disturbances, and relatively strong airflow from the south–east. The rest of the time-series was associated with weak daytime sea breeze flow from the south–west to north–west sector. A dependence on wind direction is not evident in the hourly data of this study or that by Steyn (1985) at the same site. Thus we believe that the dependence is not due to local advection caused by spatial surface inhomogeneities but is related to synoptic-scale effects such as air mass stability or advection of air layers aloft and their interaction with the urban boundary layer.

Recent work on the modelling of regional evapotranspiration stresses the need to consider the role of the entire planetary boundary layer (PBL) on the exchanges of energy, mass and momentum at the surface and vice-versa (de Bruin, 1983; McNaughton and Spriggs, 1985). For example, Q_H controls the rate of growth of the PBL and the downward entrainment of usually drier, warmer air. This in turn modifies the saturation deficit of the PBL, thereby controlling Q_E, which itself is inversely related to Q_H via the surface energy balance. In the suburban context, we are dealing with a very rough surface that is likely to be strongly coupled to the moisture and thermal characteristics of its mixed layer, and via the preceding argument, to the nature of the air entrained into the PBL from above. The air above the PBL owes its nature to synoptic influences.

The turbulent surface layer over grassed surfaces is poorly coupled to the mixed layer because of low aerodynamic roughness and stomatal resistance characteristics. Thus, as documented by McNaughton and Jarvis (1983), grassland evapotranspiration tends toward the equilibrium rate. The present rural results illustrate this situation well. McNaughton and Jarvis develop a parameter, Ω, which gives the appropriate weighting to the radiative and advective components of the Penman–Monteith evapotranspiration model. It is defined:

$$\Omega = \left[1 + \frac{\gamma}{s + \gamma}\frac{r_c}{r_{as}}\right]^{-1}, \qquad (4)$$

where γ is the psychrometric constant, s the slope of the saturation vapour pressure/temperature curve and r_c and r_{as} are the canopy and aerodynamic resistances, respectively. Note that r_{as} is defined as the aerodynamic resistance from $(z_0 + d)$ to the top of the surface layer. The following calculations use r_a, rather than r_{as}, where r_a is the aerodynamic resistance from $(z_0 + d)$ to the instrument height (i.e., the height at which C, D and the energy balance components are measured). Values of Ω were computed for the 1983 suburban results. Following de Bruin and Holtslag (1982):

$$r_c = \left(\frac{s}{\gamma}\,\beta - 1\right) r_a + \frac{C}{\gamma}\,\frac{D}{Q^* - \Delta Q_s}\,(1 + \beta)\,, \tag{5}$$

where C is the heat capacity and D the saturation deficit of air. Using the logarithmic wind profile yields $r_a = 23$ s m^{-1} so that $r_c = 91$ s m^{-1} and $\Omega = 0.44$. Alternatively, the semi-empirical aerodynamic expression of Thom and Oliver (1977) gives $r_a = 5$ s m^{-1}, $r_c = 81$ s m^{-1} and $\Omega = 0.16$. These Ω values encompass those for forests suggested by McNaughton and Jarvis (Ω forest ≈ 0.2, Ω grassland ≈ 0.8). Hence, suburbia may resemble the forest environment in terms of the coupling between the mixed and surface layers. Continuing this argument, it is, therefore, possible for suburban Q_E values to be very different on any two days despite similar radiation levels, because the surface fluxes are strongly linked to the thermal and moisture characteristics of the mixed layer, which can vary in response to meso-scale and synoptic influences. This could explain the observed day-to-day, and perhaps the year-to-year, variability in turbulent fluxes.

Hildebrand and Ackerman (1984) show the entrainment of warm, dry air into the urban boundary layer over St. Louis to be both larger, and more variable than that in surrounding rural areas, a result which supports our previous argument.

3.4. Year-to-Year Variations

Finally, some comment is necessary regarding the reason for the differences between the 1980 and 1983 suburban energy balance results. At least three possibilities exist. First, there may have been differences in surface moisture availability. Soil moisture values for the unirrigated suburban greenspace in the two years reveal little. If anything, 1980 was slightly drier than 1983, which would not explain the greater Q_E values in the OM study. Irrigation differences between the two years could yield differing evaporation rates; however, this cannot be confirmed as no external water use data were collected in 1983.

Second, these differences may be attributable to synoptic boundary-layer differences, as forwarded to explain the day-to-day variability. The summary climatological statistics show few differences between the two years; although the synoptic variability and the air quality statistics reveal marked contrasts, there was greater variability and poorer air quality in 1980. The fact that the rural results are similar for the two years, while the more closely coupled suburban surfaces are different, lends some support to the importance of this explanation.

Third, it should be noted that different measurement approaches were used in the two studies. There is no reason to suspect problems with either system (e.g., Figure 2), but it is possible that the extent to which the assumptions underlying the two approaches are fulfilled in the suburban environment may contribute to discrepancies, as may have the differences in the sensor height (10.5 m above zero-plane displacement in 1980, versus 20 m in 1983).

4. Summary

The present study of summertime suburban and rural energy balances has yielded results which may be considered as typical for a large, mid-latitude city. In many respects they show the suburban evapotranspiration regime of the OM study-year to have been anomalous. Our results elucidate those key features which differentiate the energy balances of the two environments, and hence provide further understanding of the causes of local-scale urban climate. These features include:

Daily total net radiation is about 4% greater at the suburban site. This is largely attributable to the lower suburban albedo.

Evapotranspiration is almost always less at the suburban site than at the rural. However, the evapotranspiration term remains an important energy sink in the suburban environment, especially the evaporation of intercepted water in the early morning.

The turbulent flux of sensible heat is usually greater than that of latent heat at the suburban site (i.e., β is usually greater than unity). The asymmetry in the diurnal cycle of Q_H, and the large value of χ in the late afternoon is one of the most consistent differences between the rural and suburban sites.

The average energy partitioning by both sites confirms the 'typical' values suggested by Oke (1982).

The partitioning of energy between the turbulent terms indicates a greater day-to-day variation in the suburban context. This may be due to the enhanced sensitivity of the suburban surface layer to synoptic influences.

Acknowledgements

This research was supported by funds from the Natural Sciences and Engineering Research Council of Canada and one of us (HC) was the recipient of a Commonwealth Postgraduate Scholarship. Thanks are due to Transport Canada and B.C. Hydro and Power Authority for making their property available for the rural and suburban sites, respectively. Special thanks are due to Steven Hilts for his assistance in the field and for the contents of Figure 2. Dr John Hay provided data from his meso-scale radiation network and Drs Douw Steyn and Harry McCaughey were very helpful in field observation and discussion. The diagrams were drawn by Paul Jance.

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