Exchange Processes at the Land Surface for a Range of Space and Time Scales (Proceedings of the Yokohama Symposium, July 1993). IAHS Publ. no. 212, 1993.

The role of "rural" in comparisons of observed suburban-rural flux differences

C. S. B. GRIMMOND
Climate and Meteorology Program, Geography, Student Building 120, Indiana University, Bloomington, Indiana 47405, USA

T. R. OKE
Atmospheric Sciences Programme, Geography, #217-1984 West Mall, The University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z2

H. A. CLEUGH
School of Earth Sciences, Macquarie University, Sydney, New South Wales 2109, Australia

Abstract Simultaneous measurements of surface energy balance fluxes and other climate variables were made at suburban, wet rural and dry rural sites in the Sacramento region, California, during late August 1991. The rural sites have "classic" energy partitioning; with average Bowen ratios much greater than 10 at the dry site and 0.18 at the wet site during the daytime. These values remain reasonably constant from day-to-day. In the suburban area the partitioning between sensible, latent and storage heat fluxes is more equal (average daytime Bowen ratio 1.39). Unlike the rural sites the predominant flux is more variable from day-to-day; changing through the twelve day period between storage heat flux and sensible heat flux. The marked difference in energy partitioning between the two rural areas means that the site used as the "rural" reference for the definition of suburban-rural flux differences and urban heat islands is significant.

INTRODUCTION

This paper presents the results of a study of the surface energy exchanges of three distinct surfaces in the vicinity of Sacramento, California, U.S.A. The three locations chosen represent two broad classes of land cover type, *viz,* urban and rural. Rural measurements are often used as a reference against which to evaluate the effects of urbanization on energy and water exchanges (see for example Lowry 1977, Oke & McCaughey 1983, Cleugh & Oke 1986, Grimmond and Oke 1986, 1990); however, rural areas are themselves extensively altered by human activities. Here consideration is given to the significance of the selection of the rural site, irrigated versus non-irrigated, and the implications of that selection to the resulting urban-rural differences.

OBSERVATION PROGRAMME AND METHODOLOGY

Study area and observation period

Continuous measurements were conducted from August 19 to 30 1991 (Year/Day 91/231-242) in the vicinity of Sacramento (38° 39' N, 121° 30' W), California. The Sacramento metropolitan area has a population of 1.48 million and is surrounded by intensive agricultural land use.

The region has a mesothermal (warm, temperate) Mediterranean-type climate, with a hot dry summer. The normal average daily air temperature in August is 23.7 °C, and the normal precipitation is 1.8 mm. The average air temperature in August 1991 was 22.9°C, and it was considerably drier than normal, with only 0.25 mm of rain recorded in the six weeks prior to the measurement period. The general synoptic conditions for the measurement period were typical for the area, with an anticyclone located off the west coast of California, and predominantly westerly winds. A cold front crossed southern Oregon/Idaho on August 24th (91/236) and extended into Northern California on August 25th (91/237). A second front, which had previously been stationary over southern Oregon, passed through the Sacramento region on August 28th (91/240). During the period of observations the sky conditions were clear, with occasional night cloud (see, for example, the early hours of 91/239; Fig. 1).

Instruments to measure the energy balance fluxes and other climatic variables were installed at three sites:

a) *Dry rural (DR)*: located 18.1 km southeast of downtown Sacramento, with a surface cover of tall unirrigated grass (0.5 m);

b) *Wet rural (WR):* located in an extensive irrigated grass farm, maintained at approximately 0.05 m in height, 17.7 km to the southwest of downtown Sacramento; and

c) *Suburban (SU):* located in the residential neighborhood of Carmichael, 16.6 km northeast of the downtown area. The land-use in this suburb is predominately single storey, single family dwellings, with well irrigated (mesiscape) vegetation.

The topography within the vicinity of all the sites is generally flat. The instruments were installed over three days SU: 91/231, DR: 91/232 and WR: 91/233. The measurements at all sites were continuous through until 91/241, except for a six-hour period on 91/236 when irrigation occurred at the WR site. All times referred to are Pacific Daylight Time.

During the observation period people living in the vicinity of the suburban site were permitted to irrigate on alternate days of the week depending on their address (i.e. odd-numbered houses alternated with even-numbered houses). Watering was not permitted on Sundays. Visual observations in the vicinity of the site suggested that the majority of people frequently watered their gardens to maintain them in a lush green state.

Measurements

Measurements were conducted within the energy balance framework; i.e for the rural environment:

$$Q^* = Q_H + Q_E + Q_G [\text{W m}^{-2}] \quad (1)$$

where Q^* is the net all-wave radiation; Q_H the sensible heat flux; Q_E the latent heat flux, and Q_G the soil heat flux. In the urban environment Q_G is replaced with ΔQ_S (the storage heat flux). This allows for the energy gain and release by the buildings, trees and air as well as the soil to be included. The additional heat input due to anthropogenic heat sources was neglected. This flux is typically of the order 15-50 W m^{-2} (Oke 1988).

The measurements, at the WR site conducted at 1.3 m and at the DR site at 1.8 m, are representative of the microscale (length scale of < 1 km). The suburban flux measurements taken at 29 m in the "constant flux layer" of the urban boundary layer (see Oke *et al.* 1989), are representative of the integrated surface types that constitute a "neighborhood" within the suburban area (length scale ca. 0.5 - 5 km).

At each of the sites direct measurements were made of the sensible and latent heat fluxes via the eddy correlation approach, using a Campbell Scientific Inc. (CSI) CA27 one dimensional sonic anemometer and fine wire thermocouple system, and a CSI KH20 krypton hygrometer. The air temperature, specific humidity and vertical wind velocity were sampled at 5 Hz and the covariances determined over 15 min. Flux corrections were made for oxygen absorption by the sensor and air density (Webb *et al.* 1980, Tanner & Greene 1989).

Net all-wave radiation was measured using a Swissteco miniature MK II net pyrradiometer at the SU site, and using REBS net pyrradiometers at the two rural sites. Soil heat flux was measured at each site using two REBS soil heat flux plates, with a CSI thermocouple system installed above the plates to account for thermal divergence between the flux plates and the surface. Daily volumetric soil moisture measurements were taken with a Soil Moisture Equipment Corporation Trase 6000 XI system. It is not possible to directly measure ΔQ_S in the suburban site due to the complexity of the urban surface (Oke and Cleugh 1987, Grimmond *et al.* 1991). Hence in this study it is estimated as a residual in the energy balance ($Q^*-(Q_H+Q_E)$). This has the inherent problem that all the measurement errors of the other energy balance terms are cumulated in this flux.

Wind speed, wind direction, relative humidity, and air temperatures were simultaneously measured at each site. These measurements were taken at 9 m at the SU site. At the two rural sites Everest 4000 infrared thermometers were used to obtain continuous measurements of surface temperature. All non-eddy correlation variables were sampled at 0.2 Hz and averaged over 15 min intervals. Concurrently, atmospheric profiles of temperature, humidity, pressure, wind speed and direction were measured using AIR airsondes that were released and tracked from the suburban site (see Cleugh and Grimmond, 1993).

All instruments were intercompared before being deployed. Appropriate corrections for inter-instrument differences have been made to the results. The energy balance fluxes and climatological variables are compared using hourly fluxes, which represent the average of the four 15 minute values obtained for each hour.

RESULTS AND DISCUSSION

The observed energy balance fluxes for nine days (91/232 to 91/240) for each of the three sites are shown in Fig. 1. The resulting daily (24 h) and daytime ($Q^* > 0$) fluxes and ratios are summarised in Table 1. Mean (ensemble) flux values, Bowen ratios and air temperature differences for each of the sites are presented in Figures 2 and 3.

Energy Balance Closure

At the two rural sites (DR,WR) it is theoretically, and technically, possible to measure all components of the energy balance. However, because of measurement errors associated with each of the fluxes, few empirical studies ever obtain true energy balance closure.

Comparing the wet and dry rural sites, we find that the degree of closure varies through the day. The peak in the residual, in absolute terms, occurs at 14 h at the wet site (175 W m^{-2}), and at 12 h at the dry site (103 W m^{-2}). The lack of closure is consistently greater at the wet site in both absolute and relative terms. On a daily basis this residual represents 6% of Q* at the dry site and 12% at the wet site.

Corrections were not made for frequency response and spatial separation of the eddy correlation sensors, which probably would increase Q_E by 8 to 12% (with decreasing windspeed) (S. Verma and B. Tanner *personal communication 1992*) at the WR and DR sites, and by 1% (M. Roth *personal communication 1992*) at the SU site.

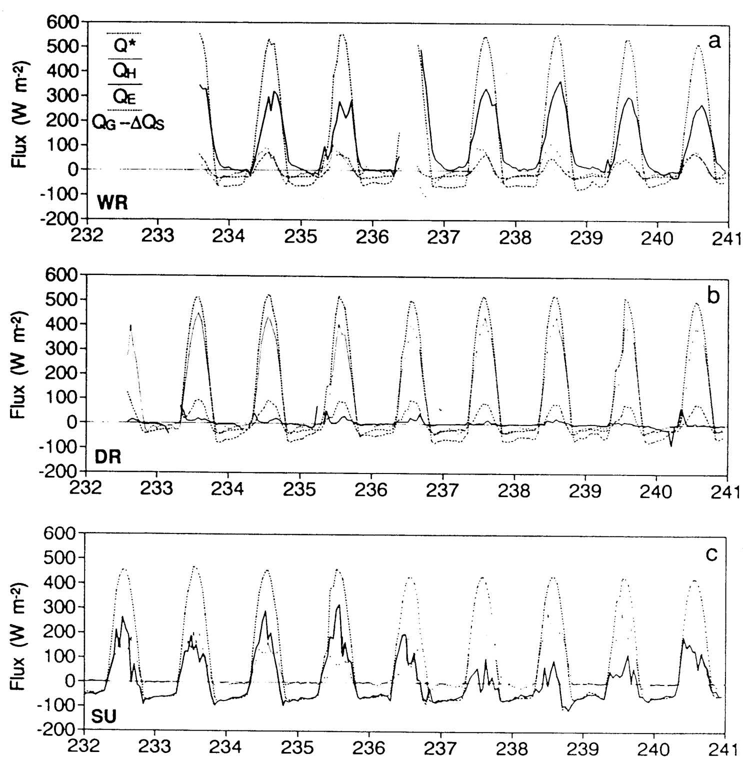

Fig. 1 Hourly energy balance fluxes for the period 91/232-240 in the Sacramento area for (a) Dry rural (DR) site, (b) Wet rural (WR) site, (c) Suburban (SU) site.

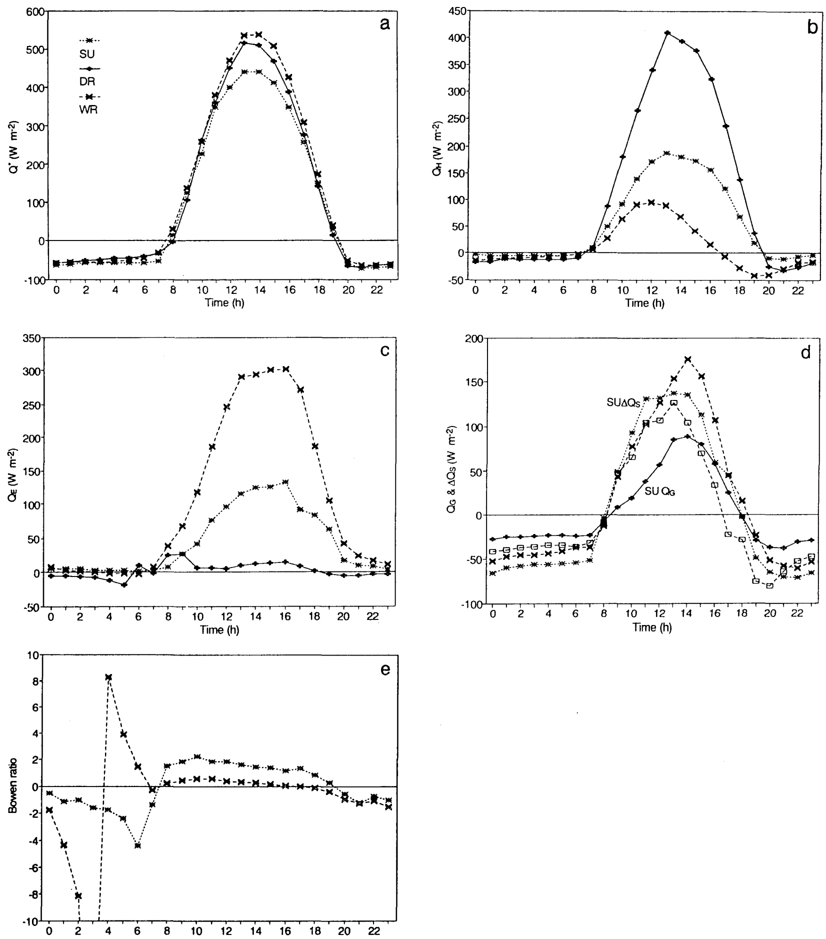

Fig. 2 Intercomparison between sites of hourly ensemble energy balance fluxes: (a) Net all-wave radiation; (b) sensible heat flux; (c) latent heat flux; (d) soil heat and storage flux; (e) Bowen ratio for SU and DR sites.

In absolute terms, the impact would be greatest at the WR site and could explain a portion of the observed non-closure. An increase of 10% in Q_E at WR, would result in a mean residual of ~ 5 W m^{-2} which represents 4% of daily Q*.

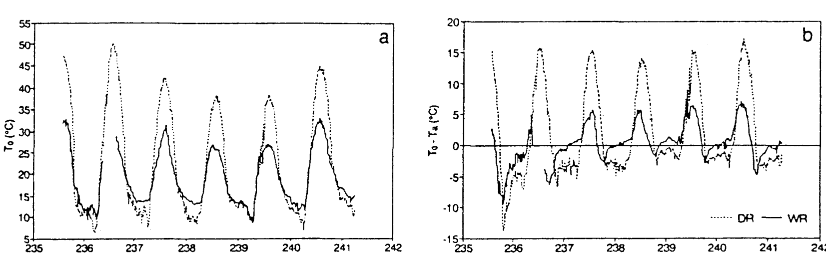

Fig. 3 DR and WR 15 minute air and surface temperatures for 91/235-241: (a) Surface temperature; (b) surface temperature − air temperature.

Table 1 Summary of flux observations: (a) Daily fluxes; (b) daytime fluxes ($Q^* > 0$ W m^{-2}); (c) daily ratios; (d) daytime ratios.

a) Day	Q^* (W m^{-2})	Q_H (W m^{-2})	Q_G (W m^{-2})	Q_E (W m^{-2})	ΔQ_S (W m^{-2})	Residual (W m^{-2})	
SU	103	54	-1	44	5		
DR	119	108	4	3		7	
WR	132	11	-1	105		16	
b) $Q^*>0$							
SU	266	114	43	82	70		
DR	291	234	35	11		46	
WR	317	36	22	200		81	
c) Day		Q_H/Q^*	Q_G/Q^*	Q_E/Q^*	$\Delta Q_S/Q^*$	Res/Q^*	Q_H/Q_E
SU		0.53	-0.01	0.43	0.05		1.24
DR		0.9	0.03	0.02		0.06	40.48
WR		0.08	-0.01	0.79		0.12	0.10
d) $Q^*>0$							
SU		0.43	0.16	0.31	0.26		1.39
DR		0.80	0.12	0.04		0.16	22.23
WR		0.11	0.07	0.63		0.25	0.18

As was noted earlier, at the suburban site ΔQ_S is determined by difference, thus forcing closure. The implication of the lack of closure at the "rural" sites is that it is highly probable that the SU ΔQ_S values, determined by difference, are slighlty larger than they should be. The rural ratios presented in Table 1 do not attempt to account for non-closure of the energy balance by adding energy to any individual flux. In order to account for all of the available energy (and to make the ratios sum to 1.0) the residual fraction needs to be incorporated.

Energy balance partitioning

The dry and irrigated rural sites in this study have "classic" energy partitioning. At the dry site, where the soil moisture was less than 2%, there was negligible Q_E during the day. The peak occurred just after sunrise when the small amount of dew evaporated. The maximum hourly Q_E fluxes of only 24 - 27 W m^{-2}, occurred for the hours ending 8 - 9 h. The predominant energy balance output flux at the DR site was Q_H (Fig. 1). This peaked on average at the same time as Q^* (13 h), with a slight asymmetry around its peak, with greater fluxes occurring in the afternoon. Average Bowen ratios (Q_H/Q_E) are about 40 for all hours, and 22 for daytime hours.

At the wet site the latent heat flux is the most significant output flux. On average Q_E reaches approximately 300 W m^{-2} at 12 h, and stays at a plateau through to 16 h (Figs. 1 & 2c). As at the dry site, Q_H is asymmetrical around its peak at noon. The average daily Bowen ratio is 0.10, and 0.18 for daytime hours (Table 1).

At the suburban site Q_H is larger than Q_E, producing an average daily Bowen ratio of 1.24, and 1.39 for daytime hours. Q_H peaks at 13 h, and again is asymmetrical, with larger fluxes in the afternoon. Q_E on average peaks at 16 h. The output fluxes, as a fraction of Q*, are in order of decreasing significance Q_H, Q_E and then ΔQ_S. It is interesting to note that the fluxes at this site were much more variable on a daily basis than at the wet or dry rural sites. The most notable variations occurred on August 25th (91/237) and August 28th (91/240), when cold fronts passed through the region.

Intercomparison of energy balance flux partitioning between sites

Net radiation was largest during the daytime at the wet site and lowest at the suburban site, with a mean peak difference of approximately 95 W m^{-2} (Fig. 2a). In general, the fluxes show a similar pattern through the day at all sites (Fig. 2a), with midnight values of Q* at all sites approximately -60 W m^{-2}. The differences between sites can be explained by considering the albedos and surface temperatures (T_o) of the respective surfaces. Typical albedos for suburban areas and long grass are similar (suburban 0.15, Oke 1988; and long grass 0.16, Oke 1987); whereas the albedo for short green grass is slightly greater (Oke, 1987). If one assumes that there will be slightly greater attenuation of incoming short-wave radiation at the suburban site (Oke 1988); then the net short-wave radiation during the daytime will be greatest over the DR site, slightly less at the SU site (at 12 h approximately 15 W m^{-2} less), and least at the WR site (for example, at 12 h about 60 W m^{-2} less than the SU site). Based on the observed surface temperatures (Fig. 3a), the outgoing long-wave radiation is approximately 80 - 100 W m^{-2} greater at the DR than the WR site, and approximately 100 - 120 W m^{-2} greater at the SU site than the DR site. When combined it is possible to explain the observed differences between sites in net all-wave radiation.

The ensemble daily patterns of Q_H for the three sites are distinctly different (Fig. 2b). The SU site falls between the two rural sites in terms of the magnitude of the mean hourly flux, and the mean daily and daytime proportion of Q* going to this flux (Table 1). Both the dry and suburban sites have peak Q_H at 13 h; however, the DR site Q_H flux (408 W m^{-2}) is more than twice the SU flux (187 W m^{-2}) (Fig. 2b). At the WR site a plateau of approximately 90 W m^{-2} occurs from 11 - 13 h, which is half the magnitude of the SU peak. The Q_H for both the DR and SU sites turns negative, in the mean, between 19 and 20 h; whereas at the WR site this occurs 2-3 h earlier. All sites show an asymmetry around their peaks with a faster rise and longer fall-off limb to their daytime cycle. The WR has the greatest downward Q_H flux, which occurs during the late afternoon daylight hours. At night SU has the smallest downward flux of sensible heat. The comparative sizes of the fluxes between the sites can be explained by considering the difference in temperatures between the surface (T_o) and the air (T_a) (Fig. 3b). The daytime differences are greater at the dry than the wet site (the difference of ΔT_{o-a} between the two sites is approximately 10°C at 12 h). At the wet site ΔT_{o-a} drops considerably earlier in the afternoon than at the dry site (Fig. 3b), and this is consistent with the earlier reduction in Q_H at the wet site (Fig. 2b).

The pattern of the latent heat fluxes between the sites is opposite to the Q_H pattern: the DR site has the lowest values, and as expected, the WR site the highest. The SU site maintains its intermediate position. However, at the DR site Q_E is virtually insignificant, except for the early morning when dew is evaporated; whereas Q_H is an important output flux at all sites. The difference between sites can be explained by considering the availability of water at each: from essentially unlimited at the WR, to virtually none at the DR. At the suburban site irrigation of gardens sustains the evaporation rates.

The resulting Bowen ratios (Fig. 2e, Table 1) clearly indicate that these three surface covers significantly alter the partitioning of the energy balance fluxes within a relatively small area (spatial scale of the order of 10^2 - 10^3 km^2). Daily Bowen ratios range from the very low 0.10 at the wet site, to 1.24 at the suburban site, to the extremely high (about 40) at the dry site. The suburban values are similar to those observed in the spring and summertime in temperate Vancouver, B.C. (Cleugh & Oke 1986, Grimmond 1992) and greater than those observed in Tucson, Arizona (Grimmond & Oke 1990) and Mexico City (Oke *et al.* 1992). The SU ratio is only slightly greater than the representative value suggested by Oke (1988) as a typical suburban value (1.0).

The ensemble soil heat flux regimes for the three sites plus the SU ΔQ_S are shown in Fig. 2d. At the SU and WR sites this represents the least important flux. At the suburban site the relative proportion is larger than for the other two sites (Table 1). The ability of the SU morphology to store energy in large quantities is driven by the strong surface to internal temperature gradients, and the extensive three-dimensional active surface area.

The in-phase relation between Q* and convective fluxes at the rural sites, and the greater day-to-day variability observed at SU have been seen elsewhere. For example Cleugh and Oke (1986) ascribe the different behavior of rural and suburban sites to the degree of coupling between the surface and the rest of the planetary boundary layer. Rural low cover sites are poorly coupled and their convective fluxes are driven by radiation. Suburban sites are rougher and better coupled to the saturation deficit of the air in the mixed layer.

Implications of the energy balance partitioning for heat islands

Since the way energy is partitioned is the critical energetic control on temperature, urban-rural differences in flux partitioning allows insight to be gained into the urban-heat island (UHI). The difference in temperature between two places, is obviously a function of the energetics of both locations. Thus the size of the UHI is not just a function of the nature of the urban area (its population, morphology etc) but also that of the surrounding rural reference area used for comparison (forested, agricultural, etc). Strictly it is the surface UHI that is explained by the surface energy balance differences. Here we will use them to gain insight into the near-surface air UHI.

The marked differences in energy exchanges between the two rural areas surrounding the metropolitan area of Sacramento suggests one can expect to obtain temperature differences (UHI) of quite different sizes depending on the site chosen as the "rural" reference. It should be remembered that the urban values are suburban rather than downtown urban data; and that the SU temperatures are hourly averages taken at 9 m (i.e. lower boundary layer rather than canopy layer data).

Comparisons of temperatures recorded at the three sites show that the size of the heat island is different depending on the rural reference (DR or WR), in accordance with the energy balance partitioning. The peak UHI for SU-WR is larger than for SU-DR (Fig. 4). The ensemble maximum heat island of 4.0 °C for this period occurred at 20 h with respect to the WR site. This difference in temperature developed steadily from ca. 15 h, reaching this distinct peak and subsequently decreasing to become the same size as SU-DR for the period 0 - 5 h. There is a secondary peak at 7 h of 3.2 °C and then a rapid decline to a small daytime heat island (<1°C) until mid-afternoon.

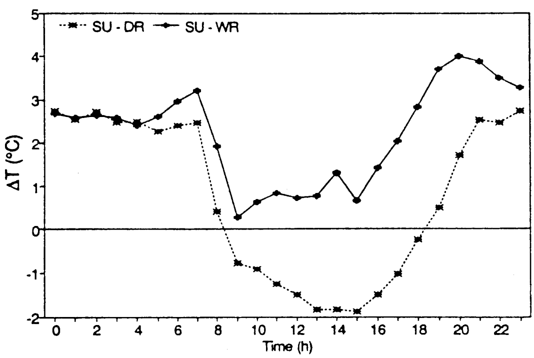

Fig. 4 Ensemble heat island intensities based on the difference SU-DR and SU-WR of the suburban and rural near-surface air temperatures.

The SU-DR UHI peaks at 2.8°C at 23 h, and remains between 2.5 and 2.8°C from 21 h to 7 h. However, by 9 h the urban area is <u>cooler</u> than the dry site (i.e. a "cool island") and remains 1 to 2°C cooler through until 17 h.

The differing cooling rates due in particular to water content, are obviously a critical factor in the energy partitioning and the resulting temperatures that occur at each location. In particular one should note that the nocturnal UHI of a city in an arid area can be smaller than in an area of moist countryside. This is because, despite the fact that its thermal inertia allows it to cool more rapidly (Oke *et al.* 1991), it starts with a significant cool island deficit from the previous daytime.

Acknowledgements Permission to locate the sites at Charles Peck Elementary School, Sierra Sod and Supply, and the Ingram family property is gratefully acknowledged. The following students provided able assistance in the field: from Indiana University, M. Belding, M. Demanes, D. Dishman and A. Johnson; and from UBC, R. Spronken-Smith and J. Voogt. This research was funded by an Indiana University Faculty Research Grant (SG), the Natural Sciences and Engineering Research Council of Canada (TO) and Macquarie University Study Leave Research Grant (HC). The research was conducted while HC was on study leave at Indiana University.

REFERENCES

Cleugh H.A. & Grimmond C.S.B. (1993) A comparison between measured local scale suburban and areally-averaged urban heat and water vapour fluxes. *(this volume)*

Cleugh H.A. & Oke T.R. (1986) Suburban-rural energy balance comparisons in summer for Vancouver, B.C. *Bound. Lay. Meteorol.*, 36, 351-369.

Grimmond C.S.B. (1992) The suburban energy balance: methodological considerations and results for a mid-latitude west coast city under winter and spring conditions. *Int. J. Climatol.,* 12, 481-497.

Grimmond C.S.B. & Oke T.R. (1986) Urban water balance II: Results from a suburb of Vancouver, B.C. *Water Resources Research*, 22, 1404-1412.

Grimmond C.S.B. & Oke T.R. (1990) Preliminary comparisons of measured summer suburban and rural energy balances for a hot dry city, Tucson, Arizona. Proceedings of the International Symposium on Urban Climatology, Air Pollution and Planning in Tropical Cities. Guadalajara, Mexico 25-30 November 1990, 101-104.

Grimmond C.S.B., Cleugh H.A. & Oke T.R. (1991) An objective urban heat storage model and its comparison with other schemes. *Atmos. Env. 25B, 311-326.*

Lowry W.P. (1977) Empirical estimation of urban effects on climate: A problem analysis. *J. Appl. Meteorol.* 16, 129-135.

Oke T.R. (1987) *Boundary Layer Climates*, 2nd ed., Methuen, London, 435 pp.

Oke T.R. (1988) The urban energy balance. *Prog. Phys. Geog.* 12, 471-508.

Oke T.R. & Cleugh H.A. (1987) Urban heat storage derived as energy budget residuals. *Bound. Lay. Meteorol.*, 39, 233-245.

Oke T.R., Cleugh H.A., Grimmond, C.S.B., Schmid H.P. & Roth M. (1989) Evaluation of spatially-averaged fluxes of heat, mass and momentum in the urban boundary layer. *Weather and Climate*, 9, 14-21.

Oke T.R., Johnson G.T., Steyn D.G. & I.D. Watson (1991) Simulation of surface urban heat islands under 'ideal' conditions at night Part 2: Diagnosis of causation. *Bound. Lay. Meteorol.*, 56, 339-358.

Oke T.R. & McCaughey J.H. (1983) Suburban-rural energy balance comparisons for Vancouver, B.C.: An extreme case? *Bound. Lay. Meteorol.*, 26, 337-354.

Oke T.R., Zeuner G. & Jauregui E. (1992) The surface energy balance in Mexico City. *Atmos. Env.,* 26B, 433-444.

Tanner B.D. & Greene J.P. (1989) Measurements of sensible heat and water vapor fluxes using eddy correlation methods. Final report to U.S. Army Dugway Proving Grounds.

Webb E.K., Pearman G.I. & Leunig R. (1980) Correction of flux measurements for density effects due to heat and water vapour transfer. *Quart. J. Roy. Meteorol. Soc.*, 106, 85-100.