Vol. 6: 45–57, 1996 | CLIMATE RESEARCH
Clim Res | Published January 30

Influence of tree cover on summertime surface energy balance fluxes, San Gabriel Valley, Los Angeles

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ABSTRACT: Trees are an important but little studied component of the urban canopy which have distinct climatic effects. This study investigates the influence of trees on local-scale surface energy balance fluxes. Simultaneous energy balance observations were conducted using eddy correlation methods for 2 suburban neighborhoods with higher (30%) and lower (10%) tree and shrub cover, in the San Gabriel Valley of the Los Angeles Metropolitan Area, California, USA. Data were collected on the materials and morphology of the urban surface through a combination of aerial photo analysis and field surveys and analyzed using a geographic information system. Information on external water use was obtained from questionnaires and the analysis of water use data from bi-monthly bills. In terms of the relative partitioning of energy, the effects of the trees are as expected: at the higher tree coverage neighborhood (HTN) the latent heat flux is increased as a fraction of net all-wave radiation, so too is the storage heat flux, whereas the sensible heat flux is decreased. However, in absolute terms, all fluxes, including the sensible heat flux, are enhanced at the HTN. A combination of lower albedos and lower surface temperatures in the HTN result in reduced loss of solar and longwave radiation respectively. Thus at the HTN there is greater net all-wave radiation, hence a greater amount of energy to be dissipated. Above the canopy, temperatures are slightly greater in the neighborhood with higher tree cover.

KEY WORDS: Urban climate · Vegetation · Energy balance · GIS · Water use

INTRODUCTION

Trees are a significant component of the urban landscape. In many regions of North America, trees cover 20 to 40% of the plan area on a city-wide basis, with values in residential neighborhoods often much higher. In many instances there are more trees in the city than in the surrounding rural area (Oke 1989). Much has been written about the benefits of urban trees: both social (aesthetic, psychologic, economic) and physical (climatic, air quality, hydrologic, biogeographic, etc.) (e.g. Platt et al. 1994). However, the effects of urban trees on meteorological processes have been little studied (Oke 1989, Rowntree et al. 1994).

Trees alter the aerodynamic, radiative, moisture and thermal properties of the urban surface (see Oke 1989 for a review). Their effects are manifested at a range of spatial scales: from the urban canopy layer (UCL), where micro-climates are determined by building and vegetation size and spacing; to the neighborhood scale, where vegetation impacts on the climate of city blocks; to the whole city scale, where the urban forest impacts the meso-scale climate. Most research has focused on the effects of trees on individual buildings, i.e. micro-scale studies (e.g. Heisler 1986, Parker 1989, Souch & Souch 1993, Heisler et al. 1994, Simpson et al. 1994). The effects of more extensive areas of urban greenscape, most notably parks, have received some attention (e.g. Jauregui 1991, Spronken-Smith 1994). However, very little research has been conducted on the local-scale effects of urban vegetation. This scale is particularly significant given that the major benefits

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that have been proposed from tree planting are expected to come from increases in evaporative cooling at this scale (Huang et al. 1987).

The objective of this study is to evaluate empirically the effect of vegetation cover on the local scale energy exchanges for 2 neighborhoods within the Los Angeles Metropolitan Area, California, USA. The data presented enhance our understanding of the effect of trees in urban environments, and provide much needed data for the evaluation of numerical models which can be used to assess the effectiveness of different tree planting strategies and management practices.

STUDY DESIGN

Boundary layer climates are determined largely by the interaction of the surface and the atmosphere through the transfer of heat, water vapor, and momentum. In order to understand how urban trees affect these exchanges, observations were conducted within the framework of the surface energy budget. For the near-surface active layer, or volume, at the local scale within a city, this can be expressed:

$$Q^{*} + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad [\mathrm{W\ m^{-2}}] \qquad (1)$$

where Q^{*} is the net all-wave radiation, Q_F is the anthropogenic heat flux, Q_H is the sensible heat flux, Q_E is the latent heat flux, ΔQ_S is the net storage heat flux, and ΔQ_A is the net horizontal heat advection. This concept, and its application to urban surfaces, is reviewed by Oke (1988) and Oke et al. (1989).

A paired-neighborhood study was conducted. Surface energy balance and ancillary climate data (temperature, wind speed, relative humidity, etc.) were simultaneously collected from 2 neighborhoods in close proximity. Of specific interest are the directly observed radiative and convective fluxes. The neighborhoods were chosen carefully to have differences in tree cover but for which all other factors (building morphology, meso-scale climate, etc.) were as similar as practically possible.

Selection and characterization of study sites

An initial, qualitative survey of potential residential sites within the Los Angeles metropolitan area was conducted from color enhanced satellite imagery (Spaceshots 1987, 1:1457280). Locations with similar built morphology but contrasting vegetation density were located on aerial photographs (Aerial Graphics 1987, 1:24000) and preliminary ground surveys conducted. A number of potential neighborhoods were eliminated at this stage due to topographical and/or building density differences, or lack of sufficient fetch. More detailed air photo analysis (Aerial Graphics 1:7200) in conjunction with ground surveys was used to identify 2 study neighborhoods both within the San Gabriel Valley (Fig. 1). Portions of the cities of Arcadia and Pasadena were selected to represent a higher tree coverage neighborhood (HTN), and the city of San Gabriel to represent a lower tree coverage neighborhood (LTN) (Fig. 1). For each neighborhood, detailed information on the morphology and materials of the urban surface were collected at 3 spatial scales (regional, local, and micro) following the methodology outlined by Grimmond & Souch (1994).

(1) Regional scale. Preliminary calculations of the source areas for the convective surface energy balance fluxes [using the Schmid & Oke (1990) source area model] were used to identify the approximate dimensions of the area influencing the observations. Based on these, an area 14 × 14 km, centered approximately on the 2 tower locations in HTN and LTN (see below) was delineated (Fig. 1). Given the focus of the study on the effects of vegetation on urban climate, the 2 primary criteria used to map land use at this scale were building dimensions/density, and vegetation cover dimensions/density. A total of 38 land use classes (22 residential categories, 5 commercial/industrial/institutional, 7 greenspace, 2 transportation, impervious/parking lots, and open water) were mapped from aerial photographs (Aerial Graphics 1:7200).

(2) Local scale (blocks/neighborhoods). A randomly located 200 × 200 m quadrat was used to collect information from the aerial photographs on surface characteristics (percentage cover of: buildings, roads, pavement, other impervious surfaces, trees and shrubs, grass, open areas of dirt, sand and wasteland, and open water; and building/tree densities) for each land use class. Schmid & Oke (1992) have demonstrated that the average suburban block (length scale 10^2 m) contains all the important surface elements to form a characteristic suburban climate. Thus this scale of analysis should provide representative estimates of local-scale variations in surface cover and morphology. Based on a minimum of 10 replicates within each land use class, means and standard deviations of densities of buildings, trees and roads, and percent plan-area cover for each land use class were calculated.

(3) Micro scale (individual properties). More detailed information on local scale building and tree morphology, and on external water use, was obtained from field surveys conducted in July–August 1993. The surveys focused on both general neighborhood conditions and individual properties. For each land use class one polygon was randomly located, and within this 30 properties surveyed in detail. Within each lot,

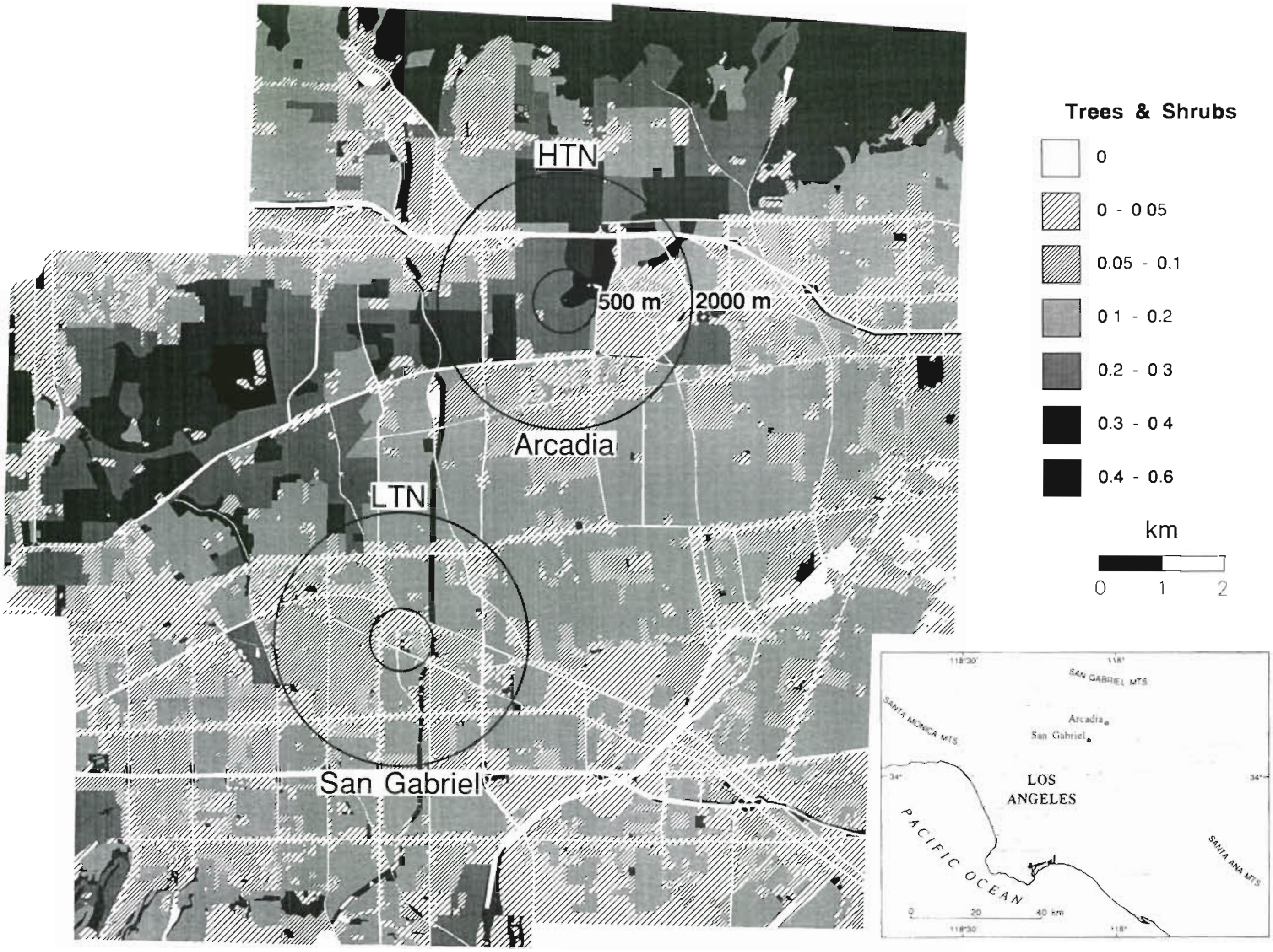

Fig. 1. Spatial variability of the fraction of plan area covered by trees and shrubs across the study region. Inset shows the location of Arcadia (HTN) and San Gabriel (LTN) in the Los Angeles Metropolitan Area

information on surface cover, structures, building dimensions and materials, and irrigation practices were collected.

External water use. In the hot, dry climate of southern California, the vast majority of vegetation found in residential neighborhoods requires irrigation. In order to learn more about external water use, 2 further sets of data were collected. First, a questionnaire was mailed to the residents of 50 properties for each land use class. The objective was to determine: what people irrigate, when, for how long, and using how much water. Second, more detailed information on the volume of water used externally was estimated from bi-monthly water bills provided by the cities of Arcadia and San Gabriel for the areas surrounding the tower sites. The procedure outlined by the American Water Works Association Committee on Water Use (AWWA-CWU 1973) was used to determine external water use (I_E):

$$I_E = I_T - I_I$$

where I_T is total piped water supply, and I_I the piped water supply used internally. In most previous studies I_I has been equated to the mean daily water use in winter. However, this approach had to be modified for application to Los Angeles, because people do irrigate their gardens for some periods in the winter-time. In this study, the minimum water use (I_{MIN}) for each property was determined and assumed to represent internal water use ($I_{MIN} = I_I$).

Surface characteristics of the study area

The distribution of vegetative (tree and shrub) cover across the study region based on the surface database is illustrated in Fig 1. Contrasts around the San

Gabriel and Arcadia sites are clearly evident. A great variety of trees are found in Los Angeles. A list of the most common species and a discussion of the enormous diversity is provided by Hodel (1988) and Causley & Wilson (1991). Here attention is directed only to the aggregate effect of the trees, not to the effects of specific species, and the trees and shrubs are quantified solely in terms of areal coverage.

During the daytime, under unstable atmospheric conditions, the areas influencing the flux measurements (their source areas) are close to the tower. Therefore the surface characteristics influencing the measurements are most likely contained within an area with a radius of 500 m of each tower, oriented in the direction of the prevailing wind. At night, as the atmosphere becomes either neutral or stable, the source areas are elongated but remain aligned upwind of the tower along the prevailing wind direction. At night the upwind lengths of the source areas are probably much greater than 2000 m, but as the relative influence of an area is weighted inversely by the distance from the observation point, the area closer to the tower has more of an influence than that further away.

Table 1 summarizes the average surface characteristics for twelve 30° sectors, with radii of 500 and 2000 m, around each of the towers, representative of day-time and night time source areas respectively. The characteristics calculated are the average fraction of plan area that is: (1) built (buildings); (2) impervious (parking lots, main roads, and pavement); (3) untended or unmanaged (open areas of dirt, sand, and wasteland); (4) trees and shrubs; (5) grass; and (6) open water.

In order to identify which sectors, and thus surface covers, have the greatest influence on the energy balance observations, the frequency of wind direction for twelve 30° sectors around the tower were calculated (Fig. 2). The data used are the 15 min average wind directions recorded at 30 min after the hour for each hour during the measurement period. The analysis is shown for the 2 sites (HTN and LTN) for the entire observation period, and for those hours when Q^* was greater than zero (day-time hours). It can be seen that winds were recorded from all directions, but for both

Table 1. Average plan area surface cover for 30° sectors of radius 500 and 2000 m from LTN and HTN towers. See text for definition of each category. See Fig. 2 for sector numbering

Sector	500 m						2000 m					
	Built	Impervious	Unmanaged	Trees	Grass	Open water	Built	Impervious	Unmanaged	Trees	Grass	Open water
HTN												
1	0.205	0.167	0.012	0.311	0.271	0.033	0.183	0.190	0.022	0.324	0.252	0.029
2	0.110	0.117	0.047	0.443	0.266	0.017	0.143	0.272	0.045	0.288	0.229	0.022
3	0.005	0.060	0.083	0.534	0.248	0.070	0.185	0.344	0.087	0.167	0.194	0.022
4	0.069	0.097	0.068	0.502	0.259	0.006	0.255	0.532	0.059	0.087	0.060	0.006
5	0.170	0.150	0.033	0.385	0.246	0.015	0.272	0.520	0.017	0.083	0.100	0.009
6	0.206	0.169	0.020	0.344	0.242	0.019	0.380	0.391	0.004	0.106	0.109	0.010
7	0.238	0.185	0.009	0.307	0.238	0.022	0.432	0.300	0.004	0.114	0.139	0.011
8	0.281	0.216	0.009	0.253	0.221	0.021	0.265	0.330	0.009	0.195	0.185	0.015
9	0.262	0.197	0.001	0.277	0.239	0.025	0.209	0.209	0.017	0.300	0.241	0.025
10	0.239	0.186	0.006	0.273	0.263	0.033	0.281	0.365	0.013	0.131	0.199	0.011
11	0.224	0.179	0.009	0.271	0.279	0.038	0.235	0.443	0.022	0.119	0.161	0.020
12	0.224	0.179	0.009	0.271	0.279	0.038	0.199	0.191	0.020	0.299	0.260	0.032
LTN												
1	0.221	0.388	0.262	0.038	0.069	0.022	0.294	0.316	0.052	0.110	0.209	0.020
2	0.236	0.430	0.093	0.076	0.151	0.014	0.251	0.396	0.059	0.098	0.175	0.020
3	0.251	0.332	0.051	0.101	0.241	0.024	0.297	0.336	0.026	0.095	0.223	0.023
4	0.220	0.356	0.018	0.101	0.279	0.026	0.234	0.379	0.080	0.077	0.217	0.013
5	0.268	0.278	0.000	0.133	0.281	0.039	0.283	0.380	0.025	0.093	0.209	0.009
6	0.242	0.325	0.000	0.120	0.252	0.060	0.250	0.329	0.057	0.101	0.241	0.022
7	0.289	0.289	0.000	0.129	0.273	0.020	0.280	0.384	0.025	0.093	0.209	0.009
8	0.300	0.432	0.003	0.067	0.184	0.014	0.345	0.379	0.003	0.070	0.189	0.015
9	0.302	0.338	0.002	0.073	0.261	0.024	0.312	0.286	0.036	0.084	0.260	0.023
10	0.300	0.336	0.010	0.068	0.265	0.020	0.324	0.302	0.036	0.078	0.243	0.018
11	0.215	0.595	0.002	0.043	0.134	0.011	0.332	0.439	0.013	0.066	0.145	0.006
12	0.373	0.514	0.003	0.042	0.065	0.002	0.299	0.433	0.019	0.084	0.154	0.011
Av 6–9 HTN	0.247	0.192	0.009	0.295	0.235	0.022	0.322	0.307	0.008	0.179	0.169	0.015
Av 6–9 LTN	0.283	0.346	0.001	0.097	0.245	0.029	0.297	0.345	0.030	0.087	0.225	0.017

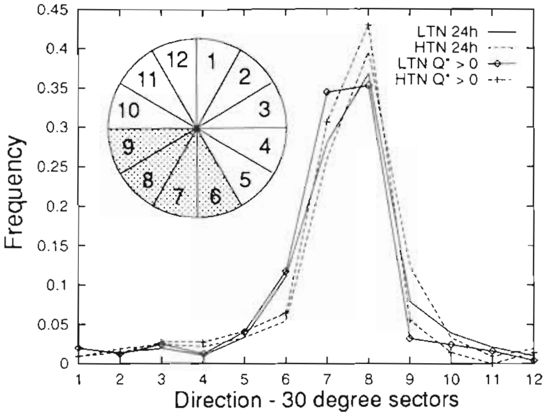

Fig. 2. Frequency of wind directions in HTN and LTN during the measurement period. Inset shows the numbering of the 30° sectors. Shaded area indicates predominant wind directions

Table 2. Average summer (June to August) daily external water use (mm d^{-1}) for sectors 6 to 9 within 500 m of the tower. Average: average depth of water distributed over entire area; Greenspace: average depth of water when just distributed over area irrigated

Sector	Average	Greenspace
HTN		
6	1.67	2.76
7	1.35	2.38
8	1.27	2.56
9	1.19	2.19
Avg 6–9	1.37	2.47
LTN		
6	1.14	1.87
7	1.38	3.26
8	1.38	5.19
9	1.38	3.85
Avg 6–9	1.32	3.54

sites the predominant wind directions are between 150° and 270° (sectors 6 to 9), with peak frequencies between 180° and 240° (sectors 7 and 8).

When the surface characteristics affecting the observations for typical day-time conditions are considered (i.e. sectors 6 to 9 within a 500 m radius), marked differences between the sites are evident: most notably in tree and shrub cover (17.8 to 22.4% greater in the HTN), and the fraction impervious (10.4 to 21.6% greater in the LTN) (see final 2 rows in Table 1). Interestingly, the area covered by grass and open water is very similar for both neighborhoods.

Data on average external water use for both neighborhoods, based on the water use billing data, are presented in Table 2. Overall very similar amounts of water are used externally in the 2 neighborhoods: 1.37 mm d^{-1} in the HTN, compared to 1.32 mm d^{-1} in the same sectors (6 to 9) in the LTN (i.e. 3.6% greater in HTN). This similarity is significant for this study, because it means external water use does not complicate the analysis of the effects of surface cover. Given the greater area of irrigated greenspace in the HTN, the actual depth of water applied to the greenspace areas is less than for the LTN (2.47 mm d^{-1} in HTN; 3.54 mm d^{-1} in LTN).

Table 3 summarizes information from the questionnaires weighted by areal fraction of each land use class present in the 2 neighborhoods. The data are the percentage of respondents giving a specific response. For many of the survey questions more than one response is possible; thus for certain questions the sum of responses may be greater than 100%. In the summer in both neighborhoods, residents typically water every other day. In general, in the HTN irrigation is more likely to occur in the cooler hours of the day than in the LTN. This may be attributed to the greater proportion of residents who irrigate manually in the LTN, and do so when they get home from work, compared to the automatic irrigation more common in the HTN, which occurs mostly at night (Table 3). On the days that people irrigate they do so for slightly longer in the LTN, but on average in the LTN the area they irrigate is smaller.

Meteorological measurements

To obtain meteorological observations representative of the neighborhood scale, measurements must occur within the constant flux layer of the urban boundary layer (Oke et al. 1989). To do this, instruments were installed on a 32.5 m free-standing triangular lattice tower located at the western edge of the Los Angeles State and County Arboretum, Arcadia (HTN), and on an 18 m pneumatic tower located in the San Gabriel Water District works yard, San Gabriel (LTN). The variables measured and instrumentation used at the 2 sites are listed in Table 4. The observations were conducted in July 1994 (Year/Day: 94/188–206).

The surface energy balance provides the framework for the direct measurements of the energy exchanges (Eq. 1; for full details, and implications, see Grimmond & Oke 1995). The convective fluxes (Q_H and Q_E) were measured using eddy correlation techniques. A Campbell Scientific Inc. (CSI) 1-dimensional sonic anemometer and fine wire thermocouple system (SAT: CA27) was used to measure the vertical wind velocity and temperature, and a CSI krypton hygrometer (KH20) to measure the absolute humidity. Data were collected and corrected, and fluxes calculated

Table 3. Summary results from irrigation survey for sectors 6 to 9 within 500 m of the towers. Any activity conducted by >10% of the respondents is reported

		HTN		LTN	
A. Method	Grass	Automatic sprinkler	70%	Hand watering	48%
		Manual sprinkler	35%	Manual sprinkler	44%
		Hand watering	34%	Automatic sprinkler	27%
	Trees	Automatic sprinkler	70%	Hand watering	49%
		Hand watering	35%	Manual sprinkler	34%
		Manual sprinkler	34%	Automatic sprinkler	9%
B. Time of day	Weekdays	20:00-06:00 h	42%	16:00-20:00 h	51%
		06:00-10:00 h	42%	20:00-06:00 h	39%
		16:00-20:00 h	21%	06:00-10:00 h	21%
	Weekends	20:00-06:00 h	42%	06:00-10:00 h	43%
		06:00-10:00 h	42%	20:00-06:00 h	41%
				16:00-20:00 h	23%
C. Duration	Grass	15-30 min	97%	< 15 min	19%
				15-30 min	49%
				30-45 min	11%
				45-60 min	12%
	Trees	< 15 min	49%	< 15 min	45%
		15-30 min	49%	15-30 min	32%
				30-45 min	12%

using the methodology outlined in Grimmond & Oke (1995). All times are reported as Local Apparent Time (LAT).

At the HTN, the HMP35C Vaisala temperature and humidity sensors were housed in a R.M. Young aspirated shield, whereas at the LTN a CSI 207 sensor mounted in a 12 plate R.M. Young Gill-type radiation shield was used. All sensors were intercompared in August 1994 at the USDA Forest Service Fire Laboratory, Riverside, California. This site is characterized by bare, dry soil, with a sparse distribution of dry grasses. All like instruments were placed next to each other (0.4 m apart) at a height 1.2 m above the ground. All data considered subsequently have been corrected for inter-instrument differences, including adjustment for the lack of aspiration at the LTN.

Table 4. Instrumentation used for measurements and heights of installation

Variable	Manufacturer/Instrumentation	Model	Level installed (m) LTN	Level installed (m) HTN
Sensible heat flux (Q_H)	CSI SAT	CA27	18	32.8
Latent heat flux (Q_E)	CSI krypton hygrometer	KH20	18	32.8
Net all-wave radiation (Q^*)	REBS net radiometer	Q*6	18	32.8
Solar radiation ($K\downarrow$)	Li-cor pyranometer	LI 200 S	18	32.8
Soil heat flux (Q_G)	REBS soil heat flux plates with CSI	HFT1	-0.08	-0.08
	averaging soil thermocouple probe	TCAV	-0.02, -0.06	-0.02, -0.06
Air temp. (T) &	CSI temperature and rel. humidity	207	18[a]	-
relative humidity (RH)	Vaisala temperature and rel. humidity	HMP35C	-	32.8[b], 21.3[b], 11.5[b]
Wind speed (u)	R.M. Young wind sentry	03101-5	18	32.8, 21.3, 11.5
Wind direction	R.M. Young wind sentry	03101	18	32.8, 11.5
Precipitation	Texas Instruments rain gauge	TE 525	-	6.7
Pressure	Vaisala barometric pressure transducer	PTA 427	-	1.5
Surface moisture status	Weiss type wetness sensor		0	0

[a]12 plate Gill-type radiation shield; [b]R.M. Young aspirated shield

RESULTS AND DISCUSSION

The observation period was characterized by predominantly anticyclonic conditions, with frequent marine onshore flow, which produced low level morning cloud that dissipated by late morning. There was no measurable precipitation during the study period, and the last recorded precipitation occurred on June 15, 1994 (1.1 mm). In May 1994, 16.6 mm of rain fell at the HTN. Based on data collected at the San Gabriel fire department NWS climate station, July 1994 was slightly cooler (–0.4 °C) and drier (–0.25 mm) than normal (NOAA 1994).

The energy balance fluxes (Q^*, Q_H and Q_E) observed during July 1994 at the 2 sites are shown in Fig. 3. In order to remove the effects of any possible differences between sites due to differences in sky conditions, the data were stratified based on cloud cover. Only days with predominantly clear-sky conditions are considered subsequently (a total of 14 days in the study period: Fig. 3), although some of these days did have early morning cloud (Figs. 3 & 4). To illustrate the average conditions at both sites, ensemble (mean) flux values and ratios were calculated (Fig. 4 & Table 5). The absolute differences in fluxes between sites for each of the 14 clear sky days are illustrated in Fig. 5. A positive value indicates higher fluxes in the HTN, a negative value higher fluxes in the LTN.

Under clear sky conditions, solar radiation receipt ($K\downarrow$) is virtually the same at the 2 sites ($K\downarrow_{LTN}/K\downarrow_{HTN} = 0.97$) (see also Fig. 3). This is expected given the close proximity of the neighborhoods. Differences between the sites are evident in the early morning (Fig. 5) and likely attributable to the effect of early morning cloud cover which has not been removed from the data. Based on the data and visual observations in the field, the clouds took slightly longer to dissipate at the LTN.

Net all-wave radiation (Q^*) shows a systematic difference between sites (Fig. 3). Overall net all-wave radiation is 19% greater at the HTN on a day-time basis (Fig. 4, Table 5). This result is rather surprising given that most previous studies have found remarkably limited intra-urban variation in radiation exchange (Oke 1989). Early in the morning there is considerable scatter, undoubtedly related to the variation in cloud commented on above. After this early morning period, in general, Q^* is greater at the HTN than the LTN during the day-time by the order of 75 W m^{-2}, while at night Q^* is similar at the 2 sites.

The source area for the net all-wave radiation measurements, based on the field of view of the radiometers, is not as large as for the convective fluxes (Schmid et al. 1991). Thus the difference in Q^* observed between the 2 sites may not be representative of actual differences between the neighborhoods, but enhanced by poor spatial sampling of the surfaces of each neighborhood at the measurement sites. Although data were only collected at one site in each of the neighborhoods in 1994, in 1993 net all-wave radiation was measured at 2 sites within the HTN (neither of these were the exact site used in 1994). In July 1993, for clear sky conditions, differences between the 2 sites were less than 3%.

As noted above, the initial radiative forcing ($K\downarrow$) is very similar at both locations, although there is a slight (3%) enhancement at the HTN. Possible physical explanations for the differences in net all-wave radiation between sites relate to differences in albedo and/or surface temperatures. A combination of higher albedos and/or higher surface temperatures in the LTN would result in enhanced outgoing solar- and long-wave radiation ($K\uparrow$ and $L\uparrow$) respectively, and thus reduced Q^*. Around the LTN site impervious surfaces are predominantly concrete and the unirrigated soils are light-colored. In contrast, around the HTN asphalt is more common, the trees are generally darker colored than the impervious surfaces, and bare soil often is irrigated. Thus higher albedos are consistent with lower tree cover and a higher proportion of impervious (concrete) surfaces at the LTN. Independent support for higher albedos in the LTN is provided by aircraft mounted radiometer data collected by Taha (Lawrence Berkeley Laboratories) (cited in Simpson et al. 1995).

The nocturnal pattern of Q^* at both sites is slightly unusual, with a noticeable step-increase on most nights (see for example, the nights of 190–191, 194–195, 195–196). These nocturnal 'steps' were also seen in data collected in 1993 at the HTN site (Grimmond & Oke 1995). Given this was evident at both sites, occurring at approximately the same time, the anomalies were likely caused by an atmospheric rather than surface effects, probably the nocturnal cloud build-up.

In absolute terms, day-time values of sensible heat flux (Q_H) are very similar at the 2 sites ($Q_{H.LTN}/Q_{H.HTN} = 0.97$). The peak daily value is almost identical, with values slightly greater at the HTN site in the morning (Fig. 4). The latent heat flux (Q_E) is distinctly larger for the HTN. The greatest relative difference occurs in the early afternoon, between 12:00 and 16:00 h, when on average Q_E is 50 W m^{-2} greater in the HTN (Fig. 4). Differences for individual hours range up to a maximum of 100 W m^{-2} (Fig. 5). On a daily (24 h) basis $Q_{E.LTN}/Q_{E.HTN} = 0.71$. At both sites the convective fluxes show the same basic diurnal pattern.

The measurements of the convective fluxes are independent of the radiation measurements and provide some support for the differences observed in Q^* between sites. When summed ($Q_H + Q_E$), greater amounts of energy (14%) enter the convective fluxes in the

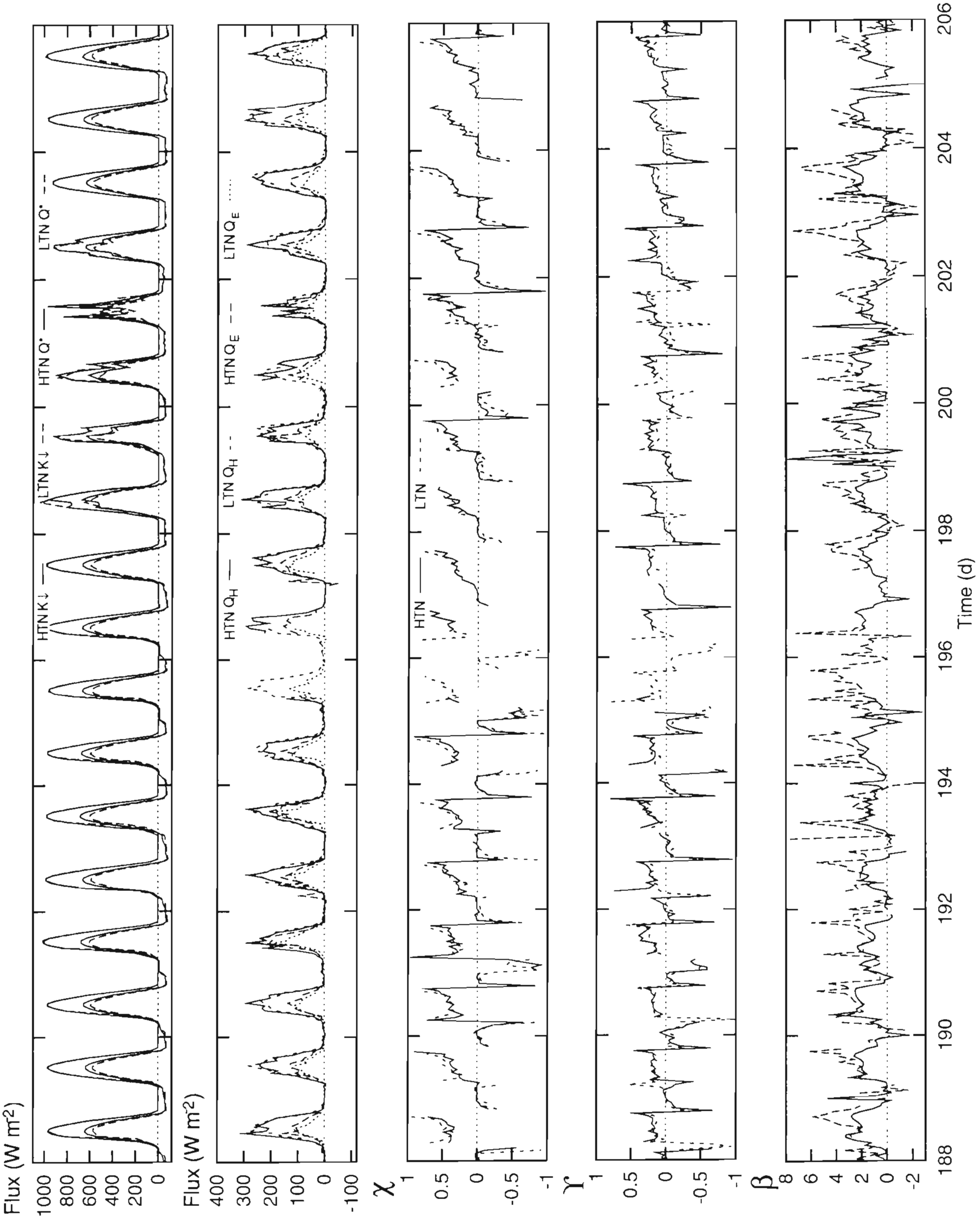

Fig. 3. Time series of surface energy balance fluxes and flux ratios: incoming solar radiation ($K\downarrow$), net all-wave radiation (Q^*), sensible heat flux (Q_H), latent heat flux (Q_E), χ (Q_H/Q^*), Υ (Q_E/Q^*), and β (Q_H/Q_E) for the HTN and LTN sites

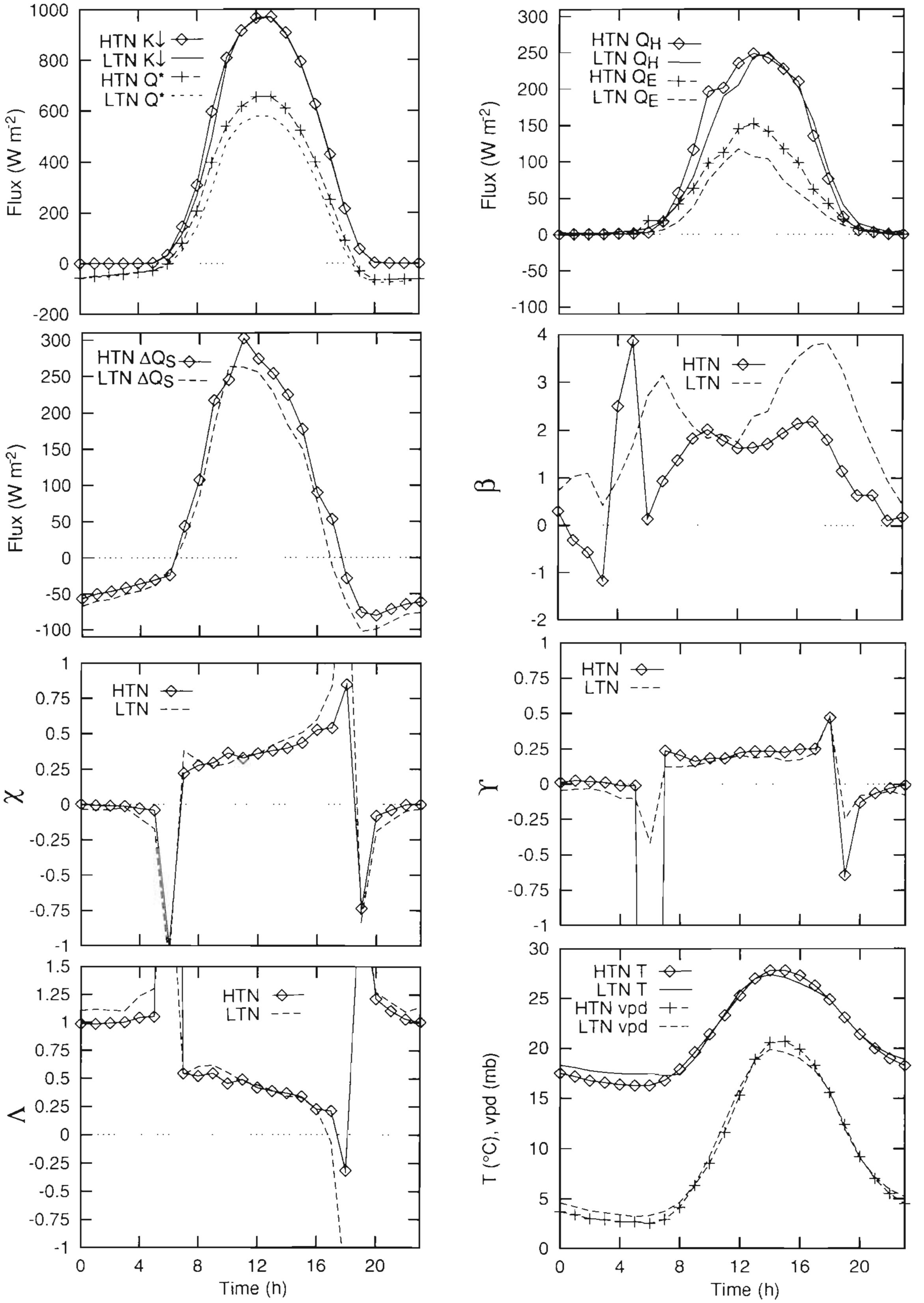

Fig. 4. Ensemble energy balance fluxes and flux ratios for clear sky conditions: incoming solar radiation ($K\downarrow$), net all-wave radiation (Q^*), sensible heat flux (Q_H), latent heat flux (Q_E), storage heat flux (ΔQ_S), β (Q_H/Q_E), χ (Q_H/Q^*), ϒ (Q_E/Q^*), Λ ($\Delta Q_S/Q^*$), temperature (T), and vapor pressure deficit (vpd)

Table 5. Average flux partitioning for the 2 neighborhoods LTN and HTN, under clear sky conditions. Data collected in 1993 at the HTN for Days 93/188–206 are included for comparative purposes, $\mathrm{HTN}_{(93)}$. All fluxes MJ d^{-1}

Site	Q^*	Q_H	Q_E	ΔQ_S	β	χ	Υ	Λ	$Q_H/\Delta Q_S$
24 h									
$\mathrm{LTN}_{(94)}$	12.94	6.98	2.92	3.04	2.39	0.54	0.23	0.24	2.30
$\mathrm{HTN}_{(94)}$	16.08	7.20	4.12	4.76	1.75	0.45	0.26	0.29	1.51
$\mathrm{HTN}_{(93)}$	14.77	5.83	4.32	4.53	1.35	0.40	0.30	0.31	1.29
$Q^* > 0$ (12 h)									
$\mathrm{LTN}_{(94)}$	15.21	6.64	2.73	5.87	2.43	0.44	0.18	0.39	1.13
$\mathrm{HTN}_{(94)}$	18.06	7.07	3.93	7.06	1.80	0.39	0.22	0.39	1.00
$\mathrm{HTN}_{(93)}$	16.26	5.84	4.10	6.32	1.43	0.36	0.25	0.39	0.93

HTN, which is consistent with greater net all-wave radiation at the HTN site. During the day-time the ratio of the net all-wave radiation to the summed turbulent fluxes, η, $[Q^*/(Q_H + Q_E)]$ is almost identical at both sites (0.62 at the LTN, 0.61 at the HTN), although on a daily (24 h) basis η is greater at the LTN (0.77 compared to 0.70 at the HTN).

Generally there are larger night-time and smaller day-time storage heat fluxes at the LTN than the HTN (Fig. 4). On a daily basis, $\Delta Q_{S.LTN}/\Delta Q_{S.HTN} = 0.83$. The magnitude of the difference increases through the course of the day, with a maximum difference just greater than 50 W m^{-2} at 17 h. As described in Grimmond & Oke (1995), the storage heat flux (ΔQ_S) is determined as the residual of the energy balance and should be interpreted with caution. This is particularly the case given the nocturnal behavior of Q^* noted above, which means at both sites limited heat loss (ΔQ_S) is calculated at night. Consequently the daily (24 h) ΔQ_S is a large positive flux, indicating a significant build-up of energy at the site.

One component of the storage heat flux, the soil heat flux (Q_G), was measured directly using soil heat flux plates at multiple sites within both neighborhoods. Although these data do not provide information on the absolute magnitude of ΔQ_S, Grimmond & Oke (1995) found that in a number of cities the diurnal trend of Q_G is very similar to that of ΔQ_S. In both neighborhoods the soil heat flux data also indicate a net gain of energy.

To investigate the relative partitioning of energy at the 2 sites, i.e. to remove the effect of the differences in net all-wave radiation, the ratios χ (Q_H/Q^*), Υ (Q_E/Q^*), and Λ ($\Delta Q_S/Q^*$) were calculated (Figs. 3 & 4, Table 5). The differences in these ratios between sites are shown in Fig. 5. Given the storage heat flux term is calculated as a residual, the ratios must sum to 1.0. Thus an increase in 1 or 2 of the ratios must be accompanied by a decrease in another

On average the data show the latent heat flux is greater in relative (Υ) as well as absolute terms at the HTN (Figs. 4 & 5). In the LTN the sensible heat flux is greater as a proportion of net all-wave radiation (χ) on a daily basis (Table 5). The diurnal pattern of χ is approximately the same for the 2 sites in the morning, but χ increases to greater values in the LTN in the late afternoon/early evening (Fig. 4). Given that Q_H in absolute terms is almost identical at both sites, this pattern is attributed to the lower Q^* at the LTN. The Λ ratio is very similar in both magnitude and trend for the 2 sites during the day-time ($Q^* > 0$), but over 24 h is greater for the HTN (Table 5). The partitioning of the sensible heat between the atmosphere and the surface ($Q_H/\Delta Q_S$) is different between the 2 sites (Table 5). During the day, a greater proportion of energy warms the atmosphere at the LTN, whereas the sensible heat is equally partitioned between the surface and atmosphere in the HTN (Table 5). The differences between the 2 neighborhoods is enhanced on a daily (24 h) basis.

The average day-time Bowen ratio ($\beta = Q_H/Q_E$) is 1.80 for the HTN and 2.83 for the LTN (Table 5) i.e. Q_H constitutes 71% of the total turbulent energy exchanges in the LTN, 64% in the HTN. These Bowen ratio values are consistent with Grimmond & Oke's (1995) suggestion that the mean daytime Bowen ratio is inversely related to the area irrigated (55% of the surface area in the HTN, 37% in the LTN). In the early morning there are obvious differences in β between the 2 sites (Fig. 5). However, at this time of day β is the ratio of 2 small numbers which do not behave consistently. During the day and early evening β is larger in the LTN, the magnitude of the differences increase though the course of the day as Q_E becomes increasingly greater at the HTN.

Energy balance data were collected at the HTN site in 1993 (reported in Grimmond & Oke 1995). These data provide an opportunity to assess the similarity in energy partitioning for the HTN for different years (Table 5). The data presented here from 1993 are just for the same time period as the 1994 study. Hence the average fluxes and flux ratios are slightly different to those presented in Grimmond & Oke (1995) where the full 1993 measurement period is reported. City of Arcadia water consumption data (whole city scale) for July 1993 and 1994 are almost identical. However, water consumption in the months of May and June 1993 was higher than in the corresponding months in 1994 by 1.16 and 1.19 times, respectively.

It is evident that while the absolute magnitudes of the fluxes differ between years, the relative energy partitioning at the HTN is very similar and consistently

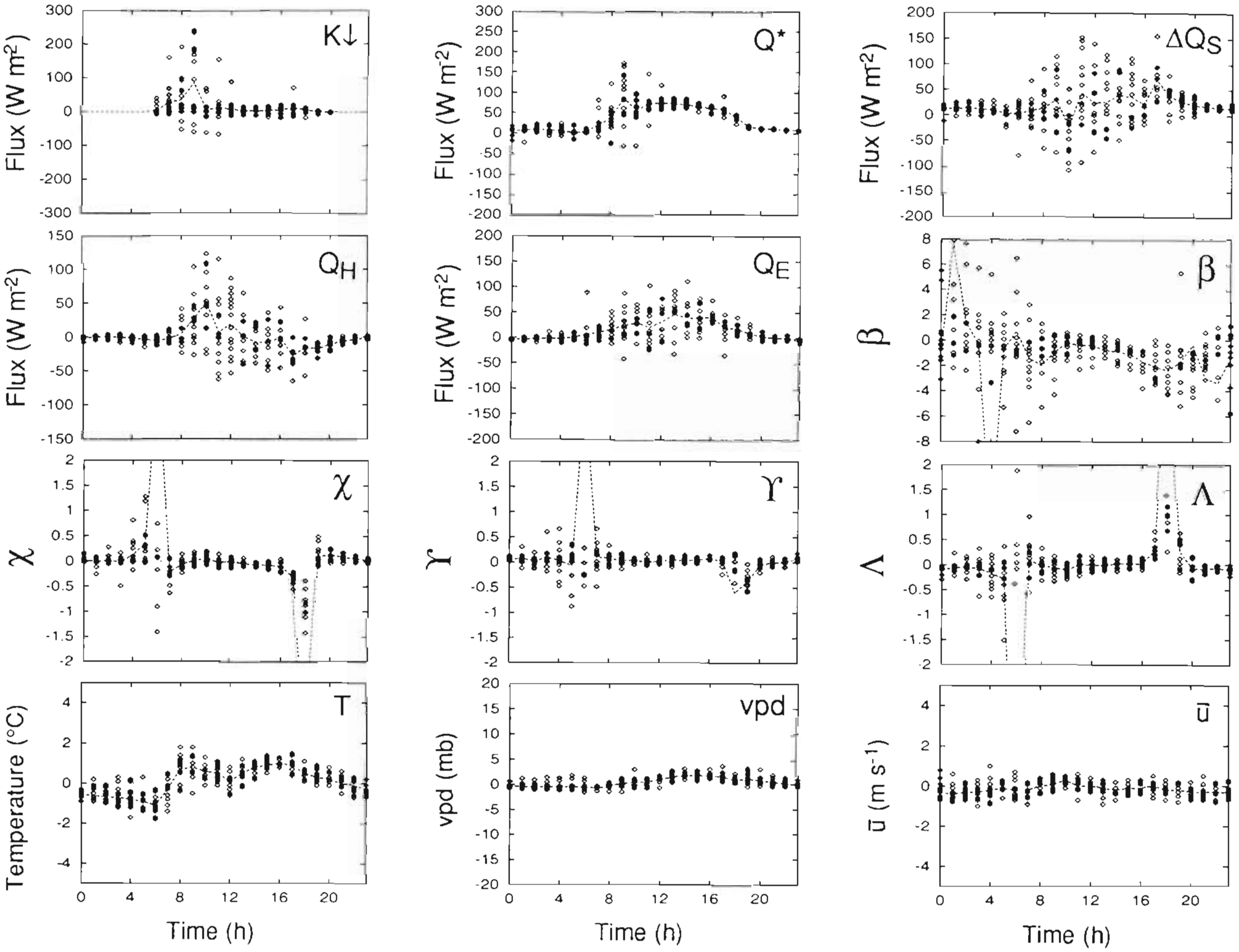

Fig. 5. Differences between neighborhoods (HTN and LTN) in: incoming solar radiation ($K\downarrow$), net all-wave radiation (Q^*), storage heat flux (ΔQ_S), sensible heat flux (Q_H), latent heat flux (Q_E), β (Q_H/Q_E), χ (Q_H/Q^*), ϒ (Q_E/Q^*), Λ ($\Delta Q_S/Q^*$), temperature (T), vapor pressure deficit (vpd) and wind speed (u). All hours for the clear-sky days are plotted. Dashed line shows the average difference

different to the LTN (Table 5). On a daily (24 h) basis, the incoming short-wave radiation ($K\downarrow_{94} - K\downarrow_{93}$ = 2.09 MJ d^{-1}; $K\downarrow_{93}/K\downarrow_{94}$ = 0.93), net all-wave radiation ($Q^*_{94} - Q^*_{93}$ = 1.31 MJ d^{-1}; Q^*_{93}/Q^*_{94} = 0.92), sensible heat flux ($Q_{H94} - Q_{H93}$ = 1.37 MJ d^{-1}; $\Delta Q_{H93}/\Delta Q_{H94}$ = 0.92), and storage heat flux ($\Delta Q_{S94} - \Delta Q_{S93}$ = 0.23 MJ d^{-1}; $\Delta Q_{S93}/\Delta Q_{S94}$ = 0.95) were all greater in 1994, while the latent heat flux was greater in 1993 ($Q_{E94} - Q_{E93}$ = −0.2 MJ d^{-1}; Q_{E93}/Q_{E94} = 1.05). Given that Q_H is greater in magnitude then Q_E, when summed more energy was put into the turbulent fluxes in 1994 than 1993 [$(Q_H + Q_E)_{93}/(Q_H + Q_E)_{94}$ = 0.90]. The daily η values (i.e. ratio of the net all-wave radiation to the turbulent heat fluxes) was almost identical in 1993 and 1994, 0.70 and 0.69 respectively. The average Bowen ratio was greater in 1994 than 1993, due to the greater Q_H in 1994, attributed to greater solar and net all-wave radiation. It is not known whether the greater solar radiation receipt in 1994 was caused by lower air pollution levels or less persistent early morning cloud. The general meteorological conditions in July 1993 and 1994 were very similar; average July temperatures were slightly greater in 1994, 23.6°C compared to 23.5°C in 1993, with no precipitation in either year.

Most applied interest and the bulk of previous studies center on the effects of trees in urban areas on air temperature, humidity and wind speed. Figs. 4 & 5 show the differences in the temperature and vapor pressure deficit measured at the 2 sites. The daily maximum air temperatures ranged between 25 and 30°C for both sites; minimum air temperatures were approximately 15°C. Interestingly, based on these above-canopy, local-scale measurements, the temperature is greater at the HTN, by the order of 1°C, in the late afternoon, but warmer in the LTN by approximately the same amount at night. Independent observations collected at the below-canopy scale (Simpson et al. 1995) document similar temperatures in both neighborhoods at noon, but slightly greater temperatures at the Arcadia (HTN) site in the afternoon (approximately 0.5°C warmer). Automobile-based temperature traverses also indicate that this may be the case (Levitt et al. 1994). The warmer temperatures are consistent with the enhanced sensible heat flux at the HTN.

The daily maximum vapor pressure deficit (vpd) at both sites ranged from 15 mb to slightly greater than 25 mb. In the afternoon, vpd was greater at the HTN by approximately 2 to 3 mb, consistent with the greater latent heat flux at the HTN. The diurnal range in vpd was slightly smaller at the LTN than at the HTN (Fig. 4), consistent with the temperature pattern documented above.

Maximum wind speeds at both sites were less than 4 m s^{-1}, with a strong diurnal pattern associated with day-time heating. The greatest differences between the 2 sites occurred at night, when the wind speeds in the LTN tended to be slightly greater (<0.5 m s^{-1}). The low wind speeds at the 2 sites suggest that the differences in the turbulent fluxes are due to free rather than forced convection. Thus in these neighborhoods the effects of trees on thermal and moisture surface characteristics are probably more important than roughness influences.

CONCLUSIONS

This study documents differences in energy partitioning for 2 neighborhoods with differing tree cover but for which regional climate and external water use are very similar. Differences between the neighborhoods are most evident in the net all-wave radiation (which is enhanced in the HTN), and the ratios of the fluxes Q_H/Q_E and $Q_H/\Delta Q_S$, both of which are greater in the LTN. In terms of the relative partitioning of energy, the effects of the trees are as expected: at the HTN the latent heat flux is increased as a fraction of available energy, so too is the storage heat flux, whereas the sensible heat flux is decreased. However, in absolute terms, all fluxes, including the sensible heat flux, are enhanced at the HTN. The data suggest that in the San Gabriel Valley, trees and shrubs and the attendant changes in other surface characteristics lower the albedo and temperatures of the surface, thereby reducing the loss of solar and long-wave radiation respectively. This results in an increase in the absolute amount of energy to be dissipated at the HTN. Thus at the HTN all fluxes, including the sensible heat flux, are enhanced in absolute terms. One outcome of this is that temperatures are slightly greater in the neighborhood with higher tree cover.

Comparison of data for the HTN for 2 years shows that although the absolute magnitude of the fluxes vary between years (attributed to greater solar radiation in 1994, and slightly greater external water use in the spring of 1994), the flux ratios for the HTN are similar and consistently different to those of the LTN.

It is important to caution that the comparative data presented represent only one set of measurements, conducted from one pair of neighborhoods, in one city, in one summer. The results indicate that the effects of trees on local-scale climates are complex, and that the full range of moisture, aerodynamic, thermal and radiative effects must be considered. More data need to be collected for a much wider range of conditions before predictions about the meteorological effects of trees and tree planting strategies in urban areas can be made with confidence.

Acknowledgements. Many people have been involved in this project; without their help the research would not have been possible. Field and research assistance was provided by: Mark Demanes, Jane Southworth, Michele Mattix, Dallas Dishman, Amy Johnson, Tom King, Rezaul Mahmood, Mark McKee and Trevor Newton. Additional research assistance was provided by: Rob Silcox, Beth Hall, Liz Connell, Harry Bannon and Dr Sherry Mitchell-Bruker. Dr Jim Simpson, Dr Dan Levitt, and Klaus Scott of the U.S. Forest Service provided assistance in numerous ways; as did Dr Paul Doose (Southern California Edison). Permission to use the sites was given by Los Angeles State and County Arboretum and San Gabriel Water District. In particular we thank John Provine and Steve Terra of these 2 organizations. Thanks also to the Cities of Arcadia and San Gabriel for providing the water use billing data, in particular Rita Kurth, and the USDA Riverside Fire Laboratory for providing the grounds to do the instrument intercomparisons. This research was funded by Southern California Edison (Grimmond).

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Editor: V. Meentemeyer, Athens, Georgia, USA

Manuscript first received: May 3, 1995
Revised version accepted: June 29, 1995