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Evapotranspiration rates in urban areas

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Abstract For a significant number of urban hydrological issues, notably, water supply, water quality, groundwater recharge, saline intrusions, and flood runoff, knowledge of evapotranspiration (*ET*) rates is required. However, because little is known about the magnitude of urban *ET* rates and their spatial variability, broad assumptions have to be made in many applications. In this paper we present direct measurements of the magnitude and variability of *ET* rates using micrometeorological techniques (eddy correlation), in seven North American cities. The data demonstrate the importance of urban *ET*, and illustrate clear differences with land use. Simple relations between *ET* and measures of land cover are shown.

INTRODUCTION

Most urban hydrological studies focus on issues of water supply and/or flood runoff. In such work, the key hydrological processes are precipitation and/or runoff (e.g. Nelen *et al.*, 1992; Thielen & Creutin, 1997); other hydrological processes, either implicitly or explicitly, are largely ignored. In some instances this is entirely appropriate; but on other occasions it comes about because of a widely held belief that urban evapotranspiration (*ET*) can be neglected because it is considerably less than from neighbouring rural areas, because of contrasts in the hydrological properties of building materials and vegetation-covered soils (Chandler, 1976). However, in many urban areas trees and other vegetated surfaces cover a significant area. In fact, in many urban environments there are more trees than in the surrounding rural landscape. Further, many of the vegetated sites are irrigated and their *ET* may be assisted by local- and microscale advection (Spronken-Smith *et al.*, 1998). Work in Vancouver, British Columbia (Grimmond & Oke, 1991), has shown that *ET* is an important component of that city's energy and water budget (constituting ~40% of annual and ~80% of summer water balance losses), but few data exist for other locations. Consequently, knowledge of the spatial variability of urban ET rates both within and between urban areas remains limited, despite the fact that such data are needed in many hydrological, meteorological, ecological and horticultural applications, notably those associated with low flow conditions, water quality, groundwater recharge, and long term water supply.

Here we report direct observations of evapotranspiration for a range of North American cities (Table 1). The results (a) extend significantly our knowledge of *ET* in cities, (b) demonstrate the micrometeorological/hydrological significance of *ET* in

Table 1 Study sites ordered by increasing fraction of the surface built (decreasing fraction greenspace). Code refers to the location and year of observation e.g. Me93 refers to Mexico City 1993. LU Land use (suburban, light industrial and downtown). Fraction plan area: buildings (Bld), impervious (Imp), unmanaged or vacant (UM), trees (TR), grass (GR), water (WT).

Site	Code	Period	LU	Bld	Imp.	UM	TR	GR	WT
Mexico City, D.F.	Me93	Dec 1993	D	0.54	0.44	0.02	0.01	0.00	0.00
Vancouver, B.C.	Vl92	Aug 1992	LI	0.51	0.44	0.00	0.03	0.02	0.00
Chicago, IL	C95u	June/Aug 1995	Sub	0.36	0.25	0.00	0.07	0.32	0.00
Tucson, AZ	T90u	June 1990	Sub	0.23	0.42	0.17	0.11	0.07	0.00
Miami, FL	Mi95	May/June 1995	Sub	0.35	0.29	0.00	0.07	0.27	0.02
San Gabriel, LA, CA	Sg94	July 1994	Sub	0.29	0.31	0.00	0.12	0.25	0.04
Vancouver, B.C.	Vs92	July/Sept 1992	Sub	0.31	0.23	0.02	0.09	0.35	0.00
Sacramento, CA	S91u	Aug 1991	Sub	0.36	0.12	0.01	0.13	0.34	0.05
Arcadia, LA, CA	A94	July 1994	Sub	0.24	0.19	0.02	0.30	0.23	0.02
Arcadia, LA, CA	A94	July/Aug 1993	Sub	0.22	0.18	0.02	0.32	0.24	0.02

urban areas, and (c) illustrate important *ET* differences with land use (notably between downtown, light industrial, and residential areas) and land cover (fraction of the surface vegetated).

MEASUREMENT OF URBAN EVAPOTRANSPIRATION

Spatial scales

The understanding and observation of any aspect of urban climate (here *ET*), is critically linked to notions of scale and boundary layer development. In the urban environment, elements (buildings, trees, roads, etc.) create their individual microclimates. Given that cities usually possess repetitive structures, such as building lots and streets, these elements recombine into larger micro-scale climate units such as street canyons, which generate their own climatic features. In turn, a larger neighbourhood comprising several similar street canyons plus their intervening buildings, gardens and courtyards, creates a local-scale climate. These when mixed together form the boundary layer of the whole city, a meso-scale phenomenon. In hydrological applications, urban watersheds, either natural or human made, are usually local- to meso-scale phenomena, with sub-watersheds representative of local-scale variability.

Measurement

Evapotranspiration is the flux that links the energy and water balances so it can be measured and analysed either in a micro-meteorological or hydrological framework. For urban areas the water balance can be written:

$$P + I + F = ET + R + S + A \quad [\mathrm{mm\,h^{-1}}] \tag{1}$$

where: P is precipitation, I is piped water supply, F is the water released due to anthropogenic activities, R is runoff, S the change in water storage in the period of interest, and A the net moisture advection. The urban energy balance is written as:

$$Q^* + Q_F = Q_E + Q_H + Q_S + Q_A \quad [\mathrm{W\ m^{-2}}] \tag{2}$$

where Q^* is net all-wave radiation, Q_F the anthropogenic heat flux, Q_E the latent heat flux, Q_H the sensible heat flux, Q_S the heat storage, and Q_A the net heat advection. $Q_E = L_v ET$, where L_v is the latent heat of vaporization.

At the micro-scale ET can be estimated using evaporation pans and lysimeters. However, it is doubtful if meaningful observations of evaporation can be made using this approach in cities. The variability of winds, the micro-scale advection of heat from built surfaces, and the problem of devising appropriate pan coefficients to cover the range of possible urban surroundings, make the collection of representative data extremely problematic. Micro-lysimeters have been used with some success in cities (e.g. Spronken-Smith *et al.*, 1998). However, issues of representativeness and appropriate spatial aggregation arise when these data need to be extended to larger areas.

The most direct way of measuring evapotranspiration at local- to meso-scales involves the eddy correlation approach. ET is measured as its energy equivalent (Q_E) using fast responses sensors which measure rapid fluctuations (5–10 Hz) in the vertical velocity (w') and moisture (q') properties of air parcels as they move towards or away from the surface (see fuller description in Oke, 1987). The covariance ($w'q'$) averaged over an appropriate period yields the latent heat flux. If the instrumentation are located at appropriate heights (> two times the height of the roughness elements) and downwind of fairly homogeneous land cover, data representative of ET for areas the size of city blocks to neighbourhoods (the local-scale) can be obtained.

At the meso- or regional-scale, theoretically it is possible to estimate ET by integrating between atmospheric profiles of the Convective Boundary Layer (CBL) (Cleugh & Grimmond, 1998). However, profiles of specific humidity are often very complex and assumptions about boundary layer conditions are very restrictive. To date such CBL methods have met with limited success in urban areas.

THIS STUDY

In the local-scale studies reported here, the eddy correlation approach was employed. Campbell Scientific (CSI) krypton hygrometers (KH20) and one-dimensional sonic anemometers (CA27) were mounted on tall towers (Fig. 1(a)), at sufficient height to be in the constant flux layer of the urban boundary layer (Grimmond & Oke, 1998a). Data were collected at 5–10 Hz and covariances determined for 15 minute periods. Data were corrected for oxygen absorption by the sensor and air density effects (Grimmond & Oke, 1998a). Results are hourly averages, corrected to Local Apparent Time (LAT) (to ensure consistency of solar noon).

The field sites are predominantly residential (with the notable exception of Mexico City and the light industrial site in Vancouver), with detached one to two-storied houses, and vegetation (trees, shrubs, grass) surrounding the building structures (Table 1). Using aerial photographs and databases for each site (Fig. 1(b)), directions with reasonably homogeneous fetch were identified and used to stratify the ET data.

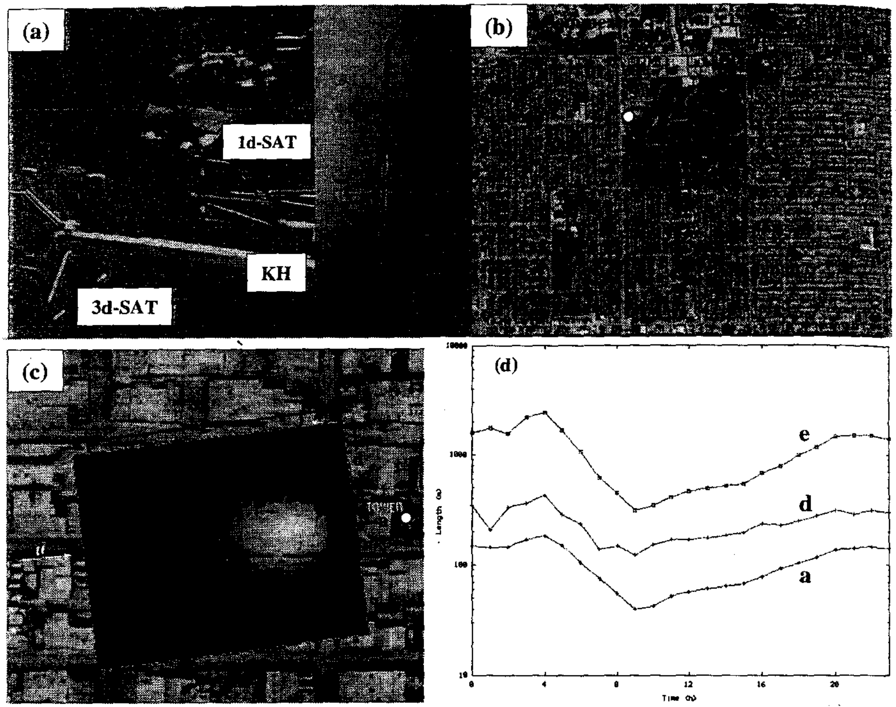

Fig. 1 The *ET* measurement scheme. (a) Eddy correlation equipment mounted on a tall (30 m) tower (A93) (data from 1-dimensional sonic anemometer thermometer (SAT) and krypton hygrometer (KH) used here); (b) aerial view of land use (~2 km × 2 km) surrounding typical measurement site (C95); (c) Flux Source Area Model (FSAM) overlain on surface database (Vl92)—the individual buildings here are warehouses (~30 × 30 m). The strength of the surface influence is shown by brightness (see Voogt & Grimmond (1998) for fuller explanation); (d) Dimensions of source area for the 90 percentile source area (S91): a = distance from the tower; d = cross-wind distance; e = along wind distance (m) (shown in panel c).

The areas influencing the turbulence measurements, the flux "source areas" or "footprints", were determined using the Schmid (1994) FSAM model for each hour of measurement. These source areas were overlain using Geographic Information Systems (GIS) (Fig. 1(c)) and average fractions of surface cover for each site determined (Table 1).

All the observations were taken in the spring or summer period with the exception of Mexico City which was in the dry season (December) (Table 1). With the notable exceptions of Vs92/Vl92 and C95 all measurement periods were fairly typical (precipitation and temperature only slightly greater or lower than normal) (Table 2). The study period in Chicago 1995 encompassed the record breaking heat and humidity wave which resulted in many hundreds of deaths. Vancouver in 1992 experienced very little rain, and for a portion of the summer an irrigation ban was in effect.

Table 2 Daily (24 h) mean fluxes and ratios for wind directions with relatively homogeneous fetch. Data ordered by absolute value of *ET*. *n* is total number of hours in analysis. *P* monthly precipitation (mm); if the study period spanned more than one month additional months in footnotes; P_N climate normal for that month (mm) (from EarthInc Data, 1995).

	Energy (MJ m^{-2} day^{-1}):				Water:			Irrigation practice
	n	Q^*	Q_E	Q_E/Q^*	E (mm day^{-1})	P (mm $month^{-1}$)	P_N (mm $month^{-1}$)	
C95	174	14.89	6.80	0.46	2.76	80.5*	92.0	Extensive irrigation
A93	588	13.74	4.93	0.36	2.00	0.0	0.0†	Extensive irrigation (see A94)
T90	131	12.50	4.90	0.39	1.99	16.3	5.4	Xeric landscaping: low water use vegetation. Greenspace irrigated automatically at night/early a.m.
A94	350	15.58	4.70	0.30	1.94	0.0	0.0	As A93. Irrigation ~1.37 mm day^{-1} (Grimmond *et al.*, 1996)
Mi95	209	13.74	4.58	0.33	1.87	79.8‡	180.9	Frequent rainfall, also irrigation
S91	223	9.72	4.38	0.45	1.77	0.0	1.8	Irrigation on alternate days
Vs92	572	8.88	2.68	0.30	1.10	23.2	41.1	Irrigation ban; External use ~0.25 mm day^{-1}
Sg94	468	12.45	3.46	0.28	1.40	0.0	0.25	As A93 but more hand watering; irrigation ~1.32 mm d^{-1} (Grimmond *et al.*, 1996)
Vl92	313	11.41	1.48	0.13	0.60	23.2	41.1	Irrigation ban as in Vs92.
Me93	81	3.38	0.31	0.09	0.14	0.0	0	Some street washing; very little external water use

* C95 June 35.6 mm fourth driest in 36 years, August 88.6 mm.

† A93 August 0 mm (August normal 3.8 mm).

‡ Mi95 June 516.4 mm fourth wettest in 48 years (June normal 271 mm).

External water use

Lerner (1990) documents that even in temperate, humid cities with frequent rainfall, piped-in water (*I*) approximates *P* as a source of water. In arid areas the relative importance of *I* can be much greater. Much of this piped-supply is used for internal industrial, commercial and domestic use. However, a significant fraction, particularly in the summertime, is used externally for garden irrigation, filling swimming pools, hosing patios/pavements, etc. In cities with little summer rainfall, irrigation is necessary to maintain urban vegetation in a lush, green state. In the southwest USA, for example, 2.5–5 mm of irrigation per day is required to sustain grass and deciduous shrubs, more is needed for ornamental flowers (Minor, 1990).

Data on external water use is difficult to obtain, particularly for specific areas rather than for a whole city. Minor (1990) estimated 40% of residential supply in Tucson is used outside, while Grimmond & Oke (1986) estimate 52% for Vancouver. Grimmond *et al.* (1986) through direct monitoring for a neighbourhood in Vancouver in the summer of 1982, estimated external water use to be 1.62 mm day^{-1} on average, with maximum daily values exceeding 5 mm day^{-1}. Grimmond *et al.* (1996) used residential water bills and a house-to-house survey for two neighbourhoods in Los Angeles (the A94 and Sg94 sites reported here), and estimated summertime external water use averaged 1.3–1.4 mm day^{-1}, again values ranged up to 5 mm day^{-1}.

Detailed data on external water use were not collected for all the sites studied here. From visual surveys and logs of water use practices, it is possible to conclude for all the residential sites, except Vs92, that irrigation of gardens and other greenspace (notably parks and golf courses), was common (see further descriptions in Table 2). Even in Chicago and Miami, where frequent summer rainfall occurred, irrigation was observed often. In Tucson, an additional source of water is evaporative coolers; typically 62 l day^{-1} (Minor, 1990), equivalent to 0.2 mm day^{-1} on an average areal basis.

RESULTS AND DISCUSSION

Magnitude of urban evapotranspiration rates

At the downtown and light industrial sites (Me93, Vl92) the daytime and daily latent heat fluxes constitute only a small energy sink and water loss (Fig. 2, Table 2). This is expected given their small areal coverage of open water and vegetation, and the lack of external water use. At the suburban sites Q_E ranges from 0.22–0.37 of Q^*. The hydrological importance of ET is evident from the $ET:P$ ratios, which range from 0.7 to 3.7 for the sites with precipitation. At A93, A94, S91 and Sg94 $ET:P$ tends to infinity because effectively there was no rain during the study periods. In absolute terms ET is highest in C95 (0.76 mm day^{-1} greater than any other site) (Table 2). These high rates were related to the record temperatures in Chicago and with no limitation on external water use extensive irrigation was observed. The smallest suburban rates were measured in Vs92 during a prolonged drought and a ban on external water use (0.67 mm day^{-1}) less than at any other residential site). These rates are lower than observed in previous years at this site (Grimmond, 1992). Daily ET at the other residential sites, in very different climate zones, cluster quite closely together (1.4–2 mm day^{-1}).

When compared with data from nearby rural sites (Oke *et al.*, 1998), ET rates can be greater (Tucson) or less (Vancouver) than in the city (Fig. 3). But the case of Sacramento shows that such statements depend as much on the choice of the rural reference site as on urban rates. Using an irrigated sod farm as the rural reference gives $ET_U < ET_R$, but using a naturally dry grassland reverses the sign.

Meteorological and surface controls

It is evident from Fig. 2 that ET rates vary significantly at a site from day-to-day. Some of this variability is due to meteorological controls, changes in cloud cover (net all-wave radiation), wind speed and vapour pressure deficit (Grimmond & Oke, 1998b), but there is much residual scatter in the relationships. In all cities, ET rates are well below equilibrium values (Fig. 2). The largest rates (at C95, S91 and C92), are 50% of equilibrium values ($Q_{E\ eq}$); in Vl92, Me93 and Vs92 $Q_E/Q_{E\ eq}$ drops to about 10%. Clearly in all these cities strong surface control is imposed by the dry impervious/built surface and the availability of water in the vegetated fraction, even when well irrigated.

Land-use or land-cover based parameterizations of ET are commonly used in

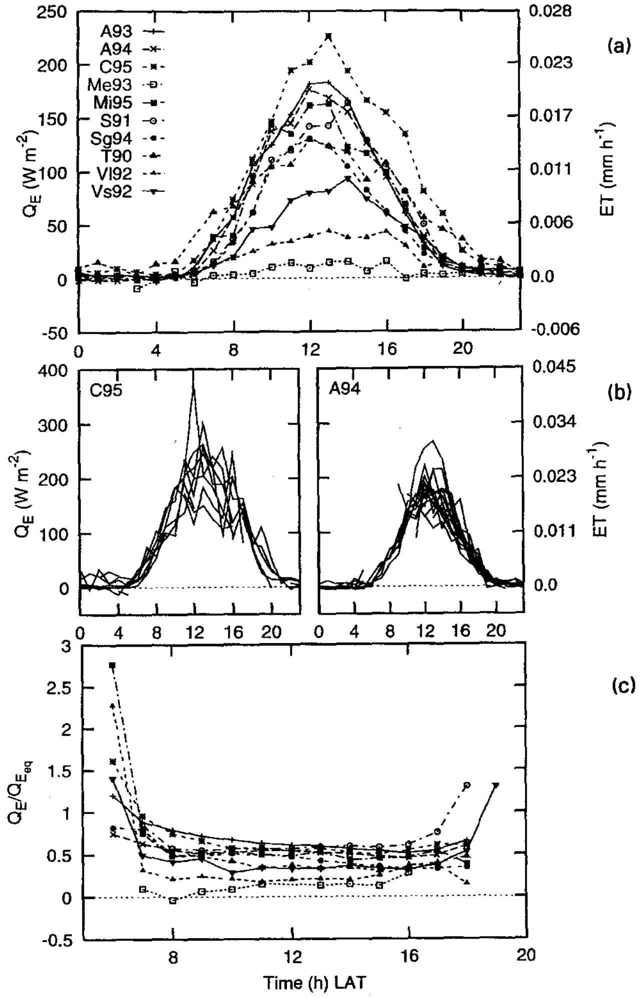

Fig. 2 (a) Mean diurnal patterns of observed *ET* both as an energy (W m^{-2}) and hydrological (mm day^{-1}) flux; (b) individual daily data for Chicago (C95) and Arcadia (A94) to illustrate variability from day-to-day; (c) average measured *ET* as a fraction of equilibrium *ET*.

cover, daily *ET* rates were plotted against the average vegetated fraction for each site (Fig. 4). A general trend is evident, but it is not well defined; part of the remaining scatter probably depends on the exact moisture status of the site. Clearly attempts to model urban *ET* rates need to capture water availability better and attention needs to be directed to quantifying this term.

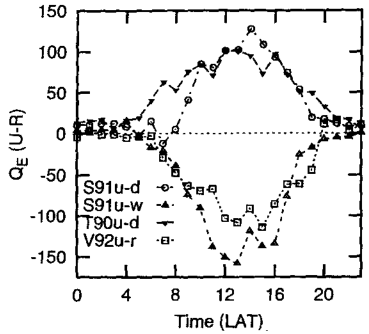

Fig. 3 Urban-rural evapotranspiration rates for Tucson, Vancouver and Sacramento (d - a dry grass site; w - an irrigated sod farm) (see Oke *et al.* (1998) for more details).

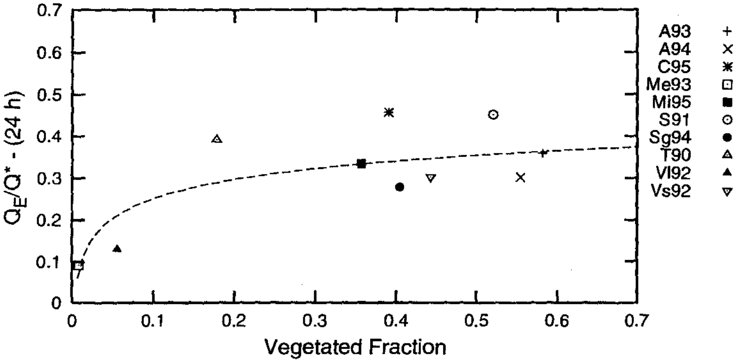

Fig. 4 Relationship between average *ET* at a site and fraction of the surface cover vegetated.

The relationship here is for average *ET* rates. As we have demonstrated, values are variable from day-to-day; and meteorological and surface conditions both impose important controls. Thus caution must be used when using general data such as this in any applications, and sensitivity analyses should be conducted to evaluate the significance of such simplifications.

CONCLUSIONS

The data presented in this paper show clearly that *ET* is an important flux in urban areas. In residential neighbourhoods it constitutes an energy sink of 22–37% of the daytime, and 28–46% of daily (24 h) net all-wave radiation. In downtown and light industrial sites it is much less important. In many instances *ET* exceeds precipitation and is sustained by external water use from the piped urban supply. In residential areas *ET* rates are remarkably conservative, maintained either by regular rainfall or

ET rates are remarkably conservative, maintained either by regular rainfall or irrigation. Even in Tucson with a landscape designed to conserve water, irrigated surfaces are extensive enough to sustain rates similar to those in Miami. An irrigation ban is capable of significantly curtailing *ET*, as evidenced in Vancouver in 1992. It appears that *ET* is water-limited in summer-time, and maximum values are only 50% of equilibrium rates during the middle of the day (under the conditions reported here). General relations between *ET* rates and the fraction of the surface vegetated are evident, but there is considerable scatter both between sites and at a given site from day-to-day.

These results suggest that *ET* should not be neglected in continuous water balance modelling, particularly simulations of low flow conditions and the associated water quality, or predictions of long-term water supply needs. Rather, *ET* should be modelled explicitly including the role of external water use.

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