Comparison of Heat Fluxes from Summertime Observations in the Suburbs of Four North American Cities

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ABSTRACT

Previous measurements of urban energy balances have been restricted to a small number of cities. This paper presents directly measured energy balance fluxes for suburban areas in four cities within the United States: Tucson, Sacramento, Chicago, and Los Angeles. They represent a range of synoptic regimes and surface morphologies (built and vegetative). Ensemble diurnal patterns and ratios of fluxes for clear, cloudy, and all sky conditions are presented. Consideration is given to both the mean and the variability of the fluxes. As expected, the magnitudes of the fluxes vary between cities; however, in general, the diurnal trends of flux partitioning are similar in terms of the timing of the peaks and changes in sign. Chicago is slightly different due to frequent wetting by rain. In the other cities, it seems that daytime Bowen ratios are inversely related to the area irrigated.

1. Introduction

Urban areas represent a location where a large and ever-increasing proportion of the world's population live, and where a disproportionate share of natural resources are used. Land surface and atmospheric alteration by urbanization leads to the development of distinct urban climates. Features such as the urban heat island, urban-induced wind circulation, precipitation enhancement downwind of urban areas, air pollution, etc., are all well documented (Landsberg 1981). Ultimately such urban climate effects are due to differences in the budgets of heat, mass, and momentum between the city and its preexisting landscape. Thus, it is necessary to add knowledge of the surface energy balance of urban areas to the already well-developed understanding of the boundary layer meteorology and climatology of rural areas. The surface energy balance of a city can be expressed as

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (\text{W m}^{-2}),$$

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 the history of its application to urban surfaces, is reviewed by Oke (1988).

Urban areas represent a wide range of land uses and surface properties. The broad category of "urban" land use incorporates a wider range of surface characteristics than others such as agricultural, forest, or wetland, etc. The most common subdivisions of urban areas are based on land use: commercial, industrial, suburban, downtown, etc. Each subdivision has distinct surface morphological characteristics that can be defined by the amounts and types of vegetation, the size of roughness elements, etc. (Auer 1981). These differences result in differences of flux partitioning across a city and the development of distinct micro- to local-scale climates (Oke 1984; Schmid and Oke 1992).

To date, most of our understanding of energy partitioning in urban areas comes from suburban areas for the following cities: Vancouver, British Columbia, Canada (Kalanda et al. 1980; Oke and McCaughey 1983; Cleugh and Oke 1986; Grimmond 1992; Roth and Oke 1994), Montreal, Quebec, Canada (Oke 1978), St. Louis, Missouri (Ching et al. 1983; Clarke et al. 1982), Indianapolis, Indiana (Hanna and Chang 1990), Sacramento, California (Grimmond et al. 1993), Chicago, Illinois (Grimmond et al. 1994), Uppsala, Sweden (Oke 1978), Bonn, Germany (Kerschgens and Hacker 1985; Kerschgens and Drauschke 1986), and Mexico City, Mexico (Oke et al. 1992); for commercial areas from studies in St. Louis (Clarke et al. 1982; Ching et al. 1983); and for downtown areas from observations in Adelaide, Aus-

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TABLE 1. Metropolitan areas studied, their populations, and land-use characteristics.
Source of population data: U.S. Census Bureau (1991).

	Tucson	Sacramento	Chicago	Los Angeles
Population 1990 ($\times 10^6$)	0.67	1.48	8.07	14.53
Population growth 1980–90 (%)	25.5	34.7	1.6	26.4
Metropolitan area (km^2)	23 794	13 193	14 553	87 971
Surface characteristics within 2-km radius of site—percent plan area (see Table 2 for center location)				
Buildings	20.7	39.2	33.3	25.4
Impervious (roads, parking lots, sidewalk)	37.0	18.6	22.5	33.8
Unmanaged (open lots, scrub, sand, etc.)	17.5	1.0	0.4	2.6
Trees and shrubs	12.0	17.2	9.4	18.5
Grass*	12.9	20.9	34.3	17.7
Open water	0.01	3.1	0.1	2.0
Built	57.6	57.8	55.8	59.2
Greenspace	42.4	42.2	44.2	40.8

* For Tucson, Sacramento, and Los Angeles, obviously unirrigated grass classified as unmanaged.

tralia (Coppin 1979), Uppsala (Taesler 1980), and Indianapolis (Hanna and Chang 1990).

However, of these only those studies in Sacramento, St. Louis, Chicago, and Vancouver (Roth and Oke 1994) have direct measurements of both turbulent fluxes (latent and sensible heat fluxes). The others either have measured only one convective flux or used a profile approach such as the Bowen ratio–energy balance. Roth and Oke (1995) conclude that the assumption of similarity in eddy diffusivities between heat and water vapor does not hold over suburban surfaces, and, hence, fluxes determined from Bowen ratio systems have a larger error than direct measurements using eddy correlation instrumentation. In addition, estimates of the urban storage heat flux, which are difficult to obtain (Grimmond et al. 1991), are needed for the Bowen ratio–energy balance approach. Roth and Oke (1994) suggest changes from Bowen ratio profile systems to eddy correlation instrumentation may explain the differences in the daytime pattern of the partitioning of the convective fluxes they observed in Vancouver in comparison to previous studies at the same site.

To fully understand the processes that occur in urban areas, and to develop and evaluate numerical models, it is important to have direct flux measurements from a greater range of cities. In this study we present results from field observations for four North American suburbs. All measurements had direct observations of both turbulent fluxes. The cities studied cover a wide range of synoptic-scale climates, surface morphologies, and latitudes. While the suburban area is not the location of the most extreme urban effects (e.g., urban heat islands), such areas represent the most extensive land use in most cities. The objective is to extend our empirical understanding of the energy balance to a broader range of suburban environments. The focus of this paper is the average behavior of the energy fluxes of each

city, their variability, and the overall similarities and differences between cities.

2. Methods

a. Study areas and measurement periods

Measurements were conducted in the suburbs of four large metropolitan areas of the United States (viz., Tucson, Arizona; Sacramento; Chicago; and Los Angeles, California). The three West Coast cities are growing rapidly (Table 1). From 1980 to 1990, Los Angeles was the fastest growing metropolitan area in the United States in absolute terms. The Los Angeles and Chicago metropolitan areas have the second and third largest populations in the United States, respectively (U.S. Census 1991). The locations of these cities cover a latitudinal range of 10°, extending from 32° to 42°N (Table 2). All measurements were conducted in the summertime (see Table 2 for dates of observations).

1) TUCSON

Tucson is located to the south of the Catalina Mountains on a valley floor with flat to gently rolling topography. The natural vegetation is predominantly creosote bushes, characteristic of a low-latitude desert climate. Measurements were conducted in June 1990 in a residential neighborhood, with predominantly single-story, residential properties (Fig. 1). The majority of residences have low-water-use vegetation, a xeric landscape.

Average temperatures in June 1990 were 28.3°C, 3°C warmer than normal. Although rainfall during June was three times the norm, it totaled only 16.3 mm. In May only 0.8 mm of rain fell. During the measurement period, the general synoptic conditions were

TABLE 2. Study period and instruments that differed between study sites.

City location	Observation period year/days	Net all-wave radiation (height, m)	EC* height (m)	Temperature and relative humidity	Wind speed	Wind direction
Tucson, AZ (32°07′N, 110°56′W)	June 1990 90/162–175	Swissteco S1 (9)	25.6	Rotronics MP 100	Met-One 012A	Met-One 024A
Sacramento, CA (38°39′N, 121°30′W)	August 1991 91/231–241	Swissteco S1 (9)	29	CSI 207	R. M. Young Wind Sentry	
Chicago, IL (41°57′N, 87°48′W)	July 1992 92/200–212	REBS Q6 (24.6)	18	Vaisala HMP C	R. M. Young Wind Sentry	
Los Angeles, CA (34°08′N, 118°03′W)	Jul–Aug 1993 93/185–223	REBS Q6 (30.5)	30.5	Vaisala HMP C	R. M. Young Wind Sentry	

* Height of eddy correlation equipment.

controlled by the presence of a thermal low over Arizona.

2) SACRAMENTO

Sacramento is located in the Sacramento–San Joaquin Valley, which is oriented generally north–south. The region has a mesothermal (warm, temperate) Mediterranean climate with hot, dry summers. Measurements were conducted in August 1991 in the residential neighborhood of Carmichael, 16.6 km northeast of the downtown area. The land use in this suburb is predominantly one-story, residential dwellings with well-irrigated (mesic) vegetation (Fig. 1).

Average air temperature in August 1991 was 22.9°C, slightly below normal (23.7°C). 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.

3) CHICAGO

Chicago is located along the southwest shore of Lake Michigan and occupies a plain that for the most part is only a few meters above lake level. As the lake is to the east of the city it does not modify the synoptic-scale flow, but its presence generates a lake breeze that reduces daytime temperatures. Summer thundershowers occur often in the city. Measurements were conducted in July 1992 in the suburb of Norridge—a densely packed, older residential area with predominantly two-story houses (Fig. 1). The neighborhood has a large number of mature deciduous trees and many greenspaces (parks and cemeteries, etc.).

The study period was characterized by the frequent passage of midlatitude cyclones. At Chicago's O'Hare International Airport, a total of 95.8 mm of rain fell on 23 days during July 1992 (normal 92.2 mm). The longest period without rainfall was 2 days. Consequently, throughout the study period the surface was almost continuously wet.

4) LOS ANGELES

The Los Angeles metropolitan area is situated with the Pacific Ocean to the west and south, and the San Gabriel, San Bernardino, and San Jacinto mountain ranges to the north and east. The Los Angeles Basin has a Mediterranean climate with hot, dry summers. Topography induces regional-scale weather patterns of light wind, sea breezes, and subsidence inversions. The dominant daily weather pattern is a sea breeze beginning after sunrise and a land breeze at night. Observations were conducted in Arcadia, located within the San Gabriel Valley, during July and August of 1993. The surrounding neighborhoods are predominately two-story, residential dwellings with lush vegetation (Fig. 1).

The observation period was characterized by predominantly anticyclonic conditions, with frequent marine onshore flow, which produced low-level morning clouds that dissipated by afternoon. There was no rainfall in July or August except for a trace on one day. The last measurable rainfall before the observation period occurred on 5 June and was less than 2 mm. For the San Gabriel Valley (Pasadena), ozone concentrations were generally "good" to "moderate" in the morning, and "moderate" in the afternoon. There were a few days at the end of July/beginning of August when afternoon levels of the pollution standard index exceeded 100 (i.e., unhealthful) (South Coast Air Quality Management District 1993).

b. Differences between cities

1) CLIMATE

The general climatic conditions observed in the measurement periods for each of the cities are summarized in Fig. 2. (See below for descriptions of meth-
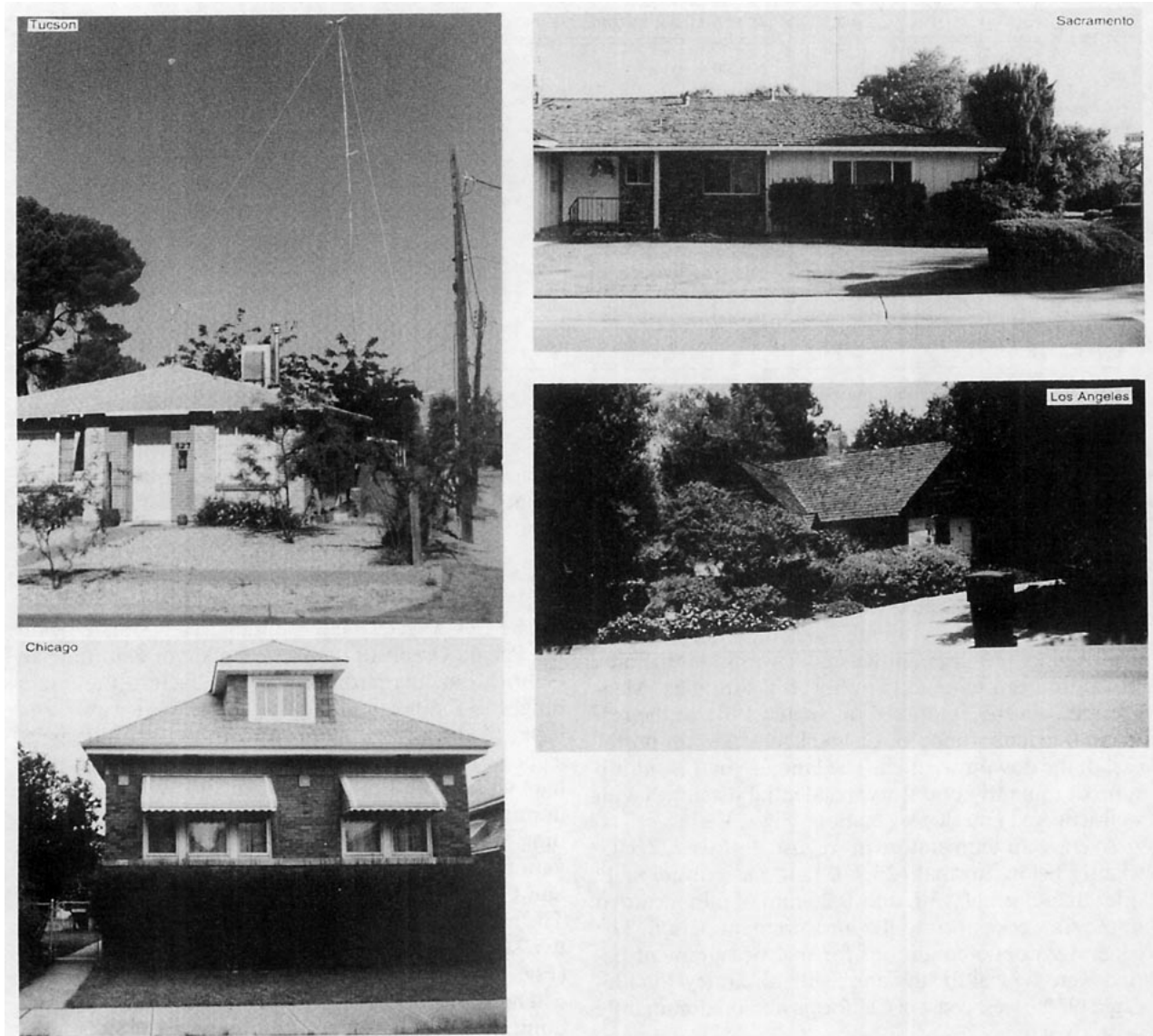
FIG. 1. Typical residential properties in the vicinity of each of the measurement sites: (a) Tucson (note pneumatic tower in background), (b) Sacramento, (c) Chicago, (d) Los Angeles.

ods and further discussion.) Differences between sites and characteristic diurnal patterns can be observed clearly. In general, Chicago was windy and moist, Tucson hot and dry with strong daily wind variations, and Sacramento and Los Angeles dry with a weak wind in the afternoon. Except in Chicago, the measurement periods were predominantly rain-free. For all cities, the meteorological conditions during the study periods were not atypical.

The frequency and interval between rainfall is an important control on the natural surface-water status. To assess the normality of the study periods in terms of timing and frequency of precipitation, summer daily rainfall data (Earthdata Inc. 1993) in each of the cities for the 30-year period ending 1990 were compared with

the respective study years. The period considered was June, July, and August for each of the cities with the exception of Tucson. Tucson experiences a significant change in synoptic conditions in July–August with the onset of the "summer monsoon" (Carleton 1987). Given the measurements in Tucson were conducted in June, precipitation data were analyzed for the May–June period.

In all cities, the summers studied had a slightly smaller than normal percentage of days when rain occurred. Chicago had the highest frequency of days with rain (normally 65.1%; 59.8% for 1992), followed by Tucson (normally 18.5%; 13.1% for 1990), Los Angeles (normally 14.2%; 4.3% for 1993), and then Sacramento (normally 8.2%; 7.6% for 1991). As expected, Chicago
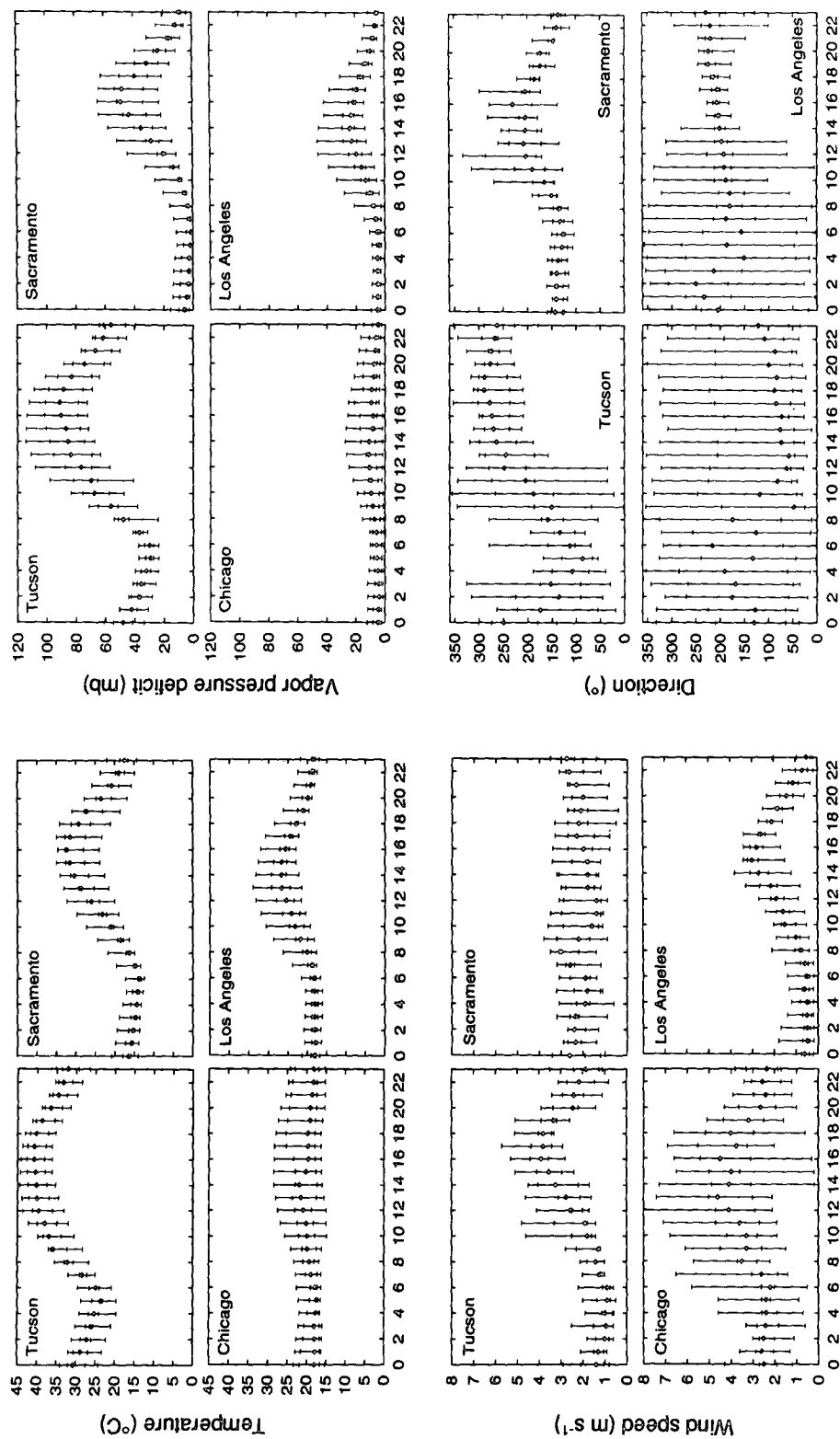
FIG. 2. Background conditions measured during the observation period: temperature, vapor pressure deficit, wind speed, and wind direction for Tucson, Sacramento, Chicago, and Los Angeles. Percentile values 0th (minimum), 25th, 50th (median), 75th, and 100th (maximum) are plotted to indicate the trend and extremes. The median is plotted as a diamond, the other percentiles as horizontal bars.

has the highest frequency of consecutive days of rainfall both normally (6.6%) and in the year of observations (5%). In Chicago in 1992 there were no periods greater than 6–10 days without rain, and when the measurements were taken no period greater than 2 days. In the other cities the periods between rainfall events were much greater.

2) SYNOPTIC CONDITIONS

Daily weather maps (NOAA 1990–93) were used to determine the regional-scale atmospheric conditions during the observation periods for each study area. Following the methodology of O'Neal (1994), an area 320 km west, north, and south, and 80 km east was delimited for each city. Each observation day was categorized as being influenced by *weak* or *strong* flow. Strong-flow days were defined as those when a front, or precipitation just ahead of a front, is in the area and/or if the 500-mb wind speed is greater than or equal to 25 m s^{-1} (50 kt) anywhere within the area. If neither of these conditions occurred (i.e., no fronts and all 500-mb winds are less than 25 m s^{-1}), the day was classified as weak flow. Strong-flow days a priori are expected to be more strongly affected by changing synoptic conditions and, therefore, the role of surface controls are expected to be less than on weak-flow days. As would be expected from the discussion about rainfall above, proportionally Chicago has the greatest number of strong-flow days (Table 3).

3) SURFACE COVER AND IRRIGATION PRACTICES

Information on surface cover and morphology was compiled for each city through a combination of aerial photograph analysis and field surveys (see description of methodology in Grimmond and Souch 1994). Average land cover (percent built, trees/shrubs, grass, etc.) for a 2-km radius surrounding each of the sites was determined using aerial photographs (Table 1). More-detailed field surveys revealed that the amount of biomass on the individual properties was greatest in the Los Angeles and Sacramento neighborhoods (compare representative properties in Fig. 1). In all cities there were some street trees; in Tucson they were least mature. The size of the houses was smallest in Tucson and increased in size from Sacramento to Chicago and Los Angeles. The Chicago suburb had the most dense housing but the greatest area of nonresidential greenspace (parks and cemeteries).

Given the infrequent rainfall in Tucson, Sacramento, and Los Angeles, the vegetation in the neighborhoods surrounding the measurement sites was maintained by irrigation. The Los Angeles and Sacramento landscapes are mesic, that is, lush green vegetation with a plentiful supply of water by irrigation. In Sacramento during the observation period, people living in the vicinity of the site were permitted to irrigate on alternate days of

TABLE 3. Regional atmospheric flow conditions for the observation days in each city. See methods section for definition of classes.

City and year	Weak-flow days	Strong-flow days
Tucson, 1990	162, 164, 166–175	163, 165
Sacramento, 1991	231–235, 239–241	236–238
Chicago, 1992	200, 203–204, 209	201–202, 205–208, 211–213
Los Angeles, 1993	185–196, 198–200, 204–209, 211–213, 215–220, 222–223	197, 201–203, 210, 214, 221

the week depending on their address (i.e., alternation of odd and even numbered). Watering was not permitted on Sundays. In Los Angeles, no regulations were imposed on irrigation and frequent watering occurred in the early morning and late afternoon. In Tucson, on the other hand, the vegetation is xeric, with a reasonable amount of biomass present that is adapted to an environment where water is a limiting factor. Much of the irrigation occurs at night as drip or subsurface irrigation for short periods and in a much more targeted manner than in the other cities. In Chicago, because of frequent rainfall, irrigation was not necessary and there was no visual evidence of its use.

c. Instrumentation

At each site measurements were made in the constant flux layer of the urban boundary layer (Oke et al. 1989). The objective is to represent the fluxes for an integrated surface type that is representative of "neighborhoods" within the suburban land use (Oke 1982).

The eddy correlation approach was used to measure directly the turbulent sensible and latent heat fluxes in all four cities. The fast response instruments, mounted less than 0.15 m apart on pneumatic towers, consisted of a Campbell Scientific Inc. (CSI) one-dimensional sonic anemometer and a fine-wire thermocouple system (CA27) to measure the vertical wind velocity and temperature, and a CSI krypton hygrometer (KH20) to measure the absolute humidity (Table 2). The vertical wind velocity, air temperature, and humidity fluctuations were sampled at 5 Hz and covariances determined over 15-min periods. Flux corrections were made for oxygen absorption by the sensor (Tanner and Greene 1989) and air density (Webb et al. 1980). No corrections were made for frequency response or spatial separation of the eddy correlation sensors. Neglect of these corrections probably underestimates Q_E by 1% at suburban sites (M. Roth 1992, personal communication).

Table 2 shows the instruments used to measure net all-wave radiation and the height at which the instruments were mounted. It is not practical to measure ΔQ_S directly at suburban sites due to the complexity

of the urban surface (Oke and Cleugh 1987; Grimmond et al. 1991). In this study it is assumed to be, and determined as, the residual in the energy balance $[Q^*$ $- (Q_H + Q_E)]$. This has the inherent problem that all measurement errors of the other energy balance fluxes are cumulated in this term.

Anthropogenic heat flux was not determined for any of these suburban areas. Grimmond (1992) calculated the size of Q_F for a Vancouver suburb based on combustion from stationary and mobile sources and metabolic rates. The magnitude of this flux depends on the spatial pattern of the sources (see Schmid et al. 1991; compare their Figs. 10 and 3). In residential areas the most notable sources are major roads and large nonresidential stationary sources (e.g., strip malls with energy-intensive users). In this study, given the location of the main potential sources relative to the measurement sites, the occurrence of summertime building cooling and the size of Q_F found elsewhere (Oke 1988), peak values are expected in the daytime and are probably of the order of 20 W m^{-2}, with nocturnal values of the order 10 W m^{-2}.

Horizontal advection ΔQ_A is difficult to determine. In all cases the observation sites were located in an extensive suburbanized area. However, in both Chicago and Los Angeles, there are regional-scale circulations generated by differential heating of land and adjacent water bodies. Steyn (1985) conducted an analysis for a suburb in Vancouver, where there is a sea-breeze circulation. He concluded that advection could be neglected. In this study the city where advection is most likely to be of concern is Chicago. The site is relatively close to a water body and is not protected by the topographic barriers present in Los Angeles. Because both ΔQ_A and Q_F have been ignored, ΔQ_S (the energy balance residual) must be interpreted accordingly.

As noted by Schmid et al. (1991), the source areas for turbulent flux measurements vary through time as a sensitive function of wind direction, atmospheric stability, and surface roughness. On the other hand, the source areas for the radiation measurements are stationary. Schmid et al. (1991) found the spatial variability of Q^* to be small (only one quarter that of Q_H). The variability of the turbulent source areas over a period of time cause spatial averaging to occur. However, there remains concern about the spatial consistency of the energy balances obtained. The effects of this are again cumulated in the residual term (ΔQ_S).

In each city ancillary climate information (wind speed and direction, temperature, pressure, relative humidity, and surface wetness) were collected at the same sites (Table 2). It should be noted that these measurements were conducted at different heights above the surface, and using slightly different instrumentation in each city (Table 2). Thus, for detailed intercity comparison, the wind speed, temperature, and humidity should be adjusted to account for height differences. In Chicago the temperature and relative hu-

midity sensors were mounted in an aspirated shield, whereas in all other cases only a radiation shield was used. In Sacramento, Chicago, and Los Angeles, REBS soil heat flux plates were installed 80 mm below the surface to measure the soil heat flux Q_G with CSI temperature sensors above them to account for flux divergence. Soil moisture measurements were made regularly to account for changes in heat capacity.

All times have been corrected to local mean solar time (local apparent time).

3. Results and discussion

A summary of the mean suburban summertime energy fluxes in the four North American cities is given in Table 4 for the respective measurement periods. The data are presented for hours when all flux measurements were available and are divided into daytime (defined here as the hours when net all-wave radiation was greater than zero, $Q^* > 0$), and daily (24 h) periods. The nocturnal Q^* data in Los Angeles contain some anomalies. Thus, the nighttime data for this city have been omitted and only daytime results are presented. For each city the number of daytime hours is indicated, so that mean hourly flux densities can be determined. The data are the mean for the period indicated (daytime or daily).

a. Radiation regimes

The latitudinal and seasonal controls on solar radiation vary between the four cities. Solar radiation is greatest in Tucson because it is at the lowest latitude and the measurements were conducted closest to the summer solstice (Table 2). The Sacramento measurements conducted in the latter part of August were farthest temporally from the summer solstice. Chicago is the most poleward location (Table 2).

Tucson and Sacramento were characterized by cloudless skies throughout; whereas both Chicago and Los Angeles experienced a variety of cloud conditions (see Q^* in Fig. 3). From the variability it can be seen that Chicago had days with cloud throughout, whereas in Los Angeles afternoons were generally less cloudy (consistent with the morning low-level marine cloud having "burned off"). In Los Angeles during the study period, the majority of hours would be classified as "cloudless" (this is evidenced by the high median values, Fig. 3).

Given these differences in amount and diurnal trend of cloud cover between the four cities, it is necessary to remove this effect to allow direct comparisons of energy fluxes. The data were stratified into clear and cloudy days for each city (Table 4). A day is defined as "cloudy" if cloud occurred anytime in the daytime. This category includes days when it was cloudy in the morning but clear in the afternoon or vice versa. Note this left only one clear day in Chicago and one cloudy day in Sacramento.

TABLE 4. Summary of mean summertime energy balance fluxes (MJ m^{-2} day^{-1}). For the daytime data, n refers to the average number of hours when $Q^* > 0$ and d is the number of days with data for clear or cloudy sky conditions in the study period (note some of these are partial days); NA means not available.

Location	n	d	Q^*	Q_H	Q_E	ΔQ_S	Q_G	χ	Υ	Λ	β
a) Clear sky conditions daytime ($Q^* > 0$)											
Tucson	12	12	16.27	7.54	4.11	4.62	NA	0.47	0.25	0.28	1.83
Sacramento	12	10	12.65	5.19	3.79	3.67	1.73	0.41	0.30	0.29	1.37
Chicago	13	1	17.20	5.58	7.11	4.51	2.65	0.32	0.41	0.26	0.78
Los Angeles	12	30	16.40	5.74	4.12	6.54	1.37	0.35	0.25	0.40	1.40
Daily (24 h)											
Tucson	Jun		12.16	6.76	4.90	0.50	NA	0.56	0.40	0.04	1.38
Sacramento	Aug		9.75	4.94	4.05	0.76	−0.10	0.51	0.42	0.08	1.22
b) Cloudy sky conditions daytime ($Q^* > 0$)											
Tucson*	11	2	16.06	6.86	4.46	4.74	NA	0.43	0.28	0.29	1.54
Sacramento	12	1	12.57	2.75	2.84	6.97	2.44	0.22	0.23	0.56	0.94
Chicago	12	12	12.16	3.94	4.48	3.74	2.08	0.32	0.37	0.31	0.88
Los Angeles	12	8	12.14	4.22	3.27	4.65	0.93	0.35	0.27	0.38	1.29
Daily (24 h)											
Sacramento	Aug		9.49	2.64	2.82	4.02	0.26	0.28	0.30	0.42	0.94
Chicago	Jul		9.96	3.46	5.00	1.50	0.66	0.35	0.50	0.15	0.69
c) All days daytime ($Q^* > 0$)											
Tucson	12		16.30	7.49	4.16	4.65	NA	0.46	0.26	0.28	1.80
Sacramento	12		12.64	4.92	3.68	4.04	1.82	0.39	0.29	0.32	1.34
Chicago	12		12.82	4.16	4.80	3.86	2.18	0.32	0.38	0.30	0.87
Los Angeles	12		15.53	5.43	3.94	6.16	1.29	0.35	0.25	0.40	1.38
Daily (24 h)											
Tucson	Jun		12.2	6.70	4.95	4.95	NA	0.57	0.40	0.05	1.35
Sacramento	Aug		9.72	4.68	3.91	1.12	−0.05	0.48	0.40	0.12	1.20
Chicago	Jul		10.6	3.71	5.25	1.68	0.63	0.35	0.49	0.16	0.71

* Tucson daytime cloudy conditions missing one hour at 700 when Q^* first becomes positive.

The one clear day in Chicago (which was not a complete 24-h period), provides the greatest total daytime net radiation of the cities (Table 4; Fig. 4). Probably this is due to a combination of three factors. First, the day length (defined as $Q^* > 0$) for this is the longest (13 h compared with 12 h for the other three cities; Table 4). Second, Chicago was the only city with rainfall during the study period, which cleansed its atmosphere. The other cities are more likely to have a greater amount of suspended dust and pollutants in the atmosphere reducing shortwave radiation. Most notably, the Los Angeles site, in the San Gabriel Valley, has a regional maximum of air pollutants (United Nations Environment Programme and World Health Organization 1992), which undoubtedly affected radiation transmission throughout the diurnal cycle. Third, the Chicago value represents a single day, not an average.

In Sacramento the peak daytime net radiation for clear days is low compared with the other cities (Fig. 4). Two net radiometers on separate towers were available at the suburban site and results from both are very similar. The suburban Q^* is less than that measured simultaneously at a nearby rural irrigated

sod farm (13.69 MJ m^{-2} day^{-1}), but similar to a nearby rural long, dry grass site (12.57 MJ m^{-2} day^{-1}) (Grimmond et al. 1993). At the Sacramento suburban site, the radiative source area included short yellow grass with visible soil patches and part of an asphalt yard. This likely resulted in a high albedo (which would increase the outgoing shortwave radiation) and higher surface temperatures and emissivity (which would decrease the net longwave radiation), both decreasing Q^*.

b. Energy partitioning under clear sky conditions

To allow direct comparisons of diurnal trends between cities, which are not biased by the absolute magnitudes of the fluxes or the effects of clouds, the respective hourly average fluxes for clear days in each city were normalized by the maximum hourly average flux (Fig. 5). In addition, Table 4 gives ratios of each of the fluxes normalized by the net all-wave radiation (viz., $\chi = Q_H/Q^*$, $\Upsilon = Q_E/Q^*$, $\Lambda = \Delta Q_S/Q^*$, and the Bowen ratio $\beta = Q_H/Q_E$). These ratios are used to look at the relative trends of fluxes through the day
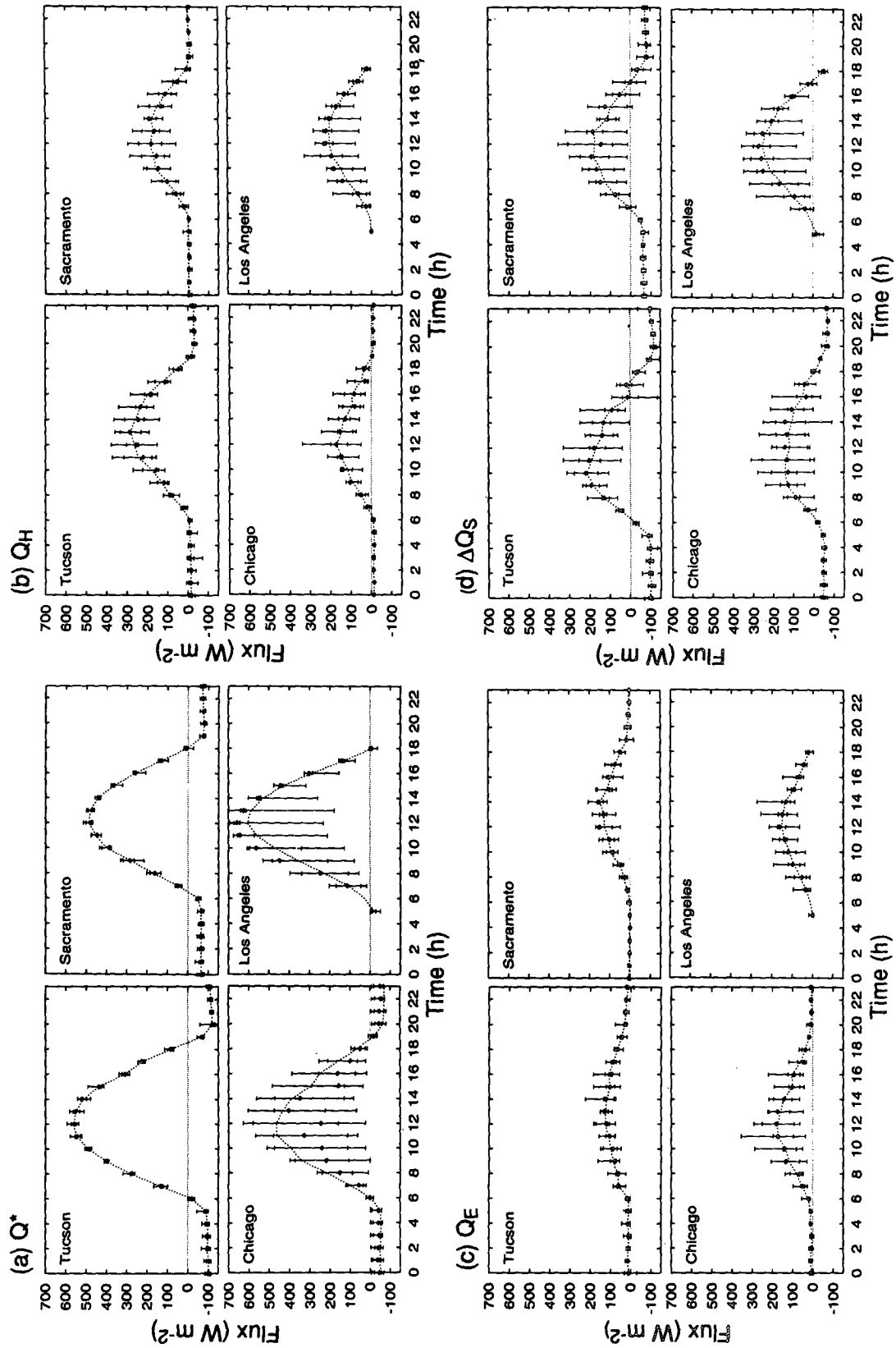
FIG. 3. Ensemble diurnal energy balance fluxes for: Tucson, Sacramento, Chicago, Los Angeles. Mean, 0th, 25th, 50th, (median), 75th, and 100th percentiles plotted. Mean values joined with a dashed line.
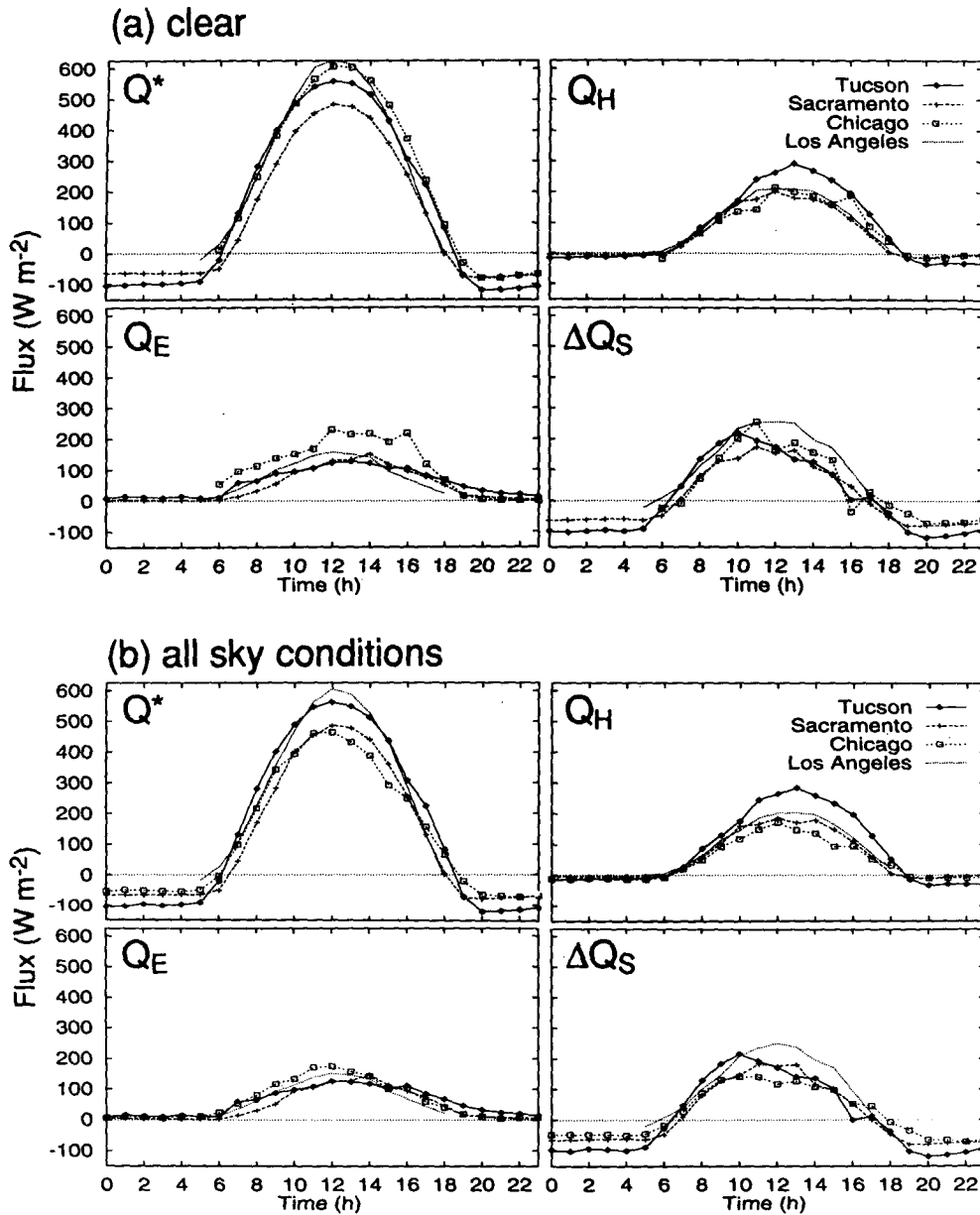
FIG. 4. Ensemble diurnal Q^*, Q_H, Q_E, and ΔQ_S fluxes for Tucson, Sacramento, Chicago, and
Los Angeles under (a) clear sky and (b) all sky conditions.

(Fig. 6) and are commonly used for parameterization (e.g., Grimmond et al. 1991; Hanna and Chang 1992; Grimmond and Cleugh 1994).

1) NET RADIATION

As already discussed, the diurnal course of normalized Q_* under clear sky conditions is very similar for all cities (Fig. 5).

2) SENSIBLE HEAT FLUX

The peak daily sensible heat flux occurs at the same time as the radiation (1200 h), except in Tucson where

it is one hour later (Fig. 5). As expected, the magnitude of the mean peak daytime Q_H value is highest in Tucson (292 W m^{-2}). Chicago (215 W m^{-2}) and Los Angeles (212 W m^{-2}) are similar, and Sacramento (202 W m^{-2}) is smallest (Fig. 4). Daytime totals show a similar trend, except Los Angeles is slightly greater than Chicago (Table 4). However, when normalized by the available radiant energy χ, the order becomes Tucson, then Sacramento, Los Angeles, and Chicago (Table 4).

All of the cities show a hysteresis pattern between Q_H and Q^*, with enhanced Q_H in the afternoon relative
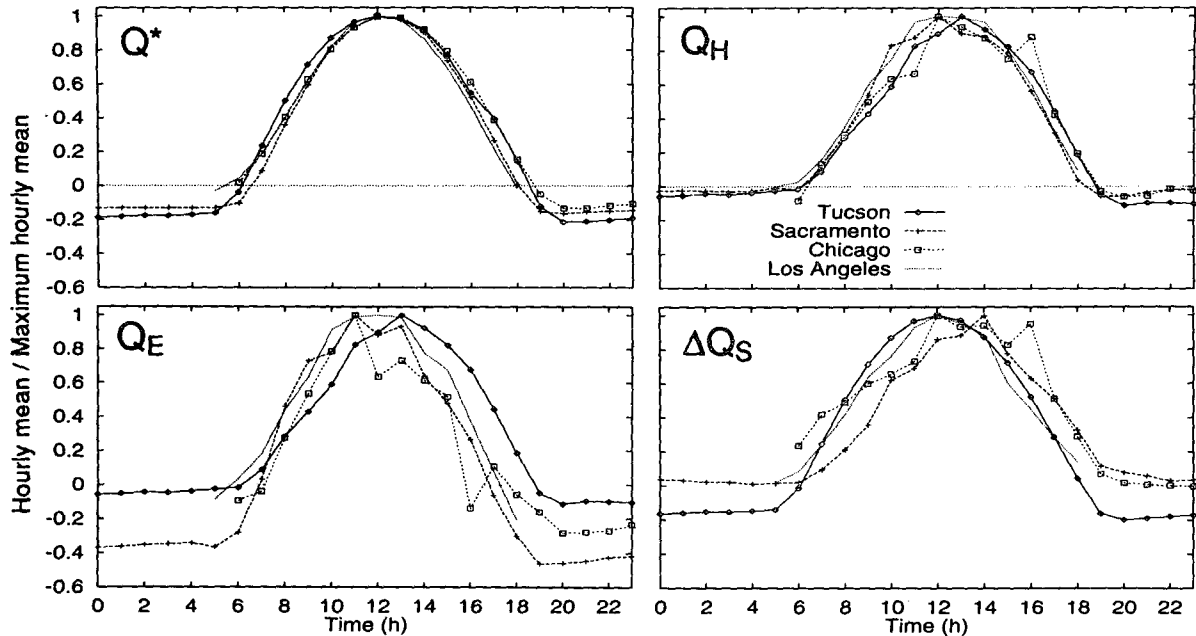
FIG. 5. Ensemble diurnal clear-sky energy balance fluxes (Q^*, Q_H, Q_E, and ΔQ_S) normalized by the maximum hourly flux for each flux in each city.

to the morning. This pattern is most pronounced in Tucson. This is seen most clearly in the upward daytime trend of the χ ratio (Fig. 6). The daily χ ratios are greater than the daytime proportions but their relative ordering remains the same.

3) LATENT HEAT FLUX

The absolute magnitude of the daytime Q_E is remarkably similar between cities except for Chicago, which is 50–80 W m^{-2} greater (Fig. 4). The maximum mean value occurred in Chicago near solar noon, with sustained high values through to 1600 h. The mean diurnal peak also occurred at 1200 LAT in Los Angeles, at 1300 LAT in Tucson, and at 1400 LAT in Sacramento (Fig. 5). The magnitude of Q_E for Sacramento and Los Angeles is very similar, but in Sacramento the entire trend is displaced by approximately 2 h into the early afternoon, with low values in the morning. In Tucson, Q_E is relatively more constant during the day, and the diurnal pattern more symmetric around its peak. On the one clear day, Chicago has a secondary peak of Q_E at 1600 LAT as it does for Q_H (see above).

The daytime total latent heat flux is 73% greater in Chicago than Los Angeles, the next largest value (Table 4). The mean daytime totals in Tucson are almost identical to Los Angeles, and Sacramento is only 8% less. Tucson and Los Angeles also have the same daytime Υ ratios (0.25), which are the smallest. Chicago's is the greatest (0.41) and Sacramento, with its lower Q^*, the second largest (0.30). As with the χ ratio, all

cities have a greater daily than daytime Υ ratio (Table 4).

In each city, Υ shows a brief peak after sunrise when dew and surface water (interception from overnight irrigation or rainfall) is evaporated. After the drop-off from this early peak, there is a gradual increase through the morning and early afternoon (less than 10%). During the daytime hours, boundary layer growth increases the mixed-layer depth. Associated with this, entrainment of drier air from aloft helps enhance Q_E. For all cities at the end of the daytime period, there is another peak (Fig. 6), probably due to sprinkling. In the evening the mean results have a small negative value due to continuing sprinkling and weak evaporation. This is despite the presence of dew on some surfaces (both observed and measured by surface/leaf wetness sensors). Observations indicated that dewfall is spatially very variable and is controlled by individual surface properties. For example, in Los Angeles dew was recorded on grass surfaces, but very rarely on bare soil or larger vegetation such as trees and shrubs or on impervious surfaces such as asphalt and concrete.

The high rates of evaporation in Chicago can be explained by the high frequency of rainfall making water freely available at the surface for evaporation. There was no evidence of a long-term drying trend over any period during the observations in Chicago. In the other cities the spatial distribution of irrigated vegetation is more significant. Sacramento has the greatest fraction of irrigated grass and open water (swimming pools, etc.) within 2 km of the measurement site (Table 1)
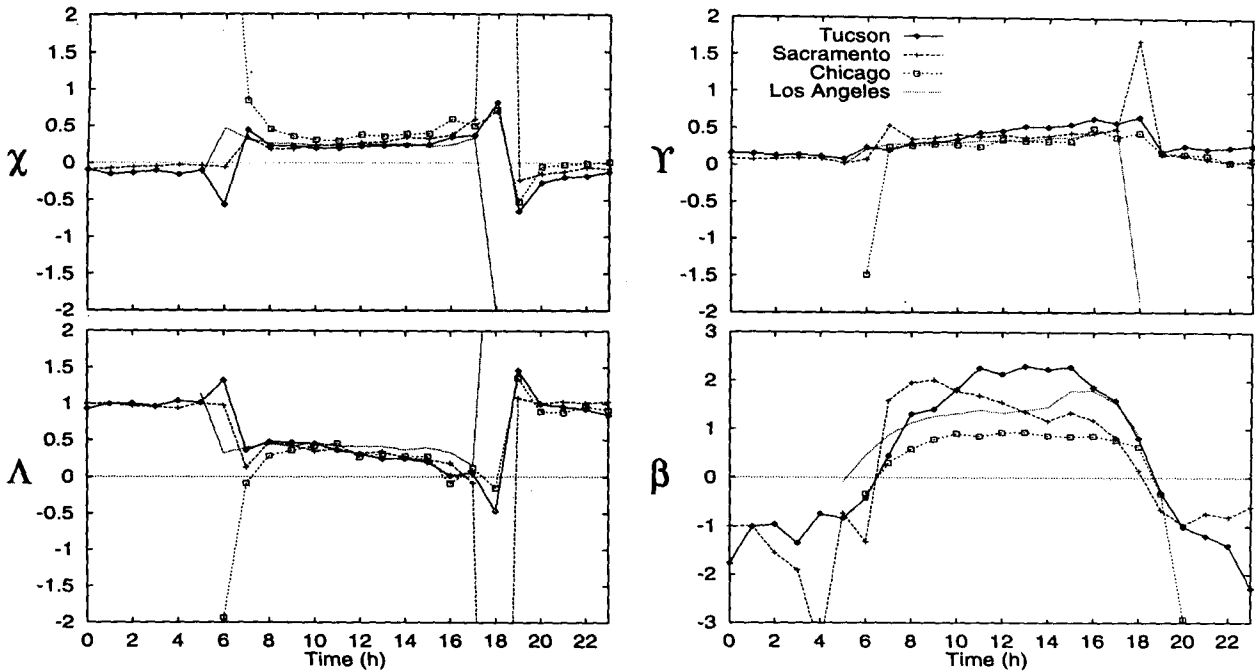
FIG. 6. Diurnal patterns of χ, Υ, Λ, and β for Tucson, Sacramento, Chicago, and Los Angeles under clear sky conditions.

and also the highest Υ. In Los Angeles the irrigated greenspace fraction is much larger than in Tucson, but Υ in the two cities remains the same.

4) BOWEN RATIO

It is useful at this point to consider the relative partitioning of the turbulent fluxes. The mean, clear sky, daytime Bowen ratios, determined from the mean daytime fluxes, range from 0.78 in Chicago to 1.37 in Sacramento, 1.40 in Los Angeles, and 1.83 in Tucson (Table 4). The influence of water availability clearly is critical here, either as a result of human activities through irrigation or due to rainfall, as in Chicago.

The area of greenspace surrounding the observation sites is similar between cities (Table 1). However, the area irrigated is less than the area of greenspace, and at a minimum excludes the "unmanaged" areas (Table 1). Thus, Tucson, which has the highest Bowen ratio, has the smallest area irrigated (Table 1), followed by Los Angeles and Sacramento. Thus, the three cities with infrequent rainfall show a pattern of β that corresponds inversely to the proportion of irrigated greenspace. In Chicago the area of freely available water is often larger than the pervious fraction because of depression and interception storage by impervious surfaces during the frequent rainfall.

The variability of β through the day, determined from the mean hourly values of Q_H and Q_E, is indicated in Fig. 6. It should be noted that β is often unstable when it is the ratio of two small numbers, as is likely at night and during day-night transition periods.

Compared with the other ratios there is a greater difference in the diurnal pattern between the cities. The trend of the daytime β for Los Angeles and Sacramento show a "mirror" reflection of each other. In Sacramento initially there is a higher daytime value that decreases through the day, whereas for Los Angeles the opposite is the case. In Sacramento the high morning β is due to reduced Q_E rather than enhanced Q_H (Fig. 4). The pattern in Los Angeles is similar in form to that observed in Vancouver (Roth and Oke 1994). The temporal pattern in Tucson is more symmetric, with a slight increase in the afternoon. Chicago's daytime pattern does not show the same degree of variability as the other cities.

The daily β's are smaller than the daytime values, but the same relative relationships between the cities hold.

5) STORAGE HEAT FLUX

The mean peak of the residual flux, termed here ΔQ_S, occurs at 1000 LAT in Tucson, at 1100 LAT in Chicago and Sacramento, and at 1100–1300 LAT in Los Angeles (Fig. 4a). The magnitude is the same in Los Angeles and Chicago (257 W m^{-2}). Sacramento's peak is the smallest at 175 W m^{-2}. The daytime ratios of Λ all show a consistent downward trend through the day (Fig. 6), that is, the reverse of χ ratios, indicating a hysteresis pattern (Grimmond et al. 1991) in all cases. Nocturnal Λ values are close to 1. The variability is much greater for ΔQ_S than for the other output fluxes (Fig. 3). It is not possible to determine how much of

this is due to physical variability in the actual flux and how much is a combination of errors and advective influences in the residual.

Daily ΔQ_S values should be expected to approach zero. However, in each city here they are a positive number, indicating net heat gain by the surface volume. This is not unreasonable given these are summertime observations. One of the fluxes that contributes to ΔQ_S is the soil heat flux Q_G, which, unlike ΔQ_S, can be measured directly using soil heat flux plates. The results therefore provide a check on the behavior of ΔQ_S.

The Q_G fluxes observed in this study are representative of the irrigated grass fraction. During the daytime, Q_G accounts for 47% of ΔQ_S in Sacramento, 59% in Chicago, and 21% in Los Angeles. In Los Angeles the low proportion may be in large part due to the soil heat flux plates being in shadows for a significant part of the day, thus reducing measured Q_G. Figure 7 shows the relation between independent estimates of ΔQ_S (residual from observed radiative and convective components) and Q_G (heat flux plates) is good in terms of relatively consistent fractions and phasing. This is in agreement with Kerschgens and Hacker (1985) and lends credibility to the ΔQ_S estimates here (i.e., omission of Q_F and ΔQ_A and the sums of other errors do not mask the storage change signal).

For Tucson and Sacramento the daily clear-sky ΔQ_S and Λ ratios of 0.04 and 0.08, respectively, are close to those expected for the time of year. The Los Angeles daytime flux is the largest of the cities, with a Λ ratio of 0.40. The plan area and height characteristics of the surrounding neighborhoods (Table 1) may be significant here. Los Angeles has the largest plan area of trees, and thus the greatest biomass in the surface volume for storing and releasing heat. The plan area of the buildings is lower in Los Angeles than Sacramento and Chicago, but the mean height of the roughness elements are greater in Los Angeles (8.4 m compared with 6.4 and 7.5 m in the other two cities, respectively). The weaker hysteresis pattern in Los Angeles is indicative of an area where trees and building canyons are significant contributors to the pattern (see Grimmond et al. 1991).

c. Cloudy conditions

Under cloudy conditions, as expected, the fluxes are more variable and all fluxes are reduced in magnitude (Table 4). The magnitude of the daytime Q^* reduction was 5.04 MJ m^{-2} day^{-1} (or 30%) in Chicago, 4.26 MJ m^{-2} day^{-1} (or 26%) in Los Angeles, and about 1% in Tucson and Sacramento. Except for Chicago, the number of days of data available for the analysis of cloudy conditions is less than for clear skies. The actual diurnal patterns observed obviously are a function of the type and timing of the cloud that occurred in each case.

In all cities the Q_H fluxes were lower than the clear-sky values. The reductions are the smallest in Tucson
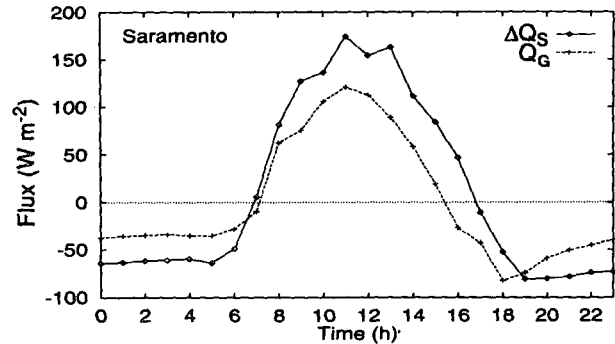

FIG. 7. Comparison of ensemble diurnal pattern of Q_G and ΔQ_S for Sacramento.

(10%) and greatest in Sacramento (47%). The daytime χ ratios were little affected, being less on cloudy days for Tucson and Los Angeles (<1%), and unchanged for Chicago. Sacramento shows the greatest change in daytime χ with a 0.19 reduction (Table 4); however, this is for one day only. The latent heat flux Q_E is reduced in three out of the four cities; from 21% in Los Angeles to 32% in Chicago. The exception is Tucson where there was a 9% increase. The response of the daytime Υ ratio to increased cloud cover is small; two cities show small increases (Tucson and Los Angeles) and the others a small decrease.

In Tucson and Sacramento ΔQ_S increases by 3% and 90%, respectively. In Sacramento Q_G increased by 41% (there are no equivalent data for Tucson). In the other two cities there were decreases in both ΔQ_S and Q_G; that is, the trend in the residual term (ΔQ_S) is the same as the independent data from the heat flux plates. Under cloudy conditions, the daytime Λ increased in all cities except Los Angeles. By far the largest increase occurred in Sacramento.

Daytime β decreased in all of the cities except for Chicago, where under cloudy skies the reduction in Q_E was greater than that in Q_H. In Chicago Q_E is more likely to be energy rather than water limited, thus a decrease in Q^* due to cloud results in a reduction in Q_E.

The diurnal trend of the fluxes changes under cloudy conditions, but this may be due to intradiurnal variability of cloud so generality is difficult to assign. In Tucson the peak in ΔQ_S is moved into the afternoon and coincides with a drop in Q_H. In Sacramento ΔQ_S is large in the morning, and the near equality of Q_H and Q_E for most of the daytime is very different from the clear-sky case. In Chicago the diurnal pattern is remarkably similar between the two sky conditions. In Los Angeles, under cloudy conditions, there is less difference between the three output fluxes in the morning hours.

d. All sky conditions

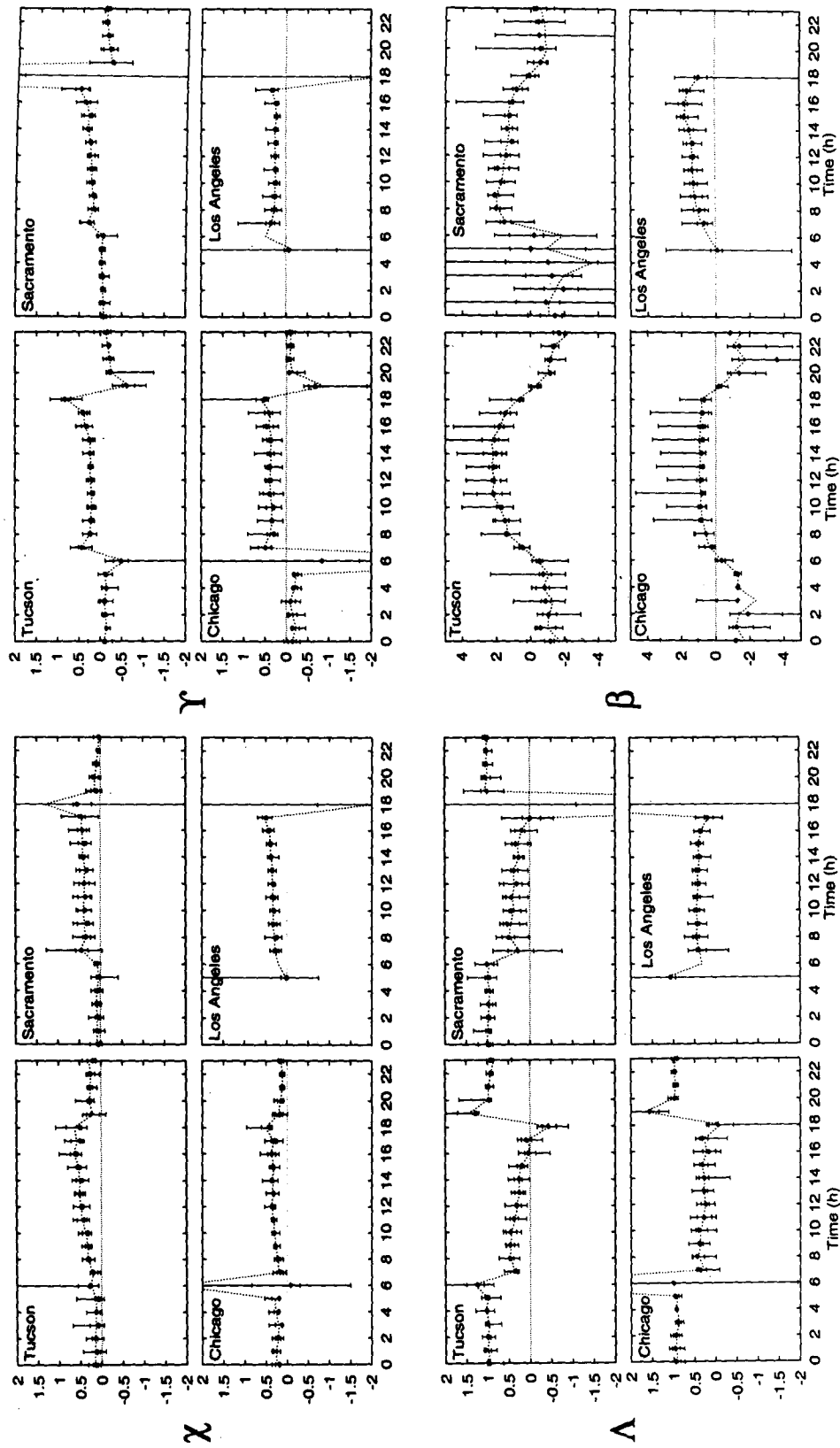Given the meteorological conditions for each of the study periods were typical, averaging all available data

FIG. 8. Range of χ, ϒ, Λ, and β ratios observed for Tucson, Sacramento, Chicago, and Los Angeles. Mean 0th, 25th, 50th (median), 75th, and 100th percentiles plotted. Mean values joined with a dashed line.
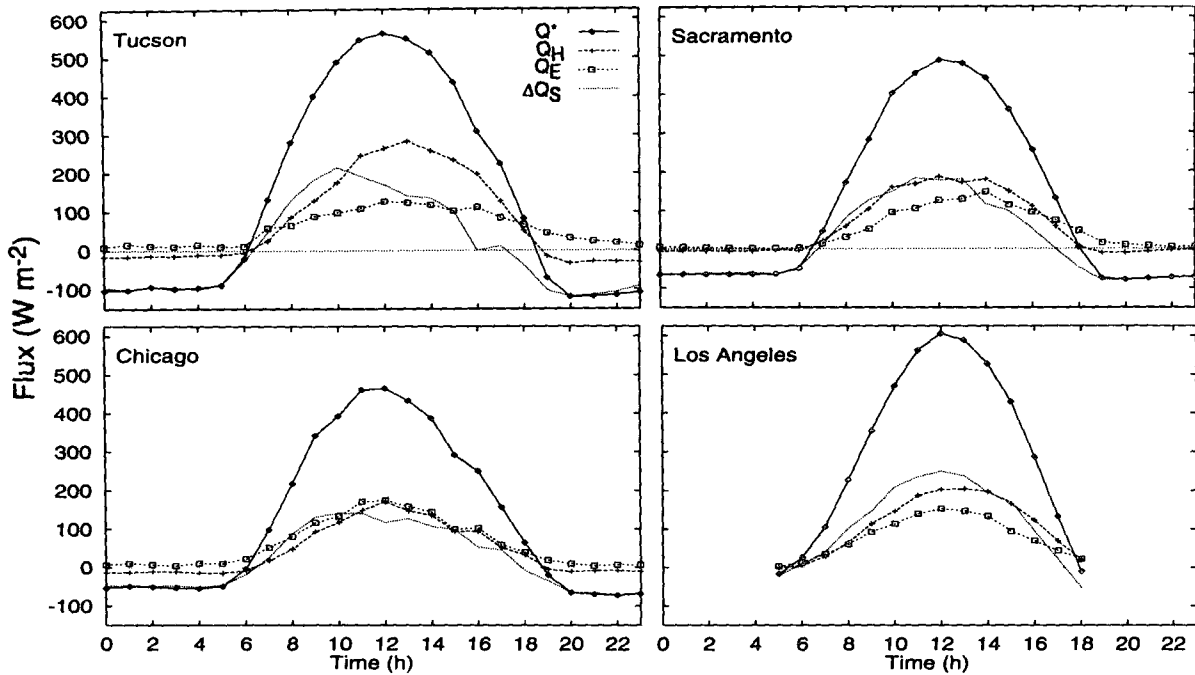
FIG. 9. Ensemble energy balance for Tucson, Sacramento, Chicago, and Los Angeles under all sky conditions.

for the respective study periods provides "representative values" for the cities in summertime. Comparison of Figs. 3 and 8 gives the observed variability of the fluxes and the ratios for the complete observation periods in each city.

The mean diurnal patterns of the partitioning of the energy fluxes for each city are presented in Fig. 9. In Tucson the pattern of energy partitioning is the most different between the individual fluxes through the day. The net storage heat flux ΔQ_S peaks first in the morning (1000 LAT), then Q_E (1200 LAT), and Q_H (1300 LAT). The latent heat flux Q_E remains smaller than ΔQ_S until 1400 LAT and smaller than Q_H until 1800 LAT, but then unlike the other fluxes continues positive until midnight. This is consistent with irrigation in the evening and night, and sustained high vapor-pressure deficits even at night (Fig. 2). In Sacramento Q_H and ΔQ_S have a similar daytime size until 1000 LAT. After this, Q_H remains larger, and ΔQ_S soon begins its downward trend. By 1400 LAT Q_E becomes larger than ΔQ_S, and at 1700 LAT larger than Q_H. In Chicago the latent heat flux Q_E is the largest flux except for a couple of midmorning hours when ΔQ_S is the maximum. The sensible heat flux Q_H follows Q_E closely through the day. In Los Angeles ΔQ_S is the predominant daytime flux until approximately 1400 LAT when it decreases to the same size as Q_H for a couple of hours and then becomes smaller.

In all cities ΔQ_S is the first output flux to peak and then to change sign (direction) in the afternoon. Latent heat flux Q_E, in all cases, remains positive after Q^* goes negative in the early evening. Sensible heat flux Q_H goes

negative at the same time as Q^*. A similar trend for ΔQ_S and Q_E was seen by Roth and Oke (1994) in Vancouver. However, the behavior they observed for Q_H in the late afternoon was different from that observed here. In their study Q_H remained positive for a few hours after Q^* turns negative. The relative sizes of the fluxes are interesting in that in a relatively dry summer (1989) Vancouver's pattern (from Roth and Oke's 1994 results) is more like Tucson's than either of the Californian suburbs.

For daytime conditions, the mean (plus/minus one standard deviation) ratios for the four suburban areas for all cloud cover conditions are β = 1.35 ± 0.38 (range 0.93), X = 0.38 ± 0.06 (range 0.14), Υ = 0.30 ± 0.06 (range 0.13), and Λ = 0.33 ± 0.05 (range 0.12). If we remove Chicago, the average ratios become β = 1.51 ± 0.25 (range 0.46), X = 0.40 ± 0.06 (range 0.11), Υ = 0.27 ± 0.02 (range 0.04), and Λ = 0.33 ± 0.06 (range 0.12). These are similar to the mean suburban ratios of 1.0 for β, 0.39 for X, 0.39 for Υ, and 0.22 for Λ proposed by Oke (1982, 1988).

Of the four ratios, β shows the greatest daytime variability followed by Λ. Los Angeles and Chicago show very little variability in X, whereas Tucson and Sacramento show little variability in Υ. However, even in the cities where these ratios (X and Υ) are more variable, they are less so than Λ. Overall, these ratios are quite conservative in the summertime in terms of their diurnal trend.

4. Conclusions

These four cities obviously do not represent the full range of surface morphologies found in suburban areas

or their regional-scale climatic settings. However, from these results we make the following generalizations about flux partitioning in suburban areas:

- The diurnal trend of the partitioning of the fluxes shows many similarities between these very different cities. These include such attributes as the timing of the peaks and changes in sign (direction) of the individual fluxes. Greater differences in behavior between the cities are observed nocturnally. As expected under cloudy conditions, the fluxes are more variable.

- The results from this study support many of the general review statements of Oke (1982, 1988). The results from this study suggest that where precipitation is limited and irrigation is practiced, a typical value for β is 1.5, whereas when there is frequent summertime precipitation, a value between 0.8 and 1.0 is appropriate. Typical values for χ, Υ, and Λ are 0.4, 0.3, and 0.3, respectively.

- An inverse relationship between mean daytime Bowen ratio and the area under irrigation may exist. If so, the measure "area irrigated" may be a useful indicator of typical summertime suburban β and its spatial variability across an urban area. Although Chicago follows the trend it is important to recognize that its "irrigated" area is maintained by frequent rainfall.

- This study demonstrates considerable variability of fluxes in each of the cities on a day-to-day basis. In future research and in model simulations, it is important to investigate not only the mean conditions but also the variability.

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