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Temporal variations in heat fluxes over a central European city centre

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With 6 Figures

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Summary

Energy fluxes have been measured over an area near the centre of the city of Łódź, Poland, since November 2000. The site was selected because the building style (surface cover and morphology) is typical of European cities, yet distinct from the majority of cities where energy balance observations have been studied thus far. The multi-year dataset permits consideration of temporal changes in energy balance partitioning over a wide range of seasonal and synoptic conditions and of the role of heat storage and anthropogenic fluxes in the energy balance. Partitioning of net radiation into the turbulent fluxes is consistent in the two years, with the largest differences occurring due to differing precipitation. The monthly ensemble diurnal cycles of the turbulent fluxes over the two years are similar. The largest differences occur during the July–September period, and are attributable to greater net radiation and lower rainfall in 2002. The latent heat flux accounts for approximately 40% of the turbulent heat transfer on an annual basis. The average daily daytime Bowen ratio and its variability are slightly reduced during the summer (growing) season. Anthropogenic heat is a significant input to the urban energy balance in the winter. The fluxes observed in this study are consistent with results from other urban sites.

1. Introduction

Global increases in the populations and extent of urban areas and their influences on the planetary boundary layer are well established justifications for urban meteorological and climatological research (e.g. Oke, 1987; Martilli et al., 2002; Arnfield, 2003). Ultimately, urban climate effects are due to changes in the surface-atmosphere exchanges of heat, momentum, water and other gases (e.g. carbon dioxide, nitrous oxides). Documenting these fluxes in a representative range of cities, weather controls and surface conditions is needed to advance empirical understanding of urban climates and to evaluate the output of numerical models. The energy balance at the interface between the urban surface layer and the overlying atmosphere can be written:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A + S \ [\mathrm{W\,m^{-2}}] \tag{1}$$

with the terms defined as: Q^*, net all-wave radiation; Q_F, anthropogenic heat flux; Q_H, turbulent sensible heat flux; Q_E, turbulent latent heat flux; ΔQ_S, the net change in heat storage within the volume; ΔQ_A, the net advected flux; and S, all other sources and sinks (e.g. heat removed by rainfall runoff, photosynthetic heat). Note that the volume is defined (Oke, 1988) such that the heat flux into the ground is incorporated in ΔQ_S.

Flux measurements to date have been limited by the temporal coverage of the data, the range of surface conditions at the measurement sites, and the confidence that can be placed on the measurements and in the estimation or neglect of unknown terms in the surface energy balance (SEB). Earlier studies of the energy, mass and momentum exchanges were conducted over a relatively limited range of urban sites, generally for short duration (see Grimmond and Oke, 1999a, b; Roth, 2000). Only recently have longer-term campaigns using eddy covariance (EC) techniques been initiated (Nemitz et al., 2002; Rotach, 2002; Moriwaki and Kanda, 2004). Such data are necessary if we are to investigate the nature of temporal variability in fluxes including the seasonal influence of anthropogenic forcing. Further, detailed information about the characteristics of the urban surface (its morphology and materials) were lacking in earlier studies. These are needed to allow independent evaluation of parameters used in urban climate models (Grimmond and Oke, 1999b, 2002; Roth, 2000).

Since November 2000 we have conducted SEB measurements near the centre of Łódź, Poland. These observations provide a unique dataset given the climate, urban structure, and wintertime anthropogenic heating of Łódź, and the duration of the measurements. The heat flux and climate observations are complemented by a database of urban surface properties from which model parameters can be derived. The objectives of this paper are to present an overview of the site and the measurements to date, and to explore in detail the temporal variability of the observed energy balance fluxes and their relation to the nature of the surface and the anthropogenic forcing.

2. Methods

2.1 Study area

Łódź (19° 27′ E 51° 46′ N), the second largest city (population ~800,000) in Poland, is located in a relatively flat area (180 to 235 m ASL from SW to NE). The area of the city is approximately 80 km^2 (Kłysik, 1996). Apart from a few high-rise structures, building heights within central Łódź range from 15–20 m, with little variation. Many are adjoined buildings 3–5 stories in height, which create sometimes contiguous block-long urban canyons (Fig. 1a). Street trees are deciduous, 8–15 m tall but generally below building height. Łódź also has many small parks interspersed with buildings and a number of larger parks away from the city center. The long-term observation site is located toward the western edge of the relatively homogeneous urban core (Fig. 2). This area would be classified as A2–A4 using the Urban Terrain Zone scheme of Ellefsen (1990) and as dense urban development (DUD) or block-edged buildings (BEB) using the classes of Theurer (1999). The majority of the roofs are slightly pitched. Within 500 m of the tower, buildings and pavement dominate the surface cover (Figs. 1b, 2). To the north and east of the site lies the urban core. In the southwest to northwest sectors there are post-industrial sites with large buildings (former factories, some of

a

b

Fig. 1. Typical street canyons in Łódź: (**a**) in the city center [April 2000], and (**b**) near the tower site [August 2002]

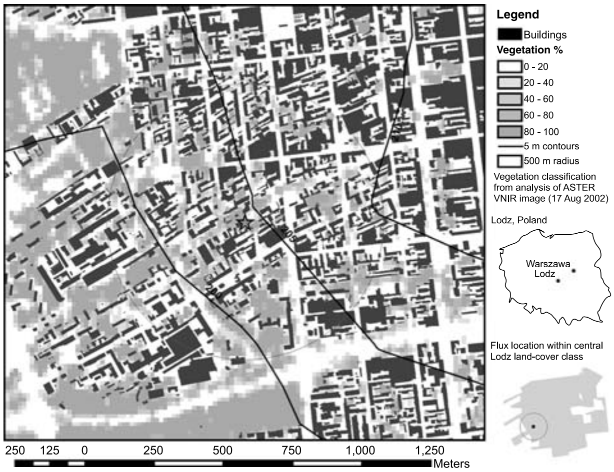

Fig. 2. Surface cover in the vicinity of tower. Insets, lower right: location of Łódź in Poland, and Lipowa flux site within the central core (shaded) district of Łódź. Vegetation % is the fraction of vegetation in each 15 m pixel (calculated from an ASTER VNIR image, 17 Aug 2002). North is at the top of all maps

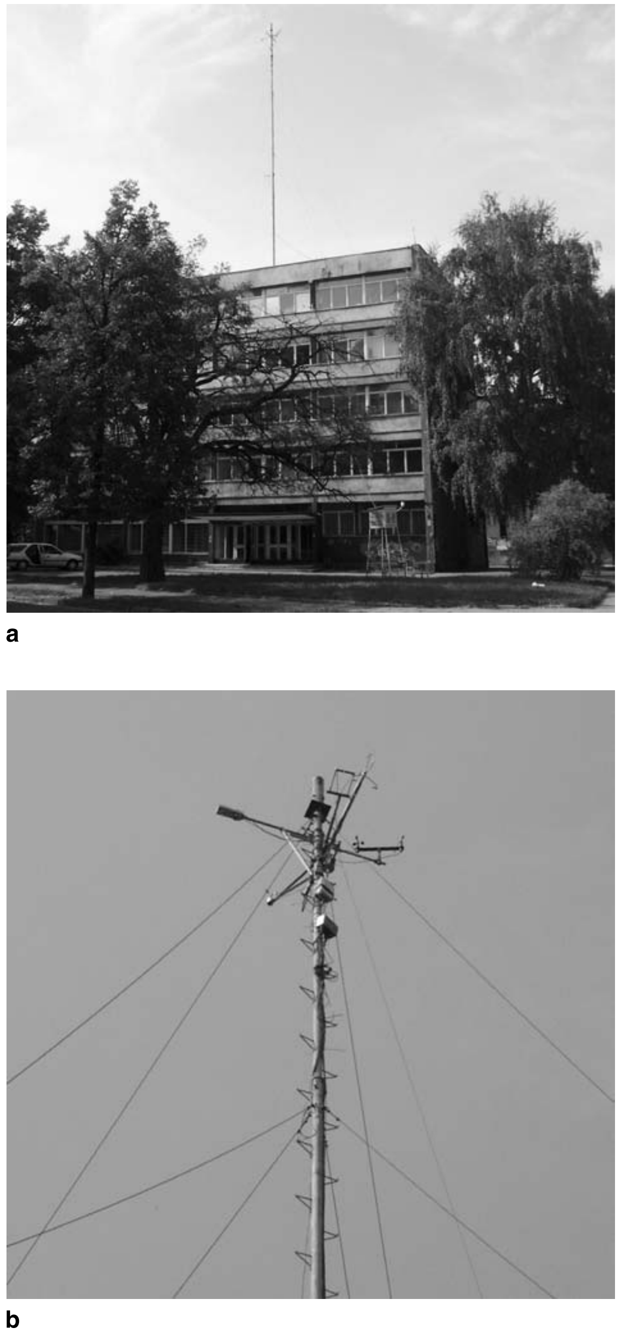

Fig. 3. Lipowa (LTM) tower site (**a**) and instrumentation at top of mast (**b**)

which have been converted to office space). To the south and west, beyond 700 m from the site, there is considerably more vegetation, with a large park to the south. These features are important to the siting and exposure of the instrumentation and to understand relations between surface structure and materials and energy exchanges with the atmosphere.

According to criteria established for EC measurements (e.g. Grimmond and Oke, 2002) taken at the height used here, it is necessary to have fetch over a uniform surface for approximately 1–2 km upwind. This is in order to minimize advective influences due to horizontal gradients in scalars (temperature and humidity), as well to allow the climatic effects of a particular surface area to become fully established. The site used here may fail this criterion when flow is from the west, particularly in wintertime when horizontal temperature gradients are strongest. To facilitate the analysis of fetch effects, a geographic information system (GIS) was developed using earlier work by Kłysik (2002), ground truth obtained during August–September 2002, and analysis of satellite and aerial imagery.

2.2 Instrumentation and operations

The instrumentation is mounted 37 m above ground level on a tubular tower (top diameter 0.08 m). The tower itself is 20 m tall and it is mounted on the roof of a 17 m building (Fig. 3); hereafter this site is referred to as Lipowa (LTM). A complete list of the instruments and sampling frequency is given in Table 1. The sonic anemometer measures 3-d wind velocities (u, v, w) and virtual temperature (T). A fast-response ($\sim$1 Hz) thermocouple is installed within the sampling volume of the sonic to provide an additional

Table 1. Instrumentation installed at Lipowa. d_{sm} is the distance from sensor to mast. AGL: above ground level; F: sample frequency is 10 Hz; S15: sample frequency 0.2 Hz and 15 min averaging period; S5: sample frequency 0.2 Hz and 5 min averaging period

Instrument/Model	Manufacturer		Sampling frequency
Tower (all at 37 m AGL)		d_{sm} (m)	
3-d sonic anemometer/ thermometer (K-type)	Applied Technologies, Boulder, CO	0.89	F
T-type thermocouple (0.13 mm diam.)	Omega Engineering, Stamford, CT	0.91	F
krypton hygrometer KH_2O	Campbell Scientific (CSI), Logan, UT	0.99	F
CNR1 net radiometer	Kipp & Zonen, Netherlands	0.84	S15
Cup anemometer and wind vane	RM Young, MI	0.61	S15
MP100H temperature & RH probe	Rotronic, Switzerland	0.37	S15
Roof level (20 m)		Ht (m) AGL	
PTA 427 air pressure sensor	Vaisala, Finland	16	S15
Surface wetness CS237	CSI	18	S15
Precipitation TE525	Texas Electronics, Dallas, TX	18	S15
Ground level			
Soil heat flux HFT3	Radiation Energy Balance Systems, WA	−0.05	S15
Soil temperature TCAV	CSI	−0.03	S15
Volumetric soil moisture CS615	CSI	0−−0.1	S15
Profiles			
T-type thermocouple profile (0.13 mm diam.)	Omega	29, 24, 20, 17, 13, 9, 6, 4, roof	S5
Infrared thermometer 4000A	Everest Interscience, Tucson, AZ	14 (N, E, S, W wall), Road	S5

way to calculate heat fluxes. The krypton hygrometer measures water vapor fluctuations ($\rho_v{}'$). These fast-response instruments are mounted on booms extending approximately 1 m from the tower, and are oriented eastward in the direction of the longest fetch and the most densely built-up area. In addition, all the incoming and outgoing shortwave and longwave radiation fluxes, air temperature, relative humidity, atmospheric pressure, precipitation, soil heat flux, soil temperature, and moisture are measured. The sonic anemometer is logged serially to a PC housed on the top floor of the building. All other instruments are monitored with dataloggers (Campbell Scientific Inc., Models 23X, 21X). In July 2002 an 8-level profile of air temperature was installed together with infrared sensors to sample the surface temperatures of the four building walls and a road intersection.

The krypton hygrometer windows were cleaned regularly (approximately bi-weekly) except at times when ice accumulation made tower access dangerous. Because "scaling" of the windows can occur rapidly, voltage levels were converted to absolute humidity using the "scaled" calibration coefficients at all times. The 10 Hz data are subjected to spike detection and rejection algorithms as described in Schmid et al. (2000). The lag between the sonic measurements and the hygrometer is determined at the point of maximum correlation between absolute humidity and vertical velocity over the flux averaging interval. Following Kaimal and Finnigan (1994) and Finnigan (2004), the data are rotated to streamwise coordinates for flux computation. At hourly intervals, Q_H, Q_E and turbulence statistics are computed, and block-averages are used to compute the instantaneous fluctuations. Corrections are applied to Q_H to account for the use of sonic temperature (Schotanus et al., 1983) and to Q_E for oxygen absorption over the krypton's bandwidth (van Dijk et al., 2003) and density effects (Webb et al., 1980). All data (raw and calculated statistics) are subjected to strict data limits to reject implausible values. Although annual precipitation is around 600 mm, days with measurable precipitation occur frequently (179 days in 2001, and 153 in 2002). Data were rejected if they are contaminated by moisture on the sensors from precipitation or dewfall, as determined by the wetness sensor. In this analysis, the data from wind directions within the range of 210–270° may have possible flow distortion due to flow interference from the mast and net radiometer. Q_E observations did not start until mid-March 2001. During the winter, ice accumulation on the sensors sometimes precluded measurement. Additionally, sonic transducer failure caused a disruption in flux measurements in May–June, of both 2001 and 2002. The data used for this analysis cover the period of January 1, 2001–December 31, 2002. The sign convention follows Eq. (1) so that LHS values are positive when directed into the volume (energy sources) and RHS values are positive when directed out of the volume (sinks).

2.3 Site characteristics

The characteristics of the surface are an important control on energy partitioning and they vary widely within and among cities. Grimmond and Oke (2002) find the Bowen ratio ($\beta = Q_H/Q_E$) exhibits a clear relation with the vegetative fraction, and the irrigated fraction, in different cities. The fractions of surface cover (vegetated, impervious, buildings) also have been used to estimate heat storage (Grimmond and Oke, 1999a), which in turn may limit the energy available to drive the turbulent fluxes. Urban construction materials and the geometric structure determine the effective surface albedo and emissivity, and thus Q^*. Further, turbulent exchanges are affected by the roughness lengths for momentum, heat and water vapor. Hence when the airflow approaching a measurement site changes its turbulent footprint due to alterations of wind direction and stability, it is changing the mix of controlling properties and that can lead to complications in the interpretation of the data.

Table 2 presents the surface characteristics of the Łódź Lipowa (LTM) measurement site determined from analysis of a GIS. Turbulent flux footprints for unstable, neutral ($\zeta = 0$), and stable ($\zeta = 0.05$) conditions were estimated using Schmid's (1994) FSAM model. The stability parameter ζ is given by $\zeta = (z_m - z_d)/L$ where L is the Obukhov length scale, z_m the flux measurement height and z_d the zero-plane displacement. For each stability condition, the parameter influencing transverse dispersion in FSAM, σ_v/u^*, was set to 1.5, 2.5, and 5. This provided a total of 9 source area weighting matrices where each represents 90% of the turbulent flux source area for those particular conditions. Each of these matrices was then rotated at 15° intervals around the LTM tower coordinates and multiplied by the fraction of building or vegetation within the 5×5 km GIS domain. In the case of stable conditions, the 90% source area extends outside this 5×5 km grid, and was truncated and reweighted. This produced a lookup table with a total of 9×24 (216) values with land cover fractions. The lookup table is then queried to set the approximate fractions for each flux measurement. The fractions used are vegetation, buildings and other, which are mainly impervious roads. Notably this approach does not

Table 2. Surface cover (%) statistics for turbulent flux measurements based FSAM (Schmid, 1994) output and the surface database which was used to create a lookup table based on stability (3 classes), transverse dispersion (3 classes) and wind direction (24 classes). Note that the neutral stability class is defined by $|\zeta| < 0.05$

	Stability	Hours	Buildings		Vegetation		Other impervious	
			Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
2001	Unstable	1972	31.7	8.1	28.0	10.2	40.3	3.6
	Neutral	1102	25.5	10.5	36.1	14.0	38.4	5.4
	Stable	848	23.5	9.5	39.3	12.5	37.1	4.2
	All	3922	28.2	9.8	32.7	12.9	39.1	4.5
2002	Unstable	2680	33.2	8.4	25.8	10.3	40.9	3.5
	Neutral	1710	29.1	11.6	31.5	15.0	39.4	5.4
	Stable	1357	27.1	10.3	34.6	13.5	38.2	4.6
	All	5747	30.6	10.2	29.6	13.2	39.8	4.6
	Overall	9669	29.6		30.9		39.5	

consider variability of either z_0 or z_d with wind direction.

When the sensible heat flux is large (unstable), source areas are typically smaller and closer to the tower. Within this range (typically within ~500 m of the tower), surface characteristics are less variable (Table 2). Under neutral and stable conditions, when source areas can extend to as far as several kilometers upstream, source area surface characteristics are more variable by direction (Table 2). However, since in these conditions fluxes contribute zero or only small negative fluxes to the average, the data should be representative of the mean characteristics around the tower. An exception is when flow is from 150–330°, where there is greater vegetation cover and less dense urban fetch. The source area for the outgoing radiative fluxes is typically much smaller than that of the turbulent fluxes and is centered around the tower. Given the height of the radiometer its 90% source area should incorporate ~14 building-space units (Offerle et al., 2003). Although the source areas for the radiometer and the turbulent fluxes are not physically congruent, they have similar surface characteristics in the mean.

Roughness lengths for momentum ($z_{0,m}$) for urban areas range from 1 m in low-density residential areas to 10 m for high-rise urban centers (Grimmond and Oke, 1999b). Based on the morphometric data incorporated in the GIS, $z_{0,m}$ at the Łódź site using the method of Raupach (1994) is estimated to be 1.7 m and z_d to be 7.4 m (Table 3). The latter estimate agrees well with the rule-of-thumb of Grimmond and Oke (1999b) that $z_d = 0.7\, z_H$. Given the availability of momentum and heat flux measurements, $z_{0,m}$ was also calculated directly from the observed friction velocity, u^*, and the horizontal wind speed, U from the stability-corrected log wind profile, given by

$$U = \frac{u^*}{k}\left[\ln\frac{z_m - z_d}{z_{0,m}} + \psi(\zeta) - \psi\left(\frac{z_{0,m}}{L}\right)\right]$$

where von Karman's constant $k = 0.4$, ψ is the integral form of the stability correction (Panofsky and Dutton, 1984) for the stability range $-1 < \zeta < 1$ only. This anemometric value of $z_{0,m}$ (1.6 m) is close to the morphometric estimate. The Lipowa (LTM) site parameters conform to those suggested by Rotach et al. (2002), and are listed in Table 3.

Table 3. Characterisitics of the Lipowa site

Parameter	
Measurement height, z_m	37.1 m
Mean building height, z_H	10.6 m
Zero-plane displacement, z_d (Raupach)	7.4 m
Roughness length, $z_{0,m}$ (Raupach)	1.7 m
Roughness length, $z_{0,m}$ (anemometric)	1.6 m
Surface fractions (buildings, other impervious, vegetation)	0.3, 0.4, 0.3
Canyon aspect ratio, H/W	0.75

3. Results and discussion

3.1 Temporal patterns in energy exchange

The observed temporal patterns in the energy balance fluxes must result from the combined effect of external forcing dynamics and changes in surface characteristics. For urban areas with little vegetation, seasonal changes in surface characteristics are smaller than over most natural ecosystems. Even large snow events only cover horizontal surfaces, leaving vertical surfaces largely unchanged. Further, since much of the precipitation is captured and removed from the system via sewers, the urban surface has little storage capacity for moisture and the response to rainfall events is more rapid than over similar terrain but is undeveloped and is primarily vegetated. Therefore we expect that temporal variations in net radiation are going to be the main forcing control on the turbulent heat fluxes; more so than over vegetation dominated surfaces. However, there will be complications due to the addition of Q_F in an environment. In Łódź contributions to Q_F from transport and industry are relatively uniform through the year but in winter the use of space heating makes it the dominant term in the balance. Hence, in Łódź the annual cycle of Q_F, is approximately in anti-phase to that of Q^*.

Results from this study show that the annual pattern for all directly measured components of the energy balance is similar for the two years in terms of magnitudes and variation of the fluxes (Fig. 4). The mean net radiation in 2001 was 50 W m^{-2} and 52 W m^{-2} in 2002, and the mean air temperature (T_a) was only 1.1 °C warmer in

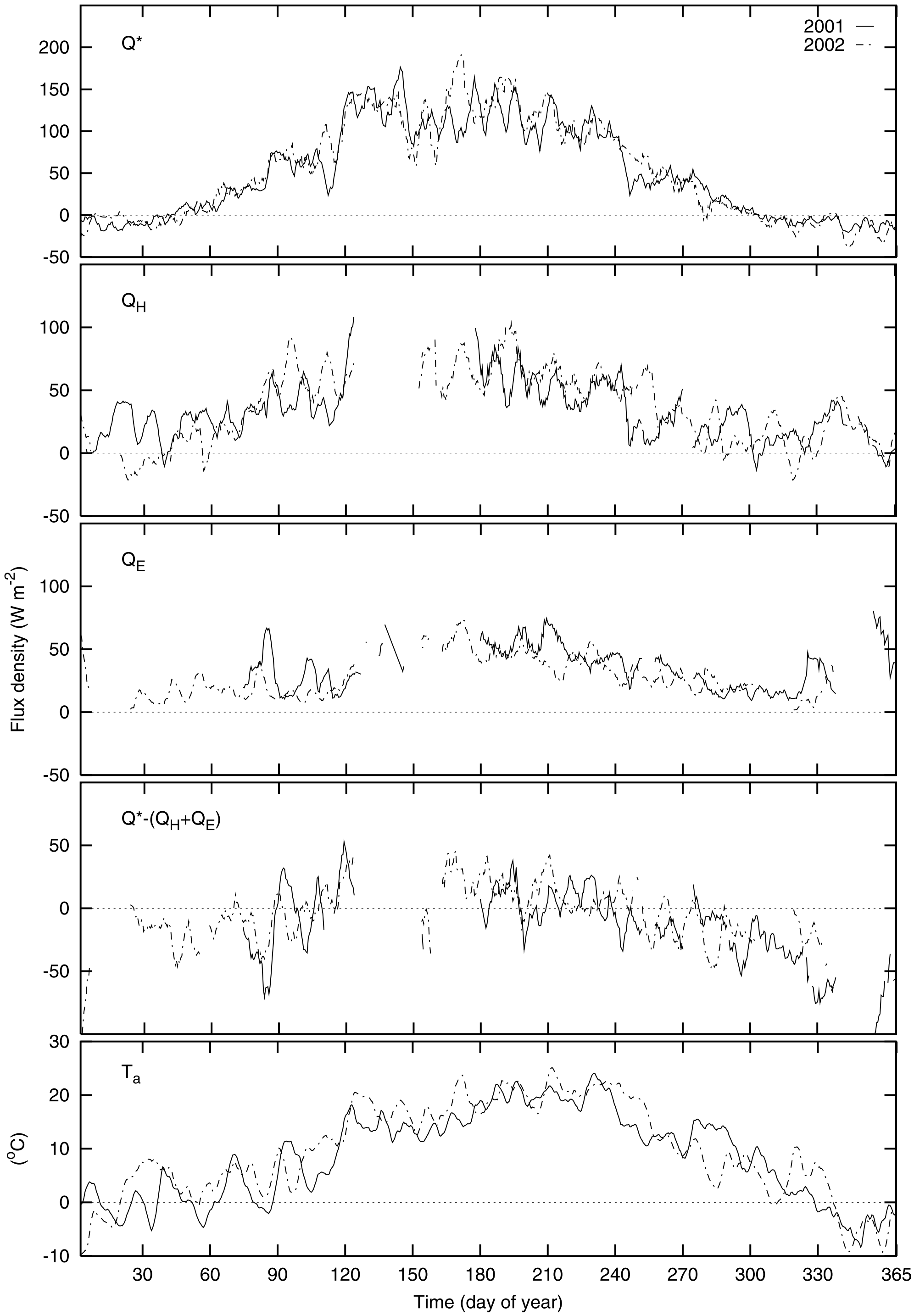

Fig. 4. Five-day moving average of energy balance components computed from hourly turbulent fluxes and 15 minute averages for Q^* and T_a

2002. Precipitation was also similar, and slightly greater than the 1951–1989 mean, for both years (Table 4). Even during mid-summer, Łódź can receive only small net radiative forcing on some days, due to overcast conditions (Offerle et al., 2003). Naturally this also affects the size of the turbulent fluxes.

The turbulent sensible heat flux closely follows the pattern of Q^* during summer but the effects of anthropogenic forcing become evident

Table 4. Monthly means of precipitation and air temperature for 1951–1989 (GHCN Station # 12465000 http://lwf.ncdc.noaa.gov/oa/climate/ghcn/ghcn.SELECT.html), 2001 and 2002 observed at Lipowa. Anthropogenic heat flux (Q_F) values from Klysik (1996). The residual of the energy balance from the diurnal ensembled flux terms is given as $Q_{res} = Q_H + Q_E - Q^*$. Note: temperature not corrected for differences in measurement height in this study relative to the GHCN. † Fewer than 12% of possible hours

	GHCN			2001			2002		
	Precip mm	Temp °C	Q_F W m^{-2}	Precip mm	Temp °C	Q_{res} W m^{-2}	Precip mm	Temp °C	Q_{res} W m^{-2}
Jan	35	−4.8	72	24	−0.4		36	−0.8	28
Feb	30	−3.6	65	26	−0.1		80	4.0	21
Mar	32	3.0	61	38	2.5	35	35	5.2	11
Apr	40	9.2	34	83	8.3	1	12	9.1	0
May	65	13.5	21	48	14.2		179	17.6	−28†
Jun	80	16.9	21	110	15.1	1†	74	18.0	−14
Jul	90	18.9	21	97	20.3	−11	41	21.0	−19
Aug	74	18.4	21	49	19.6	−7	53	21.4	−4
Sep	50	14.5	21	106	11.9	11	46	13.8	11
Oct	38	9.5	32	22	11.7	18	71	6.9	24
Nov	41	3.0	55	37	1.9	44	49	4.5	25
Dec	39	−2.0	66	23	−3.9	74	6	−5.1	51
Annual	615	8.1	41	662	8.5		680	9.7	9

in the winter (Figs. 4 and 5). Regression analysis of Q_H on Q^* (hourly data) objectively characterizes this relation (Table 5). The variance in Q_H is largely accounted for by Q^* for most of the year (coefficient of determination, $R^2 \geq 0.8$) but this drops to less than 0.3 for December and January, when Q_F is at least twice the magnitude of Q^* (Table 5).

Assuming advective effects to be minor, because of the careful choice of site and height of measurement, most of the remainder of the variability in the energy balance (Eq. (1)) is attributable to the roles of Q_F and ΔQ_S. The effects of these terms are seen in the energy balance residual term ($Q^* - (Q_H + Q_E)$) that includes net heat storage changes, that portion of Q_F that is not measured by the radiometer or EC systems, and any other unmeasured sources and sinks as well as measurement errors. It should be noted here that EC appears to underestimate turbulent fluxes (Wilson et al., 2000). This should lead to a positive bias in the residual term in the daytime. Additionally although the radiometer and turbulent fluxes have similar mean surface characteristics, temporal differences will also affect the residual. The residual is near zero on average for the summer months, but is clearly negative during the winter periods (Fig. 4). The contribution made by ΔQ_S is relatively small because these are 5-day moving averages and only the *net* storage gain or loss, leading to temperature change by the urban air-built-ground volume appears. The transition between the periods of positive and negative residuals corresponds to an increase (decrease) in internal building heating in the autumn (spring). Kłysik (1996) estimated monthly average Q_F values for Łódź based on energy consumption figures and land-use (Table 4). The Lipowa (LTM) residuals appropriately fall in the mid range of his city-wide Q_F values except during the summer months.

ΔQ_S is directly related to the temperature change in the urban volume and the part of Q_F that corresponds to building space heating is a function of air temperature. With $T_a < 10\,°C$, the residual is almost always negative (Fig. 4). The exceptions occur when T_a is increasing, leading to positive values of ΔQ_S.

Ensemble diurnal patterns in fluxes and daytime partitioning for each month were also consistent in 2001 and 2002, although the daytime Q_H for 2002 is slightly greater in the period from July to September (Fig. 5). This can be attributed to less cloudy conditions in this period of 2002 and consequently higher Q^*, though Q_E was not similarly enhanced. Volumetric soil moisture during this period was lower in 2002 than in

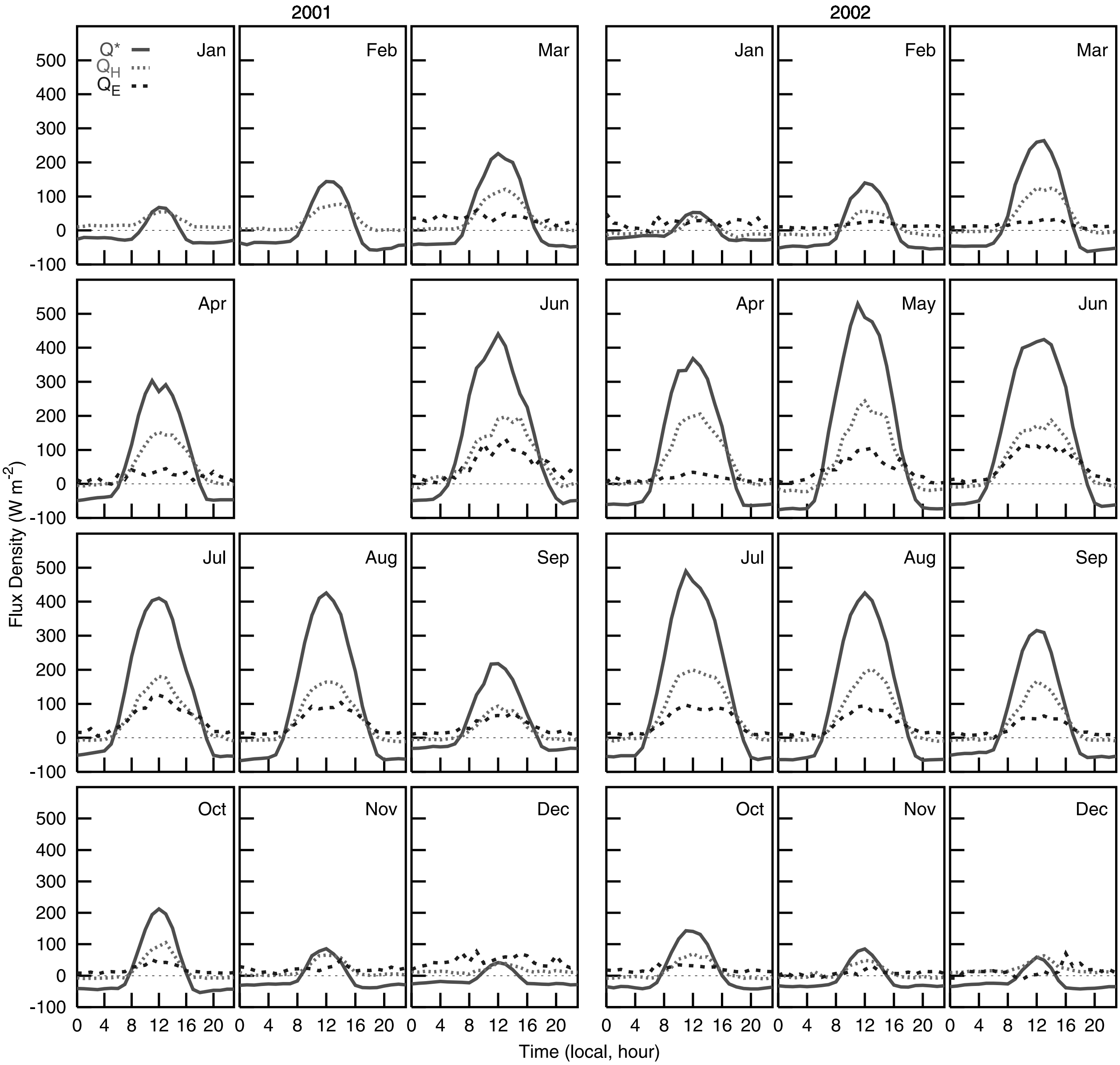

Fig. 5. Monthly ensemble diurnal energy balance fluxes for 2001 (left) and 2002 (right). Q^* is calculated only for hours possessing valid observations for Q_H. The number of observations varies between months (see n in Table 5)

2001 (Fig. 6). As is typical for urban areas, the turbulent sensible heat flux is larger than the latent heat flux. Also in agreement with other built-up sites on an hourly basis Q_H remains positive after Q^* turns negative in the late afternoon/evening due to release from heat storage (Oke, 1988). Additionally, Q_H is near zero throughout the night, indicating a near-neutral surface layer at the measurement height. During December and January, in particular, Q^* is only positive for a few hours a day, yet the sum of the turbulent fluxes is primarily positive. This is consistent with other urban wintertime observations where anthropogenic heating is a significant factor (Christen et al., 2002).

Differences in Bowen ratio (β) values between rural and urban sites have been cited as one impact of urbanization (Oke, 1987; Kuttler, 1988). Over a truly impervious surface, an evaporative flux is possible only when there is accumulated surface moisture from either rain or dewfall. Over vegetated or bare soil surfaces, water may be drawn from the subsurface (soil) reservoir and consequently, the time scale of variability is generally longer, although there will still be a diurnal course related to other factors. Thus, both β and

Table 5. Results of ordinary least squares (OLS) regression of Q_H on Q^*. N is the number of hourly observations, B is the regression slope, R^2 is the coefficient of determination and d is the index of agreement (Wilmott, 1982)

Month	2001				2002			
	N	B	R^2	d	N	B	R^2	d
1	561	0.37	0.30	0.62	328	0.21	0.11	0.57
2	572	0.35	0.53	0.72	515	0.29	0.58	0.68
3	543	0.38	0.77	0.78	608	0.37	0.74	0.77
4	538	0.35	0.80	0.75	663	0.43	0.83	0.82
5	–				78	0.38	0.88	0.76
6	141	0.34	0.73	0.71	593	0.34	0.85	0.71
7	601	0.34	0.84	0.71	680	0.38	0.86	0.76
8	663	0.34	0.86	0.73	684	0.39	0.85	0.78
9	467	0.33	0.73	0.72	547	0.40	0.80	0.80
10	621	0.34	0.64	0.74	531	0.35	0.62	0.75
11	530	0.40	0.50	0.71	570	0.41	0.32	0.70
12	473	0.25	0.11	0.51	657	0.35	0.21	0.57

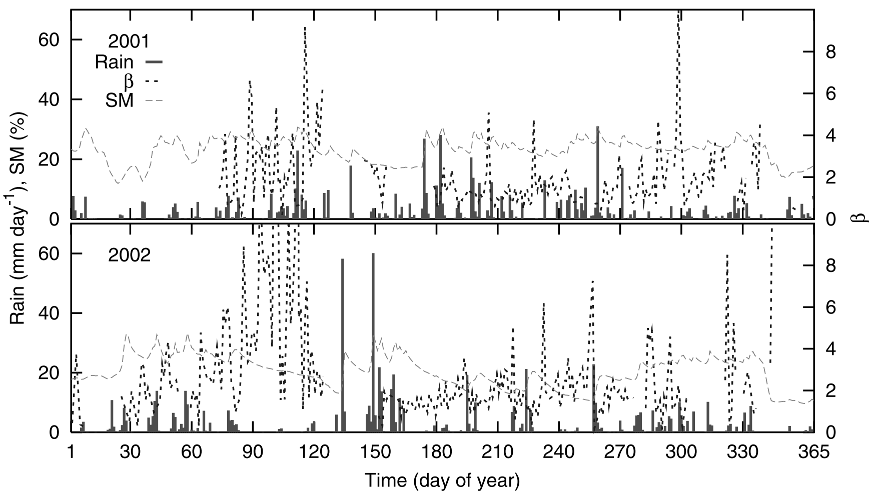

Fig. 6. Daily values for total rainfall, average volumetric soil moisture (SM) and daytime Bowen ratio ($\Sigma Q_H/\Sigma Q_E$) when Q^*, Q_H, $Q_E > 0$

its variability are expected to be reduced during the summer period due to the influence of vegetation. In Łódź, β reaches a maximum in the spring when Q^* is increasing but vegetation is not active. This is especially so during relatively dry periods (e.g. April 2002) (Fig. 6). Unfortunately due to the failure of sonic transducers in both years, few data are available for May and June so it is difficult to estimate the actual time when vegetation starts to have a major influence on turbulent partitioning. Daytime peaks in β are much less pronounced during the summertime, and there is less variance, which can be attributed to the role of vegetation. Rainfall and soil moisture were less during the late summer period in 2002 than in 2001 which resulted in slightly higher Bowen ratios in this period in 2002. In January and December of 2002, soil moisture is apparently constant, a result of the snow accumulation and/or frozen soil water. This leads to the increase in β at the end of 2002. The reverse is true when the snow covered surface or frozen soil layer is melting.

The partitioning of energy balance fluxes for 2001 and 2002 show that the fraction of the net radiation convected away as sensible heat is nearly identical in the summer periods (Table 6). However, the ratios for the latent heat fluxes vary between the years, for the reasons noted above. For the rest of the year, the data are not directly comparable due to the absence of Q_E for January and February of 2001. Still, the partitioning of Q^* into Q_H remains relatively similar. Q_E accounts for 41% of the turbulent exchange to the atmosphere in 2002, which is equivalent to $390\,\text{mm a}^{-1}$ of evaporation (using a constant

Table 6. Seasonal partitioning of the surface energy balance for the two years

Year	Period	Q_H/Q^*	Q_E/Q^*
2001	Jun–Sep	0.52	0.47
2001	Oct–Apr†	1.29	1.34
2002	Jun–Sep	0.56	0.38
2002	Oct–Apr	1.48	1.11

† Does not include January or February data

value for the latent heat of vaporization) or about 60% of the precipitation input to the site. However, it should be noted that when the heaviest rainfall occurred fluxes could not be measured.

3.2 Comparison with other urban energy balance measurements

While there are no published results of multiple year annual urban energy balance fluxes, two studies at approximately similar latitudes to that of Łódź can be used for seasonal comparisons: Edinburgh (56° N, Nemitz et al., 2002) and Vancouver (49° N, Grimmond, 1992). However, it should be noted that the climates of these two cities differ from that of Łódź. In Edinburgh the flux instrumentation was mounted at roof level on a mast extending 2.5 m from a hilltop stone tower with a diameter of 2.8 m. The principal source area upstream in the usable wind sector is the city center but also includes residential, woodland and grass. The Vancouver ('Sunset') site is located in a low-density residential section of the city with Q_H measured by EC or determined from Bowen ratio measurements. At the Sunset site Q_F was estimated independently of the other energy balance components. It should be noted that the measurement systems differed between the studies and the sites are not ideal (flow distortion and variable surface cover in Edinburgh and source area contributions from non-residential land-use in Vancouver).

Table 7 shows the results for this study broken down by year and period along with data from comparable time frames for the Edinburgh and Vancouver sites. Similarities in the magnitudes and patterns in seasonality between the sites are evident. Q_H ranges from 51–60% of $Q_H + Q_E$ except for periods when Q_F is relatively dominant for the site. At the Edinburgh site during October–November 2000, the turbulent heat partitioning changes radically from the previous year. The dominance of latent over sensible heat convection is due to an increase in rainfall compared to the previous year. A similar change in partitioning occurred in Łódź in December 2001 which shows similar changes in all the ratios from the October–April period. The growing season Bowen ratio at all sites is in the range of 1.0 to 1.5. The values for the two central city sites are perhaps surprisingly low when land use is considered; they lie in the range of suburban sites summarized by Grimmond and Oke (1999a). This stresses the importance of not neglecting to account for the land cover fraction that is vegetation even in central city locations.

Table 7. Urban energy balance comparison between sites in different cities with long term flux measurements (see text for references)

Site	Site description	Year	Month(s)	$Q_H/(Q_H+Q_E)$	$Q_E/(Q_H+Q_E)$	β
Łódź (Lipowa)	Near city center,	2001	Jun–Sep	0.52	0.48	1.09
	high density, 11 m		July	0.50	0.50	1.01
	buildings, 70% built		Oct–Apr†	0.49	0.51	0.96
			Dec	0.27	0.73	0.37
		2002	Jun–Sep	0.59	0.41	1.45
			Oct–Apr	0.57	0.43	1.33
Edinburgh	Downwind of city	1999	May–Jun	0.56	0.44	1.29
	center, residential		Oct–Nov	0.53	0.47	1.13
	grass & woodland	2000	Oct–Nov	0.21	0.83	0.25
Vancouver (Sunset)	Suburban, low	1987	Jan–Feb	0.41	0.60	0.68
	density houses		March	0.54	0.46	1.19
	an gardens, 54% built		June	0.60	0.40	1.48

† Does not include January to February data

4. Conclusions

Energy balance fluxes were measured over a densely built section of central Łódź, Poland from 2001–2002. Partitioning of net radiation into the turbulent fluxes is similar between the two years, with the largest differences occurring due to particularities of the precipitation conditions. The ensemble diurnal cycles of the turbulent fluxes for each month are also similar in the two years. The largest differences occurred in the July–September period, due to the variability of the net radiation receipt. The fraction of the net radiation used to convect sensible heat to the urban boundary layer is about 50–60% in the summer, but more like 130–140% in the winter. Similarly, the turbulent latent heat transfer is about 40–50% of the radiant input in the growing season but increases to between 90 and 120% in the colder half of the year. Clearly this boosting of the relative role of the turbulent terms is made possible by the augmentation of the available energy supply by anthropogenic heating of the building interiors. Of course the absolute value of the net radiation is small or negative in the winter so the boosted fluxes are not large. Except for larger values in the spring Bowen ratios are relatively constant throughout the year in Łódź. The character of the surface energy balance of the Łódź Lipowa site displays similarities with results from previously studied cities. These sites show that latent heat exchange is a large component of the urban energy balance over long periods (~monthly) due to evaporation of water from rain or snowfall as well as from vegetation. This highlights the importance of including urban water flows into numerical models of urban surface fluxes since much of the water is captured and removed from the system. The importance of taking into account land cover fractions, in particular vegetation, and not just land use cover is demonstrated. Even neighborhoods or districts within cities can be heterogenous with respect to land cover, particularly in terms of vegetation. The length of record and the role of anthropogenic forcing are two features that make the study particularly useful.

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