

Surface energy balance characteristics of a heterogeneous urban ballast facet

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ABSTRACT: Surface energy balance measurements were conducted during a study period from June to September 2002 at a goods station in Osnabrück, Germany. The inner-urban facet with a surface area of 0.5 km² was predominantly covered by ballast. Turbulent latent and sensible heat fluxes were estimated by a modified Bowen ratio method; the ground heat flux was calculated from temperature gradients and a laboratory derived thermal conductivity. The thermal behaviour of the ballast facet in comparison to other urban surfaces is somewhat 'two-sided'. Due to its thermal properties it behaves similarly to urban surfaces during the day, with high surface temperatures and large near-surface temperature amplitudes. About one-third of the incoming energy is converted into the turbulent sensible heat flux and 20% is converted into the ground heat flux. The latent heat flux at the site is of minor importance (16%). During the night, however, the thermal behaviour is more comparable to a 'rural-like' surface than to an urban facet. The ballast surface cools significantly and the sensible heat flux is directed towards the surface. Due to the heterogeneity of the study site the energy balance shows a closure gap of around 30%. Reasons for the energy balance non-closure are discussed.

KEY WORDS: Surface energy balance · Ballast · Osnabrück · Thermal properties · Energy balance closure · Urban climate

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1. INTRODUCTION

Studies on the energy balance characteristics at the earth's surface are important to better understand the evolution and properties of different micro- and meso-climates and also to enhance their representation in numerical weather and climate models. Therefore detailed knowledge of the energy balance properties of various surface types is of interest. Measurements of turbulent fluxes over homogeneous surfaces which are 'ideal' in terms of the flux methodology have been performed for some decades (e.g. Businger et al. 1971, Panofsky et al. 1977, Nieuwstadt 1984, Wyngaard 1990, Dabberdt et al. 1993); however, recently, more sites are established in more complex and heterogeneous terrain such as urban areas, mixed land-use or coastal zones. With an increasing complexity in the footprint of the surface flux, demands on measurements, methodology and interpretation of energy bal-

ance estimates can become complicated and challenging (Panin et al. 1998, Schmid & Lloyd 1999, Massman & Lee 2002). However, increased understanding of these 'real-world' surfaces is important for a wide range of research fields.

In urban areas complications arise due to the 3-dimensional, heterogeneous structure of the surface. In the context of urban flux measurements the city is normally treated in a box or volume approach so that the fluxes measured at the upper part of the box could be interpreted as representative local-scale flux estimates (Oke 1987, 1997). The actual measurement sites have to be installed within the urban constant flux layer, i.e. at a height above the so-called urban roughness sublayer, where individual surface roughness elements (i.e. buildings) have a direct influence on the turbulence structure (Rotach 1999, Marth 2000). The height of the urban roughness sublayer is site-specific, but is usually situated between 1.5 and 5 times the

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mean building height (Roth 2000). Studies on the urban energy balance on a city scale have been conducted in European cities such as Basel, Switzerland (Christen et al. 2003, Christen & Vogt 2004), Marseille, France (Grimmond et al. 2002), and Barcelona, Spain (Jauregui et al. 2002). Furthermore, a variety of studies from other parts of the world and from different climatic regions have been published (see detailed reviews in Arnfield 2001a,b, 2003, McKendry 2003). However, a total urban flux within the footprint or source area of interest is mostly composed of different flux fractions triggered by the thermal and physical properties of specific urban facets such as roofs, walls, streets and different land-use types within the flux source area. To gain a better understanding of urban fluxes, urban microclimates and climatic phenomena such as the urban heat island and cold-air dynamics, more information on the energy budgets of specific urban facets is needed (Arnfield 2003).

Only a few studies concentrate on the energetic features of urban facets, e.g. asphalt (Anandakumar 1999), pavements of different porosity (Asaeda et al. 1996, Asaeda & Vu 1997), urban canyon facets (Nunez & Oke 1977) and urban parks (Barradas et al. 1999, Spronken-Smith et al. 2000). Some progress has been made in the field of numerically modelling the urban energy balance. The model domains mostly lack the methodological limitations that might appear when installing sensors in urban areas. However, the models also often concentrate on calculating the energy fluxes as local-scale estimates, hence considering the city as a whole (e.g. Grimmond & Oke 2002, Roberts et al. 2003). Recently, Barlow et al. (2004) and Harman et al. (2004) attempted to quantify the contribution of different urban canyon facets (roof, walls and floor) to the total flux by a physical scale model and a numerical model.

The intention of this study is to characterise the surface energy balance of a plane inner-urban facet. Measurements were conducted at a goods station in Osnabrück, Germany. The results of this analysis in conjunction with additional measurement campaigns (Weber & Kuttler 2004) are important in understanding the microclimatic effect of a ballast facet with regards to nocturnal cold-air dynamics and the general urban climatic situation of the city of Osnabrück. A detailed understanding of these phenomena plays an important role in urban climate related decision-making processes and for instance in the field of sustainable urban planning.

In Section 2, a brief summary of the main aspects of energy balance measurements is given, while the materials and methods used are described in Section 3. The results on surface heat fluxes are presented in Section 4 and concluded by a brief discussion in Section 5.

2. THEORY

Nowadays, the measurement of turbulent sensible (Q_H) and latent (Q_E) heat fluxes is mostly done by fast response sensors (>10 Hz). Wind vectors are determined by sonic anemometers while humidity fluctuations are measured by absorption of water vapour in the infrared or Lyman alpha (ca. 122 nm) range (e.g. Foken 2003). In case fast response humidity measurements are not available, Liu & Foken (2001) proposed a method to gather Q_H and Q_E by a modified Bowen ratio method. The accuracy of this method to determine turbulent fluxes in comparison to eddy covariance measurements has been shown to be in the order of <10% for Q_H and <20% for Q_E (Liu & Foken 2001). The approach is described in the original paper but is briefly summarised here.

The ratio of the sensible and latent fluxes is known as Bowen's ratio (Bo):

$$Bo = \frac{Q_H}{Q_E} \quad (1)$$

where both Q_H and Q_E are in $W m^{-2}$. Bo can be calculated from air temperature and humidity measurements at 2 levels above ground as (e.g. Arya 2001, Liu & Foken 2001):

$$Bo = \frac{c_p \Delta T}{L_e \Delta q} \quad (2)$$

where c_p is the specific heat capacity of air at constant pressure in $J kg^{-1} K^{-1}$, L_e is the latent heat of vaporisation of water in $J kg^{-1}$, ΔT is the vertical air temperature gradient in $K m^{-1}$ and Δq is the vertical gradient of specific humidity in $kg kg^{-1} m^{-1}$.

In the first step of the modified Bo, Q_H is estimated by direct measurements of the buoyancy flux (Q_{HB} , $K m s^{-1}$) with a sonic anemometer as:

$$Q_{HB} = \overline{w'T_s'} \quad (3)$$

where w' and T_s' are the turbulent fluctuations of vertical wind speed in $m s^{-1}$ and acoustic temperature (sonic temperature) in K, respectively. The horizontal bar refers to averages over a certain time period (normally 30 min) while the primed quantities refer to turbulent fluctuations during the averaging interval.

To correct for influences of crosswind and humidity fluctuations (Liu & Foken 2001), Bo is needed. Finally, the conversion into sensible heat flux is calculated as:

$$Q_H = \rho \cdot c_p \frac{\left(\overline{w'T_s'} + 2 \frac{\overline{T} \cdot \overline{u}}{c^2} \cdot \overline{u'w'} \right)}{\left(1 + \frac{0.51 \cdot \overline{T} \cdot c_p}{L_e \cdot Bo} \right)} \quad (4)$$

where ρ is the density of air in kg m^{-3} , T the air temperature in K, u the horizontal wind velocity in m s^{-1} , and c the speed of sound in m s^{-1} . In the original papers (Liu & Foken 2001, Liu et al. 2001) an improved equation is also given for the sonic anemometers that calculate the temperature from an average along all 3 sonic paths (not shown here).

In a final step, Q_E is estimated as:

$$Q_E = \frac{Q_H}{Bo} \quad (5)$$

The ground heat flux (Q_G , W m^{-2}) can be calculated from the Fourier law of heat conduction as:

$$Q_G = \lambda \frac{\partial T}{\partial z} \quad (6)$$

where λ is the thermal conductivity in $\text{W m}^{-1} \text{K}^{-1}$, and $\partial T/\partial z$ is the gradient of soil temperature in K m^{-1} .

3. MATERIALS AND METHODS

3.1. Study site. From 12 June to 23 September 2002, energy balance measurements were conducted at a goods station (GS) in Osnabrück, Germany ($52^\circ 16' \text{N}$, $8^\circ 04' \text{E}$). The GS is situated roughly within the centre of the urban area of Osnabrück and covers a surface area of approximately 0.5 km^2 (Fig. 1). It is bordered by the urban centre to the west (building heights on average 12 to 16 m), a commercial area to the south and a residential district to the north (building heights on average 8 to 12 m). The eastern surroundings of the study area are characterised by large percentages of unsealed natural surfaces including meadow, agricultural crop land and pasture.

The surface of the GS is mainly comprised of ballast (a mixture of shattered rock types which predominantly consists of greywacke, sandstone and diabase)

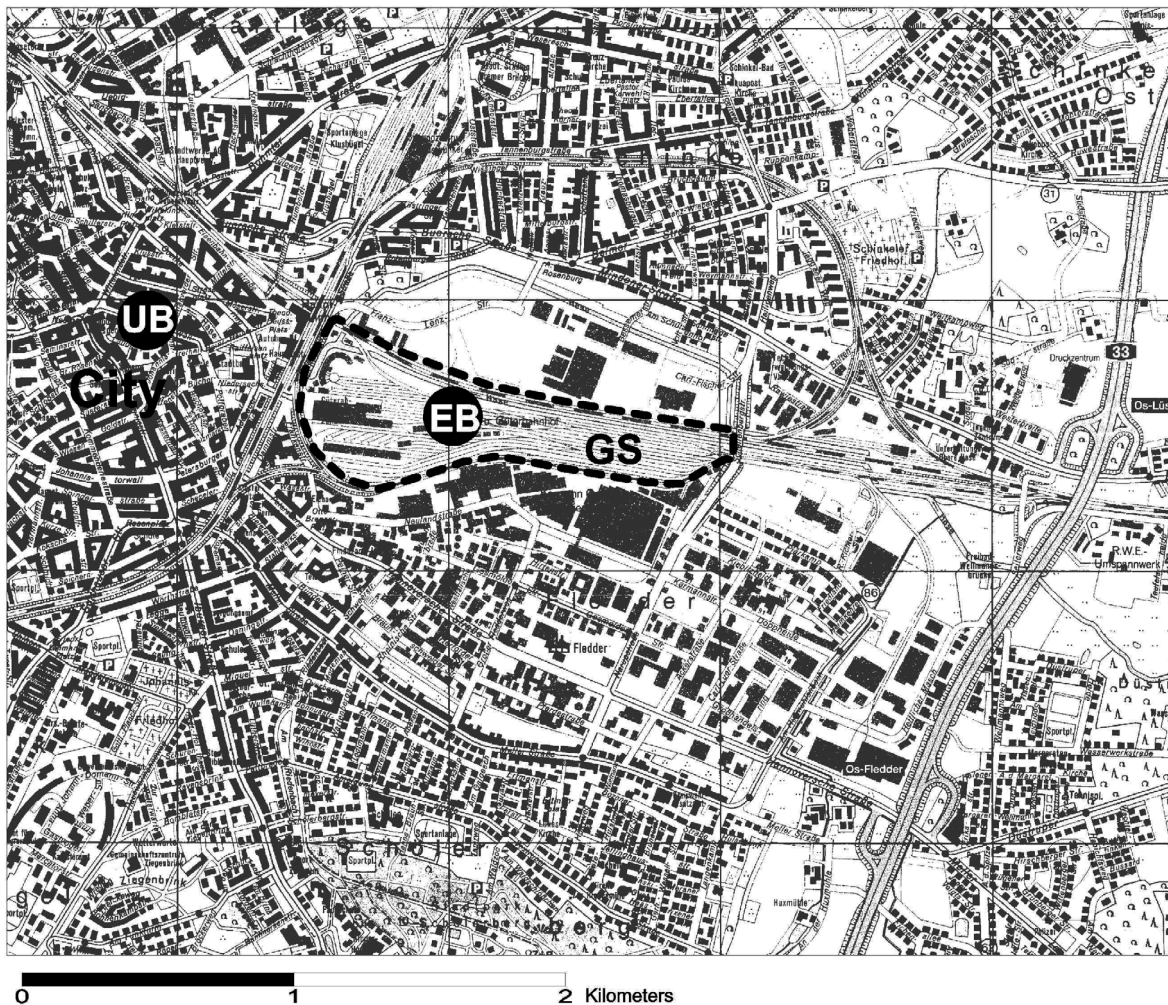


Fig. 1. The study area in Osnabrück, Germany. The area of the goods station (GS) is shown by a dashed line; the location of the energy balance station (EB) and urban centre station (UB, in 2001) are also shown

with an average layer thickness of around 0.3 to 1 m. At the measurement site the thickness of the ballast bulk is 0.5 m. The dimensions of the individual ballast pieces vary from 2.5 to 7.1 cm in diameter and 1.35 to 3.5 cm in height, which was defined normal to the diameter. The porosity of the ballast bulk, defined by the ratio of the volume of air-filled cavities to the total bulk volume, is 0.45.

The actual measurement point offered uniform fetch conditions of >800 m to the east, >175 m to the north and west and 100 m to the south. To assess whether the flux measurements represent the characteristics of the ballast surface, the analytical footprint model of Schuepp et al. (1990) was applied. It shows that under neutral stability ca. 90 % of the cumulative flux is from a source area ≤ 175 m around the instrument location so that the properties of the ballast surface are portrayed by the flux measurements.

However, in terms of surface flux measurements, the site surroundings have to be considered heterogeneous with a mix of ballast, gravel, railway tracks and sparse vegetation in the flux footprint as well as light and electricity masts in the field of flow (Fig. 2). The consequences and limitations of the complex site properties on the flux estimates will be discussed in Section 5.

3.2. Instrumentation. The energy balance station (Stn EB) at the study site was equipped with a 3-dimensional ultrasonic anemometer (USA-1, Metek) at 2.1 m above ground level (a.g.l.) which measured horizontal, lateral and vertical wind speeds at a 10 Hz sampling rate. The 10 Hz raw data were stored on a standard personal computer.

Dry- and wet-bulb temperatures were measured at 0.45 and 2.05 m a.g.l. by psychrometers equipped with

glass-coated PT 100s (Thies Clima). The dry-bulb temperatures are referred to as $T_{0.45\text{m}}$ and $T_{2.05\text{m}}$ hereafter. Net radiation Q^* was measured by a Schulze type pyrriometer (Thies Clima) at 2 m a.g.l. Soil temperatures were measured by thermistors (Thies Clima) placed within the ballast bulk at -0.05 m ($T_{b\ -0.05\text{m}}$), -0.1 m ($T_{b\ -0.1\text{m}}$) and -0.3 m ($T_{b\ -0.3\text{m}}$). Additionally, a heat flux plate (HFP 01, Hukseflux) was installed at -0.05 m.

All data, except the sonic data, were sampled at 1 Hz and stored as 3 min averages (Data logger Combilog 1020, Th. Friedrichs).

3.3. Data handling. From sonic data and dry- and wet-bulb temperatures half hourly fluxes of Q_H and Q_E were calculated with the aid of software developed by the Department of Micrometeorology, University of Bayreuth, Germany (Foken 1999). Based on post-field Quality Assurance/Quality Control (QA/QC) tests implemented in the software (Foken & Wichura 1996) more than 50 % of the data (ca. 70 % during clear and calm days) showed reasonable to good data quality during turbulent conditions in spite of the heterogeneity of the study site. Since the sonic anemometer was mounted vertically to the surface no coordinate rotation was applied. However, tests with rotated data (double rotation, cf. Aubinet et al. 2000) revealed that the effect of rotation on heat fluxes was negligible ($< 4\%$, $R^2 = 0.99$). Measurements over tall roughness elements indicated that it might be important to account for the time rate of change of storage of Q_H and Q_E in the air layer between the surface and the height of the sonic measurements since these terms can amount to 25 W m^{-2} (e.g. Vogt 1995). Storage terms were calculated (Thom 1975) but were negligible at this site, although for the sake of completeness the storage term for sensible heat (Q_{SH}) will be taken into account in Section 4.3.

Considering the complexity and heterogeneity of the ballast bulk (large air-filled cavities, varying grain size, heterogeneous geometry of individual ballast pieces) estimating Q_G precisely was not an easy task. However, based on a comparative analysis of different methods (Weber 2004, 2005) the Q_G presented in this paper were calculated according to Eq. (6) taking a laboratory-derived thermal conductivity of $\lambda = 0.45\text{ W m}^{-1}\text{ K}^{-1}$ into account. λ was estimated in a laboratory set-up by measuring temperature gradients in the ballast and a reference substrate simultaneously under steady-state conditions (Weber 2004). The soil tem-



Fig. 2. Overview of the measurement site (view to the east)

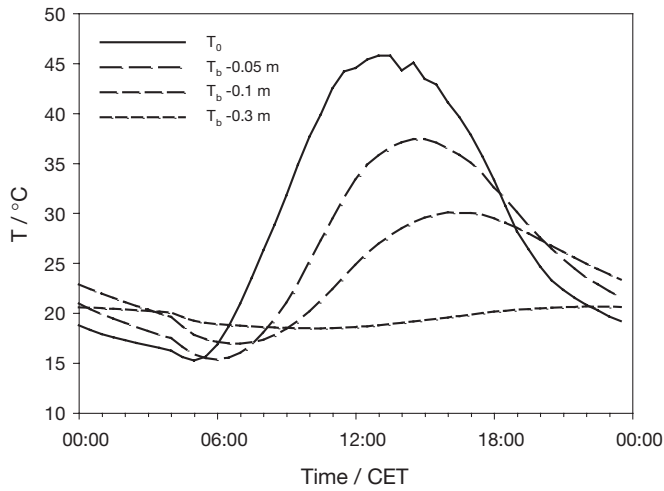


Fig. 3. Average diurnal courses of surface and ground temperatures of the ballast at the goods station in Osnabrück for 21 clear and calm days during the study period. Soil temperatures were measured by thermistors (Thies Clima) placed within the ballast bulk at -0.05 m ($T_{b-0.05\text{ m}}$), -0.1 m ($T_{b-0.1\text{ m}}$) and -0.3 m ($T_{b-0.3\text{ m}}$)

perature gradient in Eq. (6) was estimated from a modelled surface temperature T_0 (cf. Sozzi et al. 1999) and the *in situ* ground temperature measurement at -0.05 m.

In this study, all non-radiative fluxes directed away from the surface, to the atmosphere and into the ground, are assigned a positive sign.

The results presented here are based, if not specified otherwise, on 21 clear and calm days during the study period in 2002 during which urban climate effects

were most pronounced. Those nights were defined according to stability and dispersion categories (Pasquill 1961, Polster 1969) from half hourly wind speed and net radiation input data. For long-term measurements, this approach is more straightforward in comparison to the boundary layer stability parameter $\zeta = z/L$ which can be gathered from the sonic measurements. However, it could be shown that both methods result in comparable stability definitions (Weber 2004). The criteria for the definition of clear and calm nights are given elsewhere (Weber & Kuttler 2004).

4. RESULTS

4.1. Thermal behaviour of the ballast facet

In comparison to other urban surface and building materials the ballast bulk is characterised by relatively small values of thermal conductivity ($\lambda = 0.45 \text{ W m}^{-1} \text{ K}^{-1}$) and volumetric heat capacity ($C_v = 1.39 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$). Due to its thermal properties this results in distinct daily amplitudes of surface and near-surface ground temperatures. Even on a somewhat damped average diurnal course for 21 clear and calm days during the study period the average daily temperature amplitude is 31 K at the surface and 22 K at -0.05 m (Fig. 3). During noon hours the surface temperature can easily reach 46°C at the surface and 37°C at -0.05 m, since heat is not rapidly conducted down to deeper layers (small λ). Therefore, large near-surface to air temperature differences can develop during the day (Fig. 4). The temperature difference expressed

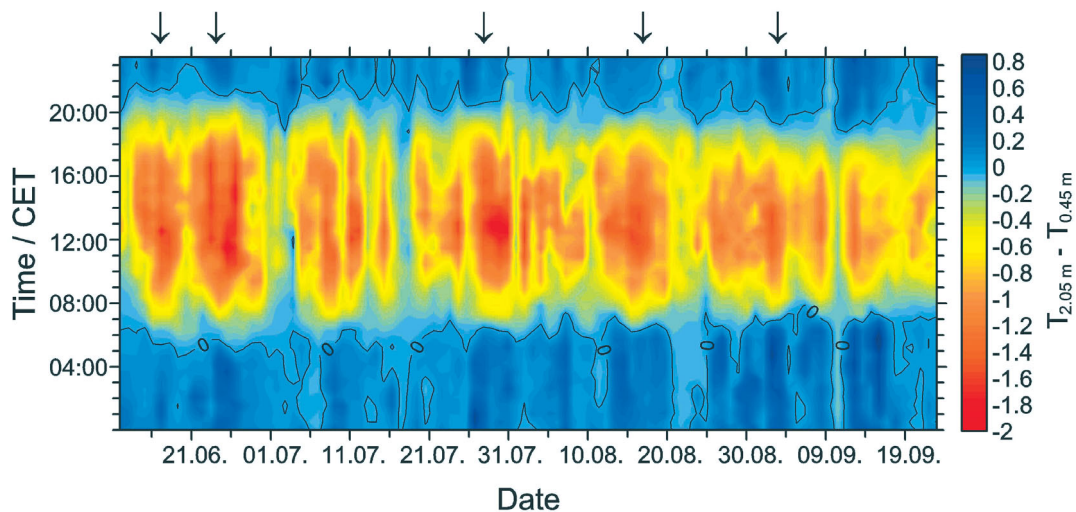


Fig. 4. Vertical temperature difference ($T_{2.05\text{ m}} - T_{0.45\text{ m}}$) between the dry-bulb temperature measurements at 0.45 m above ground level (a.g.l.) ($T_{0.45\text{ m}}$) and 2.05 m a.g.l. ($T_{2.05\text{ m}}$) for the entire study period from June 12 to September 23, 2002, based on 30 min averages. Arrows indicate contiguous periods of >1 clear and calm days (17 to 20 June, 2002; 26 to 27 June, 2002; 27 to 29 July, 2002; 15 to 20 August, 2002; and 2 to 3 September, 2002)

here as the difference between $T_{2.05\text{m}}$ and the near-surface measurement $T_{0.45\text{m}}$ reaches -1.5 to -2 K during noon hours, which is an equivalent lapse rate of -7.3 to -9.3 K 10 m^{-1} . The time course of temperature differences clearly shows periods of contiguous clear and calm days which are characterised by midday temperature differences of -2 K (arrows in Fig. 4). Surface materials with small volumetric heat capacities are able to cool rapidly during the evening and nocturnal periods (Asaeda et al. 1996). Heat can be released relatively fast during the evening hours, especially when it is stored within a shallow layer near the surface during the daytime, as is the case for the ballast in Osnabrück (damping depth of the ballast $z_d = -0.09$ m) it. T_0 starts to decrease in the early afternoon and drops below the ground temperatures $T_{b-0.05\text{m}}$ and $T_{b-0.1\text{m}}$ in the course of the evening (Fig. 3). With the highest

Table 1. Average flux ratios for day-time ($Q^* > 0$) and night-time ($Q^* < 0$) for 21 clear and calm days. Q_H : sensible heat flux; Q^* : net radiation; Q_E : latent heat flux; Q_G : ground heat flux; Q_{SH} : storage of sensible heat; Res: residual; Bo: Bowen ratio

	Q_H/Q^*	Q_E/Q^*	Q_G/Q^*	Q_H+Q_E/Q^*	Q_{SH}/Q^*	Res/ Q^*	Bo
Day $Q^* > 0$	0.36	0.16	0.20	0.52	< 0.01	0.28	2.6
Night $Q^* < 0$	0.11	-0.07	0.35	0.18	< 0.01	0.61	-0.46

temperature values of $T_{b-0.3\text{m}}$ in the early morning the entire ballast bulk has cooled down. A similar behaviour is visible in the near surface air temperature distribution. From around 20:30 h CET $T_{0.45\text{m}}$ drops below $T_{2.05\text{m}}$ so that a surface inversion develops which reaches an inversion strength of up to $T_{2.05\text{m}} - T_{0.45\text{m}} = 0.8$ K or an equivalent lapse rate of 3.9 K 10 m^{-1} . For Stn EB in Osnabrück cooling rates of the ballast surface during 21 clear and calm nights are on average 1.1 K h^{-1} . The thermal behaviour of the ballast as described above is also evident in thermal imagery of urban areas. Ballast surfaces at stations and goods stations belong to the warmest urban surface types during the day but to the coldest during morning hours (Weber 2004).

4.2. Ground heat fluxes

The time course of Q_G is governed by the temperature distribution within the ballast bulk. The surface temperature promptly reacts to absorption of short wave radiation after sunrise, but the temperature wave requires roughly 90 min to penetrate to a depth of -0.05 m (result of cross-correlation between T_0 and $T_{b-0.05\text{m}}$ temperature data, not shown here). Due to an increasing temperature gradient Q_G sharply increases shortly after sunrise and peaks during noon, with maximum values of about 120 W m^{-2} (Fig. 5a). With the start of insolation 60% of the incoming energy ($=Q^*$) is converted into Q_G ($Q_G/Q^* = 0.6$), although the flux ratio constantly decreases to a value of $Q_G/Q^* = 0.2$ at 12:00 h CET (Fig. 5a). With smaller temperature gradients between T_0 and $T_{b-0.05\text{m}}$ the absolute values of Q_G also decrease during the afternoon. At around 18:30 to 19:00 h CET Q_G changes sign and shows relatively small absolute values of around -20 to -15 W m^{-2} during night-time. The relative importance of Q_G in converting Q^* is pronounced during the morning and evening hours (Fig. 5a) with flux ratios Q_G/Q^* in the same order of magnitude. However, when comparing absolute values more energy is converted into Q_G during the

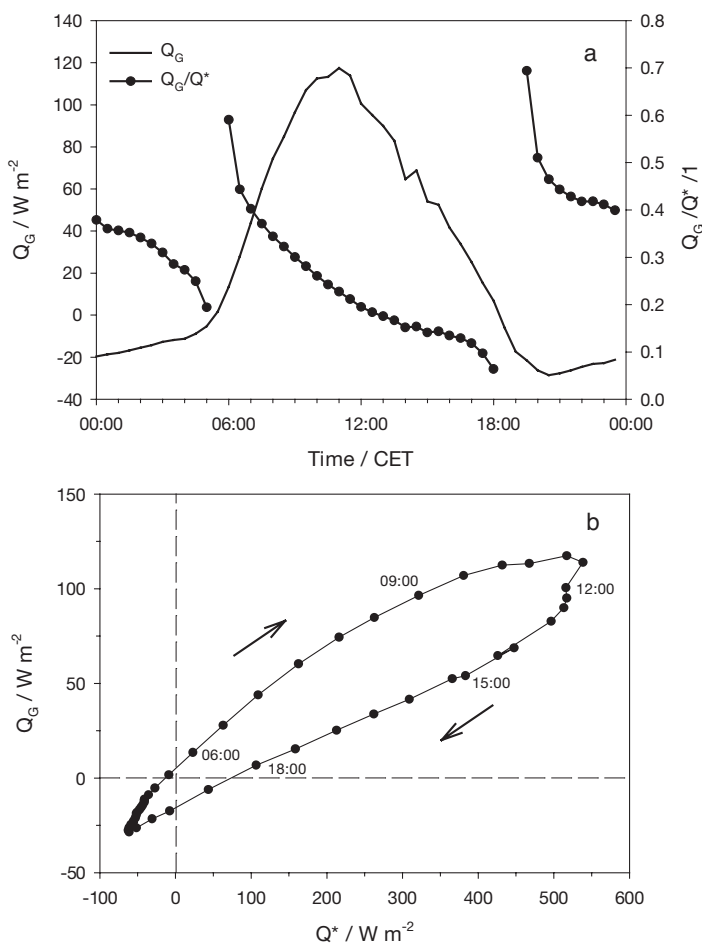


Fig. 5. (a) Diurnal course of the ground heat flux Q_G and the dimensionless flux ratio Q_G/Q^* and (b) a scatter plot of Q^* versus Q_G . Both plots are based on average diurnal courses for 21 clear and calm days in the study period

morning period. This behaviour is expressed in a clockwise hysteresis-loop when plotting the time series Q^* versus Q_G (Fig. 5b). Asaeda et al. (1996) note that this is a common feature of substrates and surface types converting the dominant fraction of available energy to Q_G during the morning period. In daylight hours ($Q^* > 0$) around 20% of Q^* is converted into Q_G (Table 1).

4.3. Turbulent heat fluxes

A composite of the measured energy fluxes during 21 clear and calm days shows that Q_H is the dominant part of the energy budget (Fig. 6). Q_H , which is driven by the large surface to air temperature gradient (cf. Fig. 4), reaches values of around 200 W m^{-2} at around noon (13:30 h CET), resulting in a flux ratio of $Q_H/Q^* = 0.39$ (Fig. 7). The ratio Q_H/Q^* continuously increases in magnitude during the course of the day to a value of 0.79 before sunset.

Due to the sparse vegetation at the site Q_E is of minor importance in the energy budget, with maximum values of 79 W m^{-2} during the afternoon (15:00 h CET, Fig. 6). This is a general behaviour of Q_E at this site which is also valid for the entire study period. Even after precipitation events water is able to drain relatively fast through the porous ballast bulk so that Q_E is not significantly larger during those periods. Bowen ratios (Bo) are large during the day, with average maximum values of $Bo = 4$ on a 30 min

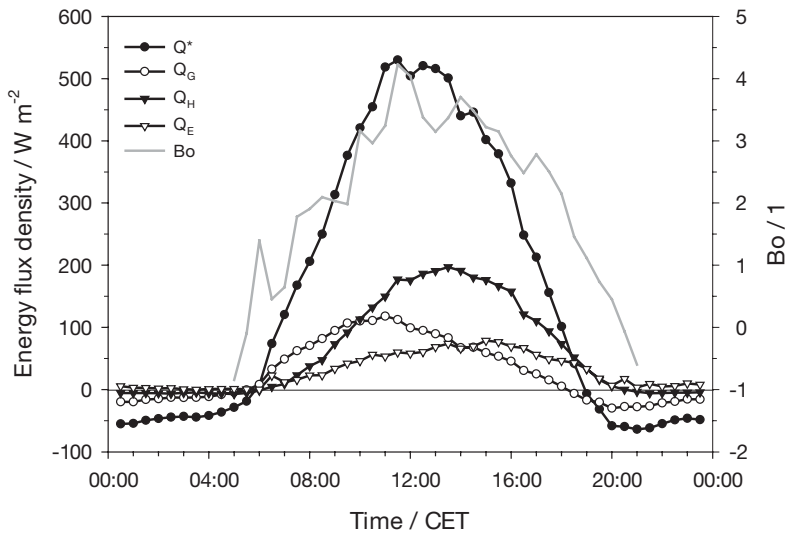


Fig. 6. Energy balance composite for 21 clear and calm days during the study period from 12 June to 23 September, 2002, at the goods station in Osnabrück based on 30 min averages. Bo: Bowen ratio

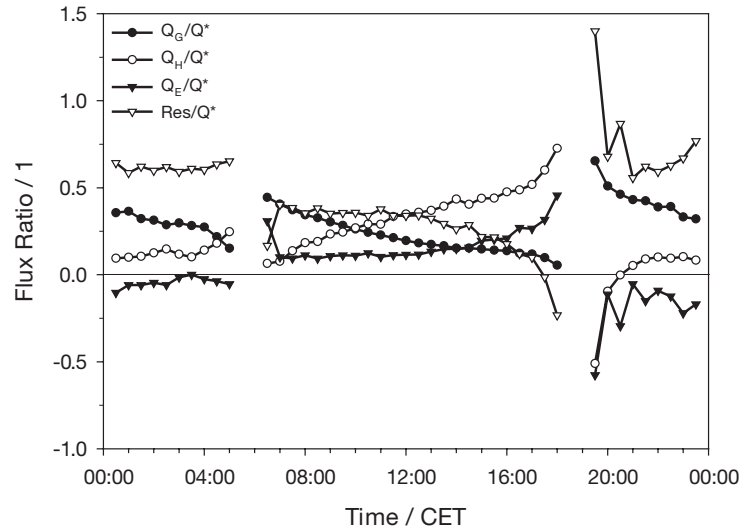


Fig. 7. Flux ratio composite for 21 clear and calm days during the study period from 12 June to 23 September, 2002, at the goods station in Osnabrück based on 30 min averages

basis. However, Bo values can be as large as $Bo = 10$ to 11. Note that due to large scatter because of small vertical humidity gradients nocturnal Bo are not plotted in Fig. 6.

After Q^* becomes negative in the evening ($Q^* < 0$) Q_H is still positive and directed towards the atmosphere. This is quite common and comparable to other urban surfaces. However, with a time-shift of around 1.5 h after Q^* changes sign, Q_H decreases to values < 0 . Sensible heat is now transported to the ground, resulting in consecutive cooling of the near-surface atmosphere. This is also indicated by a positive flux ratio Q_H/Q^* from around 21:00 h CET onwards (Fig. 7). This behaviour is in contrast to other urban surfaces, which are reported to maintain positive Q_H through the course of the night due to the high surface temperatures of urban areas (Oke 1997, Anandakumar 1999).

Average flux ratios for the 21 clear and calm days are given in Table 1. Although the turbulent heat fluxes Q_H and Q_E account for the conversion of 52% of the incoming energy, the influence of Q_E is small. During the day, Q_H is more than twice as large as Q_E and is the dominant part of the energy budget followed by Q_G , accounting for 20%. The influence of storage of sensible heat Q_{SH} below the measurement height of the sonic anemometer is negligible during both the day and night.

4.4. Energy balance closure

During recent years an increasing number of studies had to conclude that the surface energy balance equation cannot be fully closed, leaving a residual term of around 1 to 45 % or 100 to 250 W m⁻² in absolute numbers (Panin et al. 1998, Wilson et al. 2002). This means that the energy balance components for some reason do not account for all the incoming energy (for detailed discussions on that topic see Foken & Oncley 1995 or Wilson et al. 2002). The magnitude of the residual in the surface energy balance equation at our site is Res/Q* = 0.28 during the day (Res/Q* = 0.61 during the night, but absolute values are small). The overall energy balance closure for the entire study period at Stn EB in Osnabrück as evaluated from the energy balance ratio (EBR, cf. Wilson et al. 2002) is 70 %:

$$\text{EBR} = \frac{\sum(Q_E + Q_H)}{\sum(Q^* - Q_G)} \quad (7)$$

Reasons for the non-closure of the surface energy balance equation at this site will be briefly discussed in the next section.

5. DISCUSSION

5.1. Surface energy balance

Due to the methodological constraints of urban flux measurements in general regarding limited fetch, complex vertical structure of the urban atmosphere and heterogeneity of the measurement site, energy balance studies of specific urban facets are rare. Apart from the urban facet energy balance studies of Asaeda et al. (1996) and Anandakumar (1999) dealing with pavement and asphalt, respectively, our results can only roughly be compared to local-scale urban energy balance studies. However, it is evident that Q_H is the

dominant term at all urban sites, ranging from 0.35 < Q_H/Q* < 0.48, while Q_E is generally of minor importance in a range of 0.04 < Q_E/Q* < 0.25 (Table 2). Urban Q_E estimates have been shown to be very sensitive to the fraction of green within the flux footprint as well as to irrigation processes (Grimmond & Oke 1995, Christen & Vogt 2004). The comparison of Q_G to other studies is difficult since it is mostly calculated as the residual of the surface energy balance equation with the problem of accumulating measurement errors in that term. Local-scale urban Q_G estimates range from 0.28 < Q_G/Q* < 0.58 (Table 2) and they are comparable to the magnitudes of asphalt and pavement sites given with Q_G/Q* ≈ 0.5 (Asaeda et al. 1996, Anandakumar 1999). With a value of Q_G/Q* = 0.2 the ballast bulk seems to be a smaller sink for heat on average, although comparison is difficult due to residual calculation as mentioned above.

Based on the results presented the ballast energy balance characteristics are similar to other urban sites and facets during the day (cf. Table 1), but during the night this behaviour changes. Most urban surfaces release the heat that was stored in the building mass during the daytime into the atmosphere. As a result, upward directed Q_H can be observed overnight (urban heat island effect). In contrast, the ballast surface can cool significantly during the course of the night due to its thermal properties (cf. Section 4.1). From around 21:00 h CET the ballast is characterised by negative values of Q_H and subsequent cooling of the near-surface air layer. In terms of its thermal behaviour the ballast can be considered a typical urban surface type during the day but as an untypical one ('rural-like') during the night.

The effect of the ballast energy balance on the urban climate can to some extent be demonstrated by near-surface air temperature measurements which were performed at 2 m a.g.l. at Stn EB and in the urban centre of Osnabrück (UB, Fig. 1) in the summer of 2001 (for details see Weber & Kuttler 2004). During clear and calm nights near-surface air masses with average velocities of around 1 m s⁻¹ were typically directed westwards into the direction of UB as was demonstrated by tracer dispersion experiments (Weber & Kuttler 2004) and a numerical cold-air model (Weber 2004). Due to cooling of the near-surface air layers above the ballast facet, a horizontal air temperature difference of on average 0.8 K (maximum = 3 K) at 2 m a.g.l. existed between UB and Stn EB. Despite the relatively small area of the ballast facet (cf. Section 3.1) a somewhat positive

Table 2. Average flux ratios from different urban sites. Averaging interval is daytime Q* > 0 for all sites

Site	Q _H /Q*	Q _E /Q*	Q _G ^a /Q*	Bo	Source
Mexico City	0.38	0.04	0.58	8.8	Oke et al. (1999)
Basel	0.48	0.18	0.38	2.62	Christen & Vogt (2004)
Barcelona	0.34	0.09	0.56	7.1	Jauregui et al. (2002)
Tucson	0.47	0.25	0.28	1.83	Grimmond & Oke (1995)
Los Angeles	0.35	0.25	0.40	1.4	

^aIn the urban context this term is normally referred to as heat storage ΔQS. This term accounts not only for heat flux into the ground but incorporates heat storage in the air volume between the measurement height and the surface

effect of the ballast facet on the urban climate of Osnabrück by cooling near-surface air masses is evident.

5.2. Energy balance closure

In spite of the complexity of the urban flux methodology, measurements were conducted at the GS in Osnabrück. Due to the absence of large roughness elements and sufficient fetch to all wind directions near the surface, energy balance measurements at 2 m a.g.l. were achieved with a good degree of accuracy (cf. Section 3.3).

However, a surface energy balance non-closure of 30% was reported (Section 4.4). This is in the same order of magnitude as is visible in other studies. Even campaigns conducted over homogeneous and flat terrain using a variety of state-of-the-art equipment reported closure gaps of 20 to 35% (Foken 2003). In consideration of enhanced measurement accuracy, reasons for the non-closure of the energy balance are increasingly attributed to methodological uncertainties. We believe a mixture of reasons might be true for the explanation of the closure gap at our site. Since the residual of the surface energy balance equation shows a marked diurnal course a sort of systematic underestimation of energy conversion into one of the 3 fluxes seems likely. However, all terms were checked to have been measured accurately and no source of error became evident. During the night, cold air flows were observed in the GS area (Weber & Kuttler 2004), which may account for non-stationary data during the measurement intervals. However, nocturnal fluxes are of small absolute value so that resulting flux errors are small. Finally, similar sources for the closure gap, as previously discussed by other authors, seem to be likely for the present measurements: heterogeneity of the site, different footprints of the fluxes, measurement errors and possible non-turbulent horizontal advection (e.g. Foken & Wichura 1996, Grünhage et al. 2000, Massman & Lee 2002). Testing for all of these reasons would have resulted in far more methodological demands and were beyond the scope of the somewhat more applied approach of this research.

6. CONCLUDING REMARKS

During a 3 month study period, turbulent and ground heat fluxes were measured at an inner urban ballast facet. The surface can be characterised as typically urban with high surface temperatures during the day and the dominant part of incoming energy converted into heating the near-surface atmosphere. The

flux estimates are comparable to other urban facets as well as to urban flux estimates on a local scale. During night, however, the thermal behaviour is untypical for an urban surface. With negative sensible heat fluxes and significant near-surface cooling the ballast is among the coolest urban surfaces at sunrise. In terms of nocturnal thermal behaviour the ballast is referred to as a 'rural-like' surface type.

Flux measurements at complex sites may involve difficulties in methodology and interpretation but the present study has shown that they can also produce good quality data which helps to better understand microclimatic variations of different surface types. Finally, our findings support the statement of Arnfield (2003) that it is important to know more about the energy budget of specific and different urban facets in order to enhance the understanding of urban climatic phenomena in general.

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