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Multi-scale sensible heat fluxes in the suburban environment from large aperture scintillometry and eddy covariance

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Abstract

Sensible heat fluxes (Q_H) are determined using scintillometry and eddy covariance over a suburban area. Two large aperture scintillometers provide spatially integrated fluxes across path lengths of 2.8 km and 5.5 km over Swindon, UK. The shorter scintillometer path spans newly built residential areas and has an approximate source area of 2-4 km², whilst the long path extends from the rural outskirts to the town centre and has a source area of around 5-10 km². These large-scale heat fluxes are compared with local-scale eddy covariance measurements. Clear seasonal trends are revealed by the long duration of this dataset and variability in monthly Q_H is related to the meteorological conditions. At shorter time scales the response of Q_H to solar radiation often gives rise to close agreement between the measurements, but during times of rapidly changing cloud cover spatial differences in the net radiation (Q^*) coincide with greater differences between heat fluxes. For clear days Q_H lags Q^* , thus the ratio of Q_H to Q^* increases throughout the day. In summer the observed energy partitioning is related to the vegetation fraction through use of a footprint model. The results demonstrate the value of scintillometry for integrating surface heterogeneity and offer improved understanding of the influence of anthropogenic materials on surface-atmosphere interactions.

Keywords

Energy balance; Large aperture scintillometer; Seasonality; Sensible heat flux; Urban

1. Introduction

Understanding the interactions between the land surface and the atmosphere is central to developing our predictive power in terms of weather forecasting, air quality events, thermal comfort, flood risk and tools for urban design. The surface energy balance has been closely linked to land use and land cover, from studies both within and between cities. This has been achieved largely

33 through eddy covariance (EC) measurements at multiple sites in a city (e.g. in Los Angeles
34 (Grimmond et al. 1996), Basel (Christen and Vogt 2004), Łódź (Offerle et al. 2006), Melbourne
35 (Coutts et al. 2007), Montreal (Bergeron and Strachan 2010), Dublin (Keogh et al. 2012), Essen
36 (Weber and Kordowski 2010), Oberhausen (Goldbach and Kuttler 2013) and Helsinki (Nordbo et al.
37 2013)); and through comparison of measurements from different cities (e.g. Grimmond and Oke
38 (1995; 2002)). Also, studies at individual sites have combined footprint models and land cover maps
39 to capture differences in the surface cover sampled as the source area of the EC measurement
40 changes with atmospheric conditions (Vesala et al. 2008; Järvi et al. 2012; Goldbach and Kuttler
41 2013). The derived relations between surface cover and fluxes offer valuable indications of the
42 underlying processes and form a basis for modelling turbulent fluxes (Grimmond and Oke 2002; Järvi
43 et al. 2011; Loridan and Grimmond 2012).

44 Scintillometry provides a means to estimate fluxes at a much larger scale than eddy covariance,
45 typically of the order of several km² (Hoedjes et al. 2007; Guyot et al. 2009; Kleissl et al. 2009a).
46 Path-averaging along the electromagnetic beam of the scintillometer means that measurements are
47 inherently spatially integrated, offering a particular advantage over heterogeneous surfaces (Beyrich
48 et al. 2002; Meijninger et al. 2002b; Evans 2009; Samain et al. 2011a). Despite the complexity of the
49 urban surface, patches of impervious land cover (roads, car parks, paved areas) adjacent to green
50 spaces (parks, gardens) are not very different to the juxtaposition of fields containing differently
51 ripening and senescing crops in mixed agricultural landscapes. In such studies, measuring sufficiently
52 high above the surface ensures the influences of surface heterogeneity are well-blended at the
53 height of the measurement and reliable fluxes can be obtained (Meijninger et al. 2002b; Ezzahar et
54 al. 2007). In addition to the increased spatial representativeness of such large-area measurements,
55 their increased scale facilitates comparison with satellite remote sensing products or land-surface
56 models. A key conclusion of the work by Chehbouni et al. (2000a) was that model development
57 should focus on establishing relations to replicate observations made at the large-scale. Studies
58 comparing model output with scintillometry data include the work of Cheinet et al. (2011), Samain
59 et al. (2011b), Steeneveld et al. (2011) and Maronga et al. (2013).

60 The use of scintillometers in urban environments can be divided into two groups: (a) studies
61 involving small aperture instruments, usually deployed within or near the top of the roughness sub-
62 layer on path lengths of the order of 100 m, e.g. in Tokyo (Kanda et al. 2002), Basel (Roth et al. 2006)
63 and London (Pauscher 2010); and (b) studies over much longer path lengths (500 m - 10 km) using
64 large aperture scintillometers. This study uses large aperture scintillometry. The much larger
65 sampling volume enables robust retrieval of turbulence statistics and the measurement sensitivity is

66 greatest near the centre of the path, away from the instruments and their mounting structures, such
67 that the influence of locally-produced turbulence around these structures has minimal impact on the
68 measurements. Furthermore, direct access to the measurement area is not required – an
69 electromagnetic beam is simply transmitted high above the surface – unlike point measurements
70 requiring *in situ* mounting. This remote sensing capability makes the scintillometry technique
71 particularly valuable in the urban environment.

72 There are an increasing number of studies using large aperture scintillometry in urban areas.
73 Lagouarde et al. (2006) present results from a three week trial in summer 2001 in which two large
74 aperture scintillometers were used over Marseille. Other studies include work in London (Gouvea
75 and Grimmond 2010), Nantes (Mestayer et al. 2011), Łódź (Zieliński et al. 2012) and Helsinki (Wood
76 and Järvi 2012).

77 To date, the use of large aperture scintillometry in urban areas has been to derive the sensible
78 heat flux. In order to directly estimate the latent heat flux, a second scintillometer of longer
79 wavelength is required (Hill et al. 1988; Andreas 1989), however these are not yet commercially
80 available. Hence there are only a handful of two-wavelength studies documented (Kohsiek and
81 Herben 1983; Green et al. 2001; Meijninger et al. 2002a; Meijninger et al. 2006; Evans 2009). A
82 millimetre-wave scintillometer was installed alongside one of the infrared scintillometers used in this
83 study. These first two-wavelength results from the urban environment are presented in two
84 companion papers (Ward et al. in preparation a,b).

85 The goal of the work presented here is to investigate the influence of the surface on sensible
86 heat fluxes across different spatial and temporal scales in the suburban environment. Eddy
87 covariance measurements are analysed together with results from large aperture scintillometers
88 installed on 2.8 km and 5.5 km paths in Swindon, UK. The two year study period enables analysis of
89 seasonal and inter-annual patterns (Sect. 3.1) as well as the short-term response of heat fluxes to
90 solar radiation (Sect. 3.2). Consideration is given to the experimental uncertainties, including the
91 representativeness of point measurements required as inputs for scintillometry algorithms (Sect.
92 2.3) and the observational challenges associated with urban environments. The contributions of
93 different land cover classes are related to the observations at each scale by applying a footprint
94 model (Sect. 3.3).

95 2. Methodology

96 2.1. Derivation of the sensible heat flux from single-wavelength scintillometry

97 Scintillometers measure the intensity of an electromagnetic beam after propagation through the
98 turbulent atmosphere. Changes in beam intensity are related to the strength of turbulence and can
99 be converted to the structure parameter of the refractive index of air (C_n^2). First, these refractive
100 index fluctuations must be related to temperature fluctuations,

$$101 \quad C_T^2 \approx \frac{T^2}{A_T^2} C_n^2, \quad (1)$$

102 where C_T^2 is the temperature structure parameter and A_T is the structure parameter coefficient
103 which depends on temperature (T), pressure (p) and weakly on humidity (Hill et al. 1980; Andreas
104 1988; Ward et al. 2013b). The Bowen ratio (β) correction given by Wesely (1976) (see Moene (2003)
105 for full details and a discussion) is not implemented in Equation 1 because β is not known *a priori*.
106 The effect of this is discussed in Sect. 2.3.

107 The conversion from structure parameters to fluxes entails iteration of similarity functions, $f_{MO}(\zeta)$,
108 using Monin-Obukhov similarity theory (MOST) and the effective height of the scintillometer, z_{ef} , the
109 wind speed, U (which is measured at height z_U), displacement height, z_d , and aerodynamic
110 roughness length, z_o . Commonly used forms of the similarity functions are

$$111 \quad f_{MO}(\zeta) = c_{T1}(1 - c_{T2}\zeta)^{-2/3} \quad (2)$$

112 for unstable conditions and

$$113 \quad f_{MO}(\zeta) = c_{T1}(1 - c_{T3}\zeta^{2/3}) \quad (3)$$

114 for stable conditions. The stability variable ζ is given by $(z_m - z_d)/L_{Ob}$, where L_{Ob} is the Obukhov length
115 and z_m the measurement height, or z_{ef}/L_{Ob} when z_{ef} has been calculated incorporating the
116 displacement height (Hartogensis et al. 2003). Different values of the empirically derived constants
117 c_{T1-3} are used in the literature (Andreas 1988; Hill et al. 1992), and alternative functional forms
118 appear, e.g. Thiermann and Grassl (1992). The Wyngaard (1973) values were adjusted by Andreas
119 (1988) to give $c_{T1} = 4.9$, $c_{T2} = 6.1$ and $c_{T3} = 2.2$ (hereafter An88). De Bruin et al. (1993) found $c_{T1} = 4.9$,
120 $c_{T2} = 9$ and $c_{T3} = 0$ (hereafter DB93). These similarity functions relate the temperature structure
121 parameter to the temperature scaling variable (T_*),

122
$$T_* = \left\{ \frac{C_T^2 (z_m - z_d)^{2/3}}{f_{MO}(\zeta)} \right\}^{1/2}. \quad (4)$$

123 The friction velocity, u_* , is estimated from measured wind speed assuming a logarithmic wind profile
 124 adjusted for stability and a value for the roughness length (e.g. Stull (1988)). The wind profile
 125 equation is solved iteratively with

126
$$L_{Ob} = \frac{u_*^2 T}{g \kappa_v T_*}, \quad (5)$$

127 where g is the acceleration due to gravity and κ_v is the von Kármán constant (0.4). Note that this
 128 equation for L_{Ob} neglects the buoyancy correction. Finally, the sensible heat flux is obtained using

129
$$Q_H = -\rho c_p u_* T_*, \quad (6)$$

130 where ρ is the density of air and c_p the specific heat capacity at constant pressure. In the following,
 131 Q_{H_BLS} and Q_{H_LAS} are used to denote the sensible heat flux for the 5.5 km path and 2.8 km path,
 132 respectively (Sect. 2.2). The sensible heat flux from the EC station is denoted Q_{H_EC} .

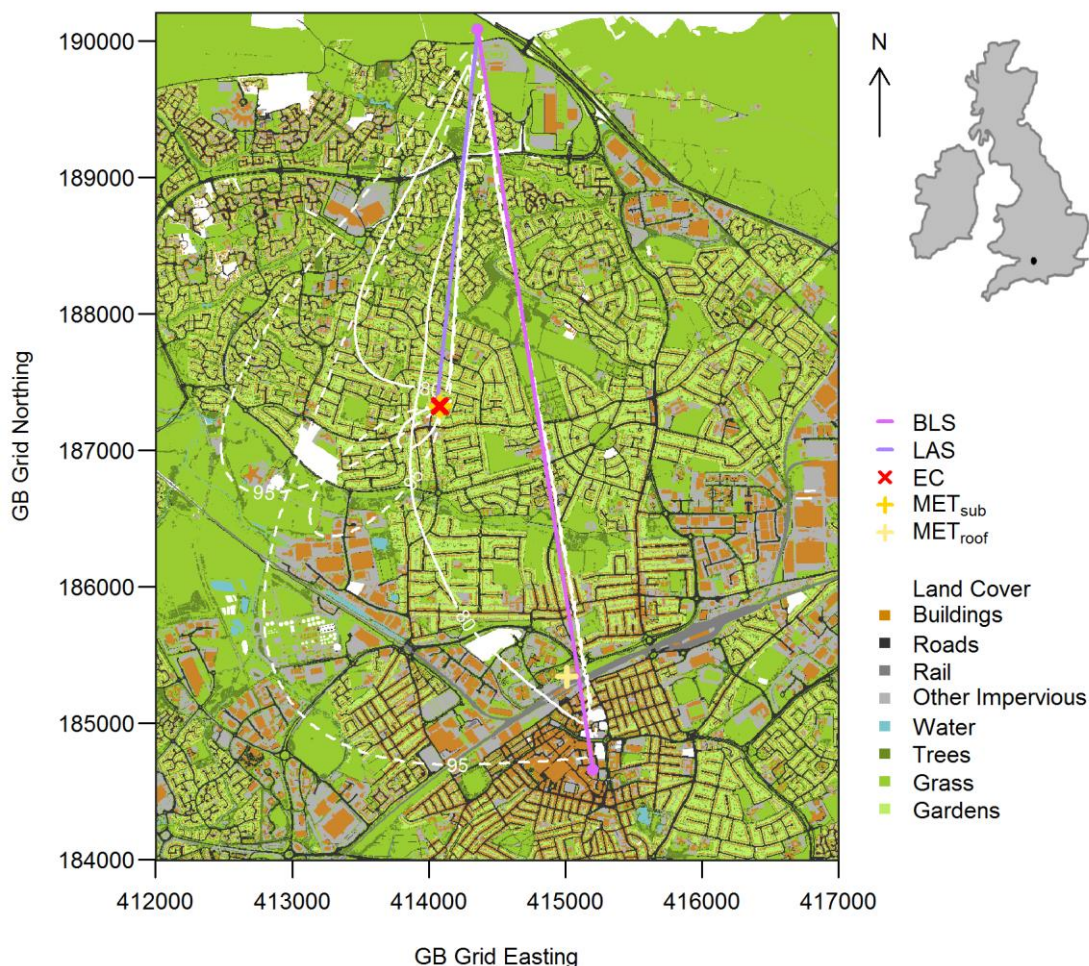
133 One drawback of scintillometry is that the sign of the heat flux is unknown and must be assigned
 134 based on other information. Following a comparison of possible algorithms, Samain et al. (2012)
 135 recommended using an algorithm based on the minima in the diurnal cycle of C_n^2 to indicate a
 136 transition of stability. We follow a similar methodology here, which has the key advantage that it is
 137 based on path-averaged information.

138 2.2. Site description and experimental details

139 This study took place in Swindon (population 175 000), situated 120 km west of London (top
 140 right, Fig. 1). Typical of the UK suburban landscape, Swindon consists mainly of residential areas with
 141 houses of varying ages extending outwards from the town centre, interspersed with greenspace,
 142 small parades of shops and institutional buildings. Larger industrial and commercial zones are mostly
 143 situated towards the edges of the development. The town centre comprises commercial areas, with
 144 some pedestrianized streets, offices, public buildings and transport hubs. Building density in the
 145 town centre is greater than in the surrounding suburbs and buildings are taller, larger and more
 146 variable in height. Outside of the urban core the buildings are more uniform, houses are mostly 1-3
 147 storeys, semi-detached or terraced and usually have at least a small garden. There are a few small
 148 blocks of flats (4-5 storeys) and larger warehouses in industrial areas. Trees are of a similar height to
 149 the buildings and found mostly in undeveloped green corridors between residential areas, along

150 roadsides and in gardens. The area is relatively well vegetated (cover fraction 53%), largely due to
 151 the prevalence of grassed areas: parks, playing fields, green corridors, gardens, verges and a large
 152 nature reserve near the centre of the study area (Fig. 1).

153



154

155 **Fig. 1** Land cover surrounding the two scintillometer paths (BLS and LAS), eddy covariance station (EC) and two
 156 meteorological stations (MET_{sub} and MET_{roof}). Example footprints for typical atmospheric conditions (wind direction = 225°,
 157 $L_{Ob} = -200$ m, $u_* = 0.5$ m s⁻¹ and $\sigma_v = 0.9$ m s⁻¹) are indicated by the cumulative source area: the region within the solid
 158 (dashed) line contributes 80% (95%) to the measured flux. The location of Swindon within the British Isles is shown (top
 159 right). Details of the land cover classification are given in the text. Where land cover data were unavailable areas are left
 160 unclassified (white).

161

162 Observations at multiple scales are achieved through a combination of the eddy covariance
 163 technique and two scintillometer paths. The largest measurement scale reaches between the town
 164 centre and the rural fringe at the northern edge of the settlement: an infrared scintillometer, the

165 BLS900 (Scintec, Rottenburg, Germany), was installed on a 5.5 km path orientated approximately
166 north-south. A second infrared scintillometer, a LAS 150 (Kipp and Zonen, Delft, The Netherlands),
167 was aligned on a shorter path of length 2.8 km. This path is located over relatively recently
168 developed suburbs (in the last 20 years or so) 3-5 km north of the town centre. Both are large
169 aperture scintillometers operating at a wavelength of 880 nm. Although LAS is an abbreviation for
170 large aperture scintillometer, in this study BLS is used to denote the scintillometer on the long path
171 and LAS the scintillometer on the short path. The EC system was installed approximately 3 km north
172 of the town centre, close to the middle of the long path.

173 Footprint models can be used to aid the interpretation of observed fluxes by relating them to the
174 probable area of the surface that influenced the measurements. Although some of the assumptions
175 may be challenged by complex environments, footprint models have been used successfully in urban
176 areas (Schmid et al. 1991; Järvi et al. 2009; Hiller et al. 2011), providing measurements are made at
177 sufficient height that the influences of individual obstacles or heterogeneities are averaged out.
178 Meijninger et al. (2002b) extended footprint theory to scintillometers by combining source areas
179 calculated for a single point measurement with the scintillometer path weighting function. This has
180 since been adopted by other studies (Meijninger et al. 2006; Hoedjes et al. 2007; Samain et al.
181 2011a; Evans et al. 2012; Liu et al. 2013). A range of footprint models exist; here we use the
182 analytical model of Hsieh et al. (2000) and assume the lateral dispersion is Gaussian (Schmid 1994;
183 Detto et al. 2006).

184 Results of the footprint model for each of the three systems are shown in Fig. 1 for typical
185 atmospheric conditions (wind direction = 225°, $L_{Ob} = -200$ m, $u_* = 0.5$ m s⁻¹ and standard deviation of
186 lateral wind $\sigma_v = 0.9$ m s⁻¹). Source areas vary depending on atmospheric conditions and wind
187 direction, as well as measurement height and surface roughness. The difference in measurement
188 scales is apparent. The sizes of the areas contributing 80% (95%) of the observed fluxes are
189 approximately 0.06, 1.0 and 3.0 km² (0.5, 3.0 and 7.5 km²) for the EC, LAS and BLS, respectively. The
190 size of the footprints increases with stability.

191 Beam heights, land cover and building and tree height were obtained using a spatial database
192 incorporating surface cover information (OS MasterMap 2010 ©Crown Copyright), a digital terrain
193 model and digital surface model from lidar (2007, ©Infoterra Ltd) and aerial photography (2009,
194 ©GeoPerspectives). For this study a spatial resolution of 5 m was used, further details are given in
195 Ward et al. (2013a). Some of the residential area at the far north-west of the study area has very
196 recently been completed, with some ongoing development of the rural outskirts during the study
197 period. The overall effect here may be a small overestimation of the vegetated land cover fraction

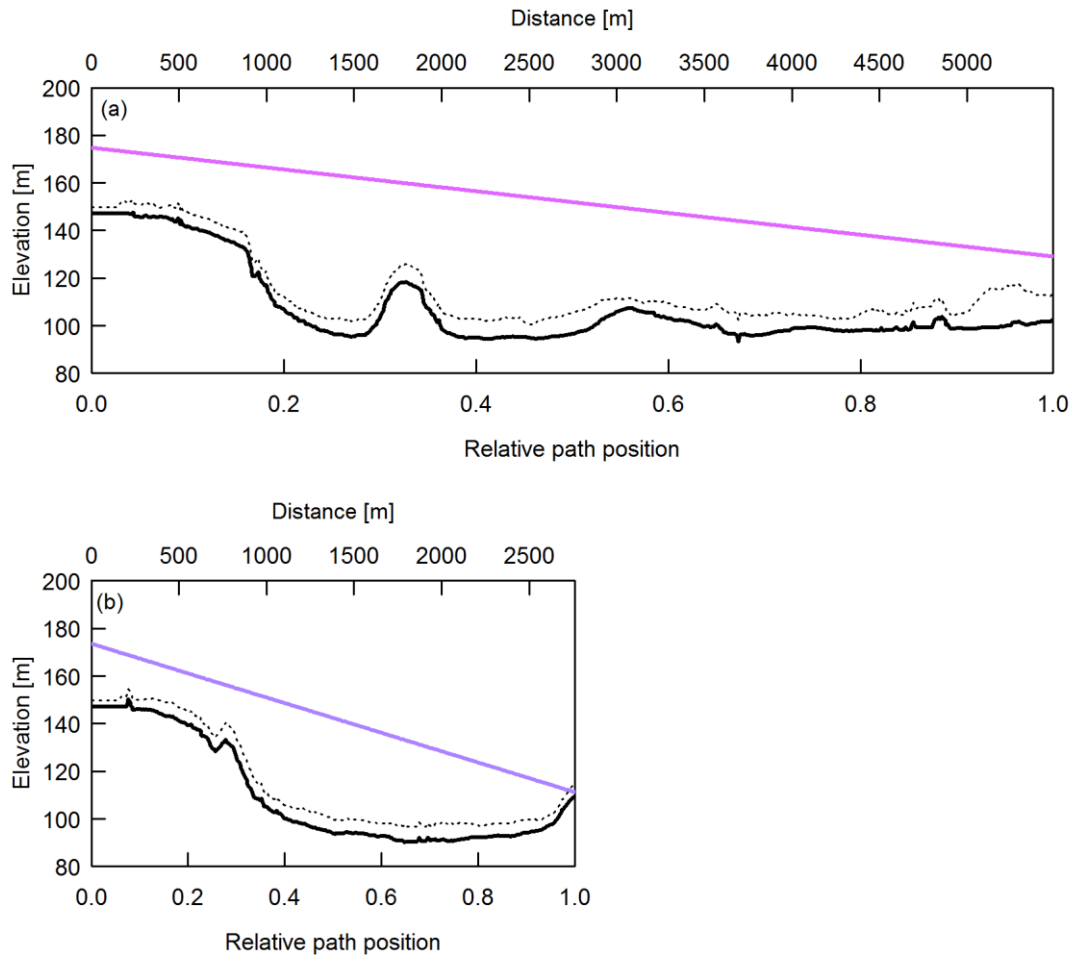
198 for the LAS path, when winds are from the west or north-west and in stable conditions, as this recent
199 development has not yet been incorporated in the spatial database.

200 The roughness length for momentum was estimated based on the mean height of the roughness
201 elements (z_H) within the area influencing the measurements using the approximation $z_0 = 0.1z_H$
202 (Garratt 1992). The resulting values (Table 1) are reasonable based on comparison with the
203 literature (Grimmond and Oke 1999), however there is appreciable uncertainty associated with this
204 (and other) methods (Sect. 3.1). The zero plane displacement height, $z_{d,0}$, is estimated at $0.7z_H$ and
205 incorporated into the effective height calculation for the scintillometers, after Hartogensis et al.
206 (2003) (their equation 15).

207 Both infrared scintillometer transmitters were installed on a telecommunications mast at the
208 northern edge of the suburbs at 27.9 m (BLS) and 26.6 m (LAS) above ground level. The LAS receiver
209 was bolted to a 1.7 m high post at the same property as the EC mast, whilst the BLS receiver was
210 mounted on a building in the town centre at 26.2 m. The combination of the topography (Fig. 2),
211 mounting on existing structures and the path weighting provides sufficient beam height for the
212 scintillometers to be above the blending height (which is estimated to be between 15 and 30 m
213 (Pasquill 1974; Garratt 1978)). The blending height will be larger above landscapes with larger scale
214 heterogeneity (e.g. Wood and Mason (1991)), or may not exist at all once the scale of heterogeneity
215 exceeds the boundary layer height (Maronga and Raasch 2013). With these limitations in mind, the
216 Swindon sites were selected such that the patches of different land cover within the footprints are,
217 for the most part, reasonably small (100 - 300 m or less).

Instrumentation	Dates	Location	z_m [m]	z_{ef} [m]	Path length [m]	Bearing [°]	z_0 [m]	z_d [m]
BLS	12 Jan 2011 –	51°36'33.9" N	44.3	45.0	5492	170	0.7	4.9
	31 Dec 2012	1°47'38.6" W (Tx) 51°33'38.1" N 1°46'55.3" W (Rx)						
LAS	22 Jun 2011 –	51°36'33.9" N	32.4	35.9	2761	184	0.6	4.5
	31 Dec 2012	1°47'38.6" W (Tx) 51°35'4.9" N 1°47'53.0" W (Rx)						
EC	09 May 2011 –	51°35'4.6" N	12.5	-	-	-	0.5	3.5
	31 Dec 2012	1°47'53.2" W						
MET _{sub}	09 May 2011 –	51°35'4.6" N	10.6 (WXT)	-	-	-	0.5	3.5
	31 Dec 2012	1°47'53.2" W	10.1 (NR01)					
MET _{roof} *	01 Jan 2011 –	51°34'0.3" N	2.0 (WXT)	-	-	-	-	-
	31 Dec 2012	1°47'5.3" W	1.1 (NR01)					

218 **Table 1** Details of the instrumental setup. Tx denotes transmitter, Rx receiver. For the scintillometers the mean heights of
219 the beams above the surface (z_m) and the effective measurement heights (z_{ef}) are given. The date range refers to the data
220 used here. *For MET_{roof} the heights above the roof surface are given; z_0 and z_d were not calculated for this site.



221

222 **Fig. 2** Cross section of the topography (solid black line) and mean obstacle height (dotted line; buildings and trees within a
 223 radius of 100 m) along the (a) BLS and (b) LAS paths (coloured lines).

224

225 A CR5000 datalogger (Campbell Scientific Ltd., Loughborough, UK) sampled the intensity of the
 226 received LAS beam at 500 Hz and measured the C_n^2 signal (calculated onboard the instrument and
 227 stored as a logarithm) every second which was then output at 1 min intervals and these were
 228 averaged to 10 min. For the BLS, the mean and standard deviation of the beam intensity of each disk
 229 (the BLS900 is a dual disk instrument with two transmitting apertures) were obtained from the
 230 supplied signal processing unit at 30 s intervals, then converted to log-amplitude variances and C_n^2
 231 and averaged up to 10 min. Data from a single disk are presented here.

232 The EC system consists of a sonic anemometer (R3, Gill Instruments Ltd., Lymington, UK) and an
 233 open-path infrared gas analyser (LI-7500, LI-COR Biosciences, Lincoln, USA) at a height of 12.5 m. As
 234 this is 2-3 times the height of the surrounding buildings and trees, it is therefore sufficiently high to
 235 deliver fluxes representative of the local-scale. Data were processed using EddyPro (LI-COR)

236 following conventional procedures. Further details of the EC measurements can be found in Ward et
237 al. (2013a).

238 Meteorological instruments were installed on the same mast as the EC equipment (denoted
239 MET_{sub}). A second set of meteorological data were collected at a rooftop site close to the town
240 centre (MET_{roof}). Both stations included a four-component radiometer (NR01, Hukseflux, Delft, The
241 Netherlands), automatic weather station (WXT510, Vaisala, Helsinki, Finland) and tipping bucket rain
242 gauge (0.2 mm tip, Casella CEL, Bedford, UK). At MET_{sub}, the radiometer was installed at a height of
243 10.1 m so that the downward-facing field of view comprises a mixture of surfaces: grass lawns and
244 verges, road, pavement, hedges and small trees, bare soil, gravel, roofs of garages, small sheds and
245 single-storey extensions and walls (brick and painted). At MET_{roof}, the radiometer was installed at 1.1
246 m above the roof surface made of grey synthetic material and black rubber matting. Additionally at
247 MET_{roof}, a heat flux plate (HFP01, Hukseflux) was installed between the roof surface and rubber
248 sheet, providing an approximation of the change in storage through the roof. At both sites the
249 meteorological data were logged at 1 min intervals (CR1000, Campbell Scientific Ltd.) and
250 subsequently averaged to obtain 10 min resolution for calculation of the scintillometer fluxes or 30
251 min for comparison with EC fluxes. The 10 min scintillometer fluxes were also averaged to 30 min for
252 comparison with EC results. Details of the observational setup are summarized in Table 1.

253 To provide nearly continuous auxiliary data required for scintillometry processing, results from
254 the two meteorological stations were combined. When available, data from MET_{sub} are used as the
255 siting of this station is more appropriate. Based on the regression of concurrent data (9 May 2011 -
256 31 Dec 2012), temperature, relative humidity (RH), pressure and wind speed at MET_{roof} were
257 adjusted to gap-fill the combined dataset, including the period prior to installation of MET_{sub} on 9th
258 May 2011. This is considered further in Sect. 2.3.

259 All data were subject to quality control routines. Data were removed at times of known
260 instrument malfunction. Meteorological data were excluded when they (or their standard
261 deviations) fell outside physically reasonable thresholds. Quality control of the scintillometry data
262 included rejecting times when the received signal intensity dropped below half of the value in clear
263 conditions, which usually indicated rain or fog. Data points neighbouring those that failed the
264 intensity check were also removed. Out of the total data collected, 84% of BLS and 82% of LAS data
265 (10 min) remained for analysis.

266 Both scintillometers were corrected for the effects of saturation using the modulation transfer
267 function of Clifford et al. (1974). Using the threshold value suggested by Kleissl et al. (2010), 16% of

268 the BLS data and 0.2% of the LAS data might be expected to suffer from saturation. Overall, the
269 correction increased C_n^2 by 4% and 1% for the BLS and LAS respectively (naturally the corrections are
270 larger with increased scintillation and rise to 8% and 2% for the midday periods).

271 Recent studies have indicated sometimes severe discrepancies between certain scintillometers,
272 in particular the LAS 150 model (Kleissl et al. 2008), whereas the BLS900 model tends to give more
273 reproducible results (Kleissl et al. 2009b). Prior to deployment in Swindon, the LAS and BLS were run
274 alongside each other at a fairly homogenous grass test site at Chilbolton Observatory, Hampshire,
275 UK (17 April 2010 – 25 May 2010). Observed C_n^2 ranged between $10^{-16} \text{ m}^{-2/3}$ and $10^{-12} \text{ m}^{-2/3}$, which
276 spans the range of values observed for the Swindon paths. Results suggested the response of the
277 LAS is reasonable but compared to the BLS C_n^2 is overestimated by 9.8%. This adjustment has been
278 applied to the LAS C_n^2 for the Swindon data. As a result of these comparisons (e.g. Kleissl et al.
279 (2008; 2009b), Van Kesteren and Hartogensis (2011)), Kipp and Zonen have updated their original
280 LAS 150 instrument to a LAS MkII model (Mustchin et al. 2013).

281 **2.3. Assessment of the input meteorological data**

282 First, the suitability of the combined meteorological input data used to process the scintillometry
283 fluxes is considered. To calculate Q_H from single-wavelength scintillometry, air temperature,
284 pressure and humidity are required to first obtain the structure parameter of temperature, C_T^2 . Both
285 T and RH are similar between the MET_{sub} and unadjusted MET_{roof} sites. The regression slopes are
286 within 3% and there is high correlation ($r^2 > 0.98$). Sensitivity of Q_H to these input meteorological
287 variables is small (Hartogensis et al. 2003) and indeed these very small differences have minimal
288 impact on the fluxes. The average difference in Q_H is $< 0.5\%$ when calculated using T , RH and p from
289 each site. Use of this combined dataset is therefore judged unproblematic and to be a sufficiently
290 accurate representation of T , RH and p across the study area.

291 An initial estimate of the Bowen ratio is recommended to account for the contribution of
292 humidity and combined temperature-humidity fluctuations to optical C_n^2 (Wesely 1976). Usually the
293 value of β is arrived at iteratively through incorporation of the available energy (e.g. Meijninger et al.
294 (2002b)). However, estimating the available energy is challenging in urban areas as the net storage
295 heat flux (ΔQ_s) plays a more significant role in the energy balance than for most rural areas (e.g.
296 grassed or agricultural land), yet it is very difficult to measure directly (Offerle et al. 2005; Roberts et
297 al. 2006). Other (rural) studies have used β measured at a nearby station (Hoedjes et al. 2002;
298 Samain et al. 2011a) or have calculated Q_H using a series of values of β (Meijninger and De Bruin
299 2000). When β is expected to be large (e.g. > 0.6 for Chehbouni et al. (2000b); > 1 for Moene (2003))

300 the correction may be neglected. Given the uncertainty in estimating the available energy and the
301 lack of representative EC data across the whole study area, the Bowen ratio correction has not been
302 applied for the results presented here. The potential impact is an average overestimation in Q_H from
303 the scintillometers of less than 5% for $\beta > 1$, and less than 10% for $\beta = 0.5$. For the BLS, the C_T^2 values
304 here were found to be within around 6% of the C_T^2 values calculated incorporating data from the
305 millimetre-wave scintillometer (Sect. 1), which do not require a Bowen ratio correction (see Ward et
306 al. (in preparation b) for details).

307 To process scintillometry data, the friction velocity is usually estimated from wind speed
308 measured at a single point and adjusted to beam height using the logarithmic profile accounting for
309 stability. As with the other meteorological inputs, wind speed from MET_{roof} was adjusted to produce
310 the combined dataset with optimum availability of input data. Concurrent Q_H values calculated using
311 the MET_{sub} wind speed or the adjusted MET_{roof} wind speed differ by less than 3%, r^2 is high (0.98) and
312 there is little scatter (root mean squared error, RMSE < 10 W m⁻²).

313 The dual-disk design of the BLS900 enables estimation of the path-averaged crosswind, i.e. the
314 component of the wind speed perpendicular to the scintillometer path. To check that the point
315 measurements of wind speed were a realistic proxy for the wind field over the scintillometer source
316 area, a comparison was made between the BLS crosswind speed and the equivalent crosswind speed
317 calculated using wind speed and direction from MET_{sub} and scaled to the effective height of the BLS
318 using stability from the EC station. Overall the crosswind estimates displayed similar trends across a
319 range of wind speeds and directions. The high correlation obtained ($r^2 = 0.922$) implies that these
320 point measurements generally capture the variability of the wind field at the larger scale and gives
321 confidence in their use in processing the scintillometry data.

322 **3. Analysis of sensible heat fluxes**

323 **3.1. Assessment of seasonal cycles and annual variations**

324 Large-area sensible heat fluxes from the 5.5 km scintillometer path are presented for two years
325 (2011-12), alongside 18 months of data from the shorter 2.8 km scintillometer path and almost 20
326 months of eddy covariance data (Fig. 3). The annual cycle is evident, with mean daily (24 h) Q_H
327 reaching a maximum in early summer (May-June in 2011, May in 2012) and minimum in December.
328 In December, average Q_H is negative even during daytime (defined as times when incoming
329 shortwave radiation $K_{\downarrow} > 5 \text{ W m}^{-2}$, see Fig. 3b) as the typical diurnal course of Q_H becomes positive
330 only for a few hours around midday (Fig. 4). This behaviour is observed consistently across the three
331 datasets and in both years but contrasts with the majority of urban studies in more built-up areas,

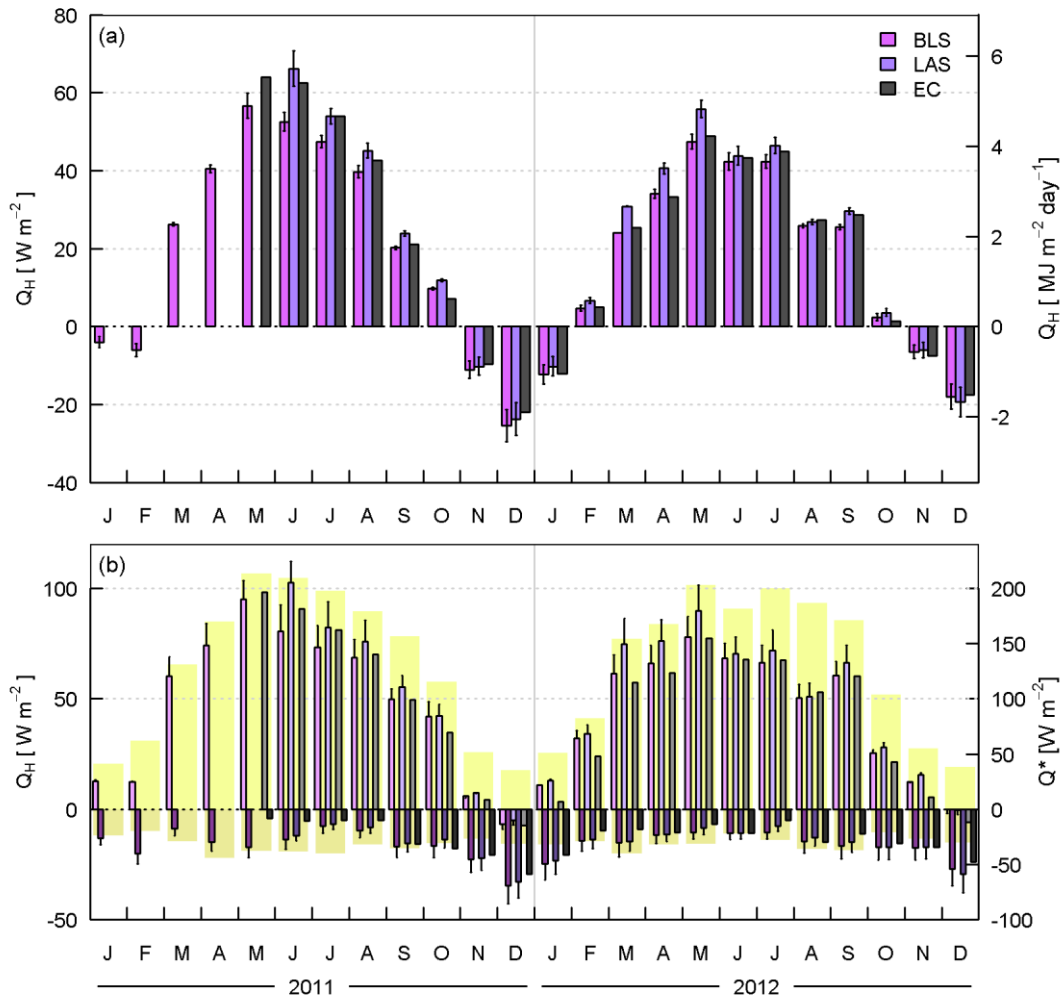
332 where greater heat release from storage and anthropogenic activity can maintain a positive sensible
333 heat flux all year round (Offerle et al. 2005; Kotthaus and Grimmond in press-a). For two sites in
334 Oberhausen, Germany, Goldbach and Kuttler (2013) found Q_H to be positive for most of the daytime
335 throughout the year at their urban site, whereas their suburban site exhibits similar behaviour to
336 Swindon. Besides the smaller storage and anthropogenic heat flux in suburban areas, more of the
337 available energy is partitioned into evaporation, owing to increased moisture availability from soil
338 surfaces and greater total evapotranspiration from a larger vegetation fraction.

339 Within the trends of the expected annual cycle, there are notable differences between the two
340 years studied. Peak Q_H is larger in summer 2011 compared to 2012 and month-to-month variation is
341 smaller in 2011. Broadly speaking, much of 2011 was under threat of drought, with dry soil moisture
342 conditions and depleted ground water supplies. Despite frequent rain and very few clear sky days
343 the annual rainfall total was 530 mm compared to the average 780 mm for southern England¹. Dry
344 conditions continued through early spring 2012, until early April. Very wet weather followed and
345 remained throughout 2012 (total rainfall 1020 mm), with brief drier and warmer spells in late July
346 and early September.

347 June 2012 was particularly wet and cloudy (sunshine hours were only 70% of normal¹; mean
348 daytime K_{\downarrow} was 174 W m^{-2} in 2012 compared to 212 W m^{-2} in 2011). Monthly mean daily Q_H was
349 19%, 34% and 31% lower than in June 2011 for the BLS, LAS and EC, respectively. August 2012 also
350 had a notably lower Q_H during daytime compared to 2011 (also shown in Fig. 4), despite similar
351 radiative energy inputs in both years. A long dry spell and generally sunny weather in September
352 2012 allowed surfaces to dry out and Q_H to increase, resulting in a larger average value than for the
353 previous month. Large negative nocturnal Q_{H_BLS} in February 2011 means the daily (24 h) average is
354 negative, whereas high Q^* and high daytime Q_{H_BLS} in 2012 contribute to a positive 24h average in
355 2012 (Fig. 3).

356

¹ Met Office climate statistics (1971-2000), <http://www.metoffice.gov.uk/climate>, last accessed 29 March 2013

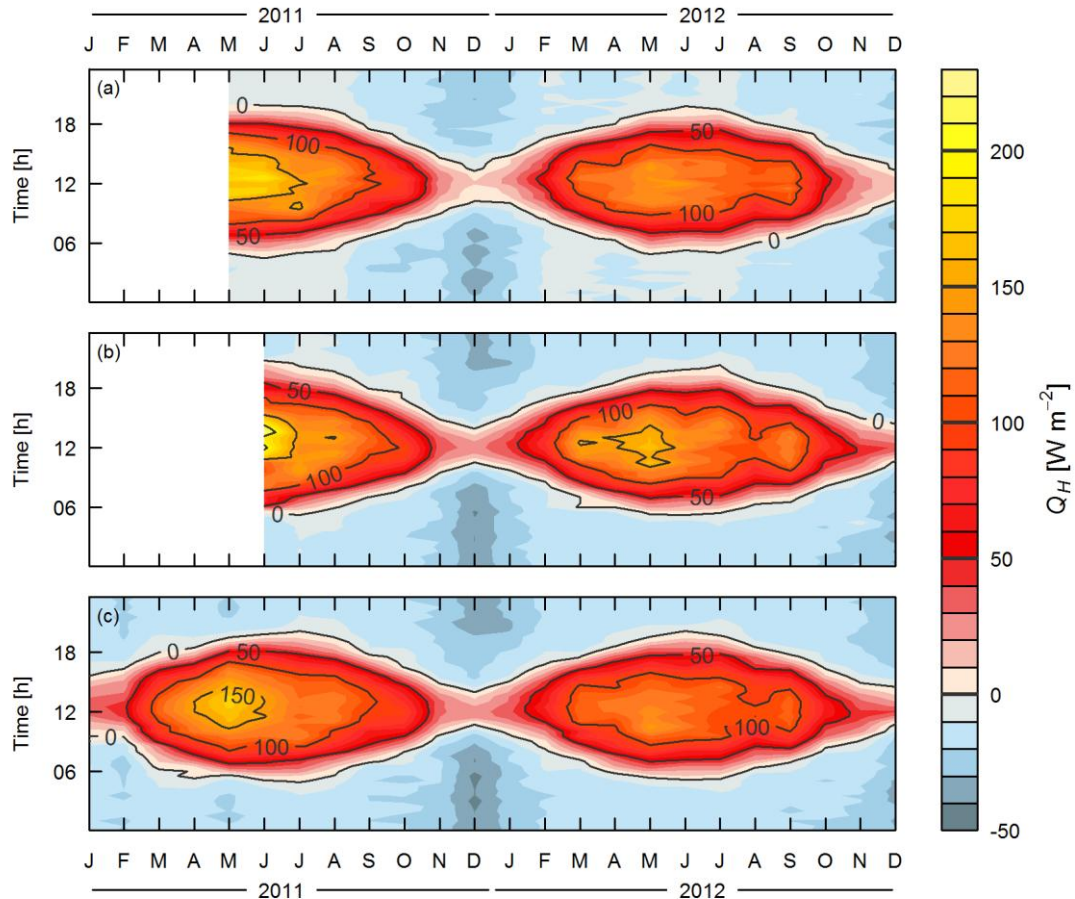


357

358 **Fig. 3** Monthly mean sensible heat flux observations from scintillometry (BLS and LAS) and eddy covariance (EC) for all
 359 available data (a) over 24 h and (b) separated into day ($K_i > 5 \text{ W m}^{-2}$) and night times. Partial months in relation to the
 360 installation dates (Table 1) are January 2011 (BLS), May 2011 (EC) and June 2011 (LAS, note only 4 days of data due to an
 361 instrument fault). Error bars indicate the impact on the scintillometer fluxes of altering the input roughness length by ± 0.2
 362 m (a) or using the similarity functions of De Bruin et al. (1993) (b). The net radiation is indicated by shading (b, right-hand
 363 axis).

364

365



366

367 **Fig. 4** Temporal variation of monthly mean diurnal cycles of sensible heat fluxes from (a) eddy covariance, (b) the LAS and
 368 (c) the BLS.

369

370 Overall there is remarkably good agreement across the three datasets, which capture seasonal
 371 similarities and inter-annual variability. The different source areas of each instrument, and that the
 372 BLS measures across a large proportion of northern Swindon, suggest that these trends are local-to-
 373 city-scale responses to regional weather variability. Furthermore, this agreement implies that any
 374 bias in the monthly averages due to the effect of the wind direction distribution on the
 375 measurement footprints is outweighed by the changes in surface conditions, prevailing weather and
 376 the resulting surface-atmosphere interactions. Given the much smaller source area of the EC
 377 technique compared to scintillometry, it is reasonable to expect that heterogeneity of the surface
 378 has a larger influence on the EC observations than the scintillometry observations (Sect. 3.3).

379 The LAS tends to give the largest Q_H , particularly during daytime, compared to both EC and the
 380 BLS. In summer 2012 the EC and BLS average values do not reach above 150 W m^{-2} , in contrast to
 381 Q_{H_LAS} (Fig. 4). During winter months (November 2011-January 2012) and at night the BLS gives the

382 largest fluxes. Daily average $Q_{H_{EC}}$ often lies between the two scintillometer averages but during
383 winter (November-December 2011, December 2012) and at night the scintillometers tend to give
384 larger magnitude Q_H . This can also be seen in Fig. 4: the absolute size of Q_H from the scintillometers
385 is larger (e.g. around transition times in December), whether positive or negative, whereas EC values
386 are much closer to zero. Larger scintillometer fluxes in neutral-to-stable conditions may reflect the
387 performance of the similarity functions (Sect. 3.2).

388 The widely implemented similarity functions of Andreas (1988) were used here. Using the De
389 Bruin et al. (1993) similarity functions instead increases Q_H by about 13-14% (bars in Fig. 3b). This is
390 similar to results in Marseille (Lagouarde et al. 2006) and within the 10-15% range given by Beyrich
391 et al. (2012). The large uncertainty introduced by the choice of similarity function is a major
392 limitation of the scintillometry technique across all environments; it is not confined to urban sites
393 although there is the added question of whether functions developed over homogeneous terrain
394 should be applied to more heterogeneous locations. Kanda et al. (2002) and Roth et al. (2006) both
395 derived 'urban forms' of the similarity functions for their small aperture scintillometer studies,
396 however their paths were closer to, or within, the roughness sub-layer. Other large aperture studies
397 in urban environments have used the more common functions (Lagouarde et al. 2006; Zieliński et al.
398 2012).

399 Typically, the uncertainty in z_0 is large as z_0 can vary spatially, with time of day and stability
400 (Grimmond et al. 1998; Hoedjes et al. 2007; Zilitinkevich et al. 2008), and with shape, density and
401 arrangement of surface structure (Grimmond and Oke 1999). For the study area, the true value is
402 expected to be within the range 0.4 to 1.0 m based on values in the literature. The impact on the
403 scintillometer estimation of Q_H of changing the prescribed values of z_0 by ± 0.2 m is $\pm 7\%$ (error bars
404 in Fig. 3a). Although the flux is fairly sensitive to the value of z_0 used, the overall trends do not
405 change significantly. No adjustment was made to account for seasonal variation in z_0 (or z_d), though
406 these values may be 10-20% smaller in winter than in summer (Grimmond et al. 1998). Using a
407 smaller value of z_0 during leaf-off periods decreases the wintertime fluxes slightly (the error bars in
408 Fig. 3a represent a change in z_0 of about $\pm 30\%$).

409 Allowing a $\pm 5\%$ uncertainty in z_{ef} (± 2.25 m) affects the fluxes by $\pm 3\%$. This uncertainty in z_{ef}
410 includes measurement accuracy and variation of the effective height with stability as well as
411 accounting for spatial differences in obstacle height (hence z_d) and topography. The large beam
412 height and relatively small displacement height help to keep the sensitivity to z_{ef} (and z_d) small.

413 3.2. Short-term variability

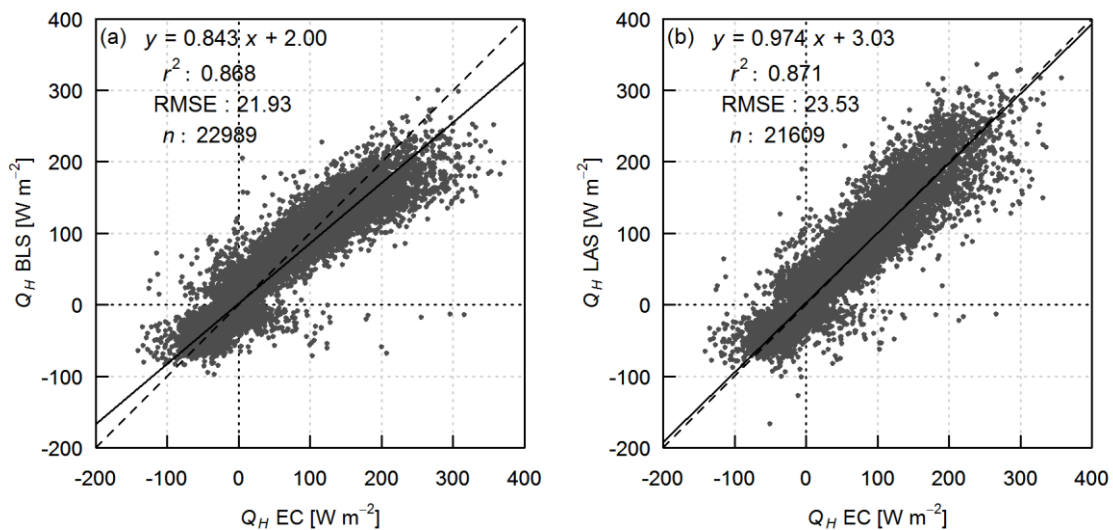
414 Direct comparison of 30 min sensible heat fluxes obtained from scintillometry and EC (Fig. 5)
415 indicates reasonably good agreement between the measurement techniques and across the scales
416 with strong correlation ($r^2 \approx 0.87$). The slope of the regression between Q_{H_LAS} and Q_{H_EC} is close to
417 1, with a small positive offset, whereas the BLS tends to give lower Q_H than EC particularly towards
418 large values of Q_H . Whilst the linear fit between Q_{H_LAS} and Q_{H_EC} indicates a good match between
419 these data, the BLS data distribution appears more curved at high Q_{H_EC} . The source area of the EC
420 mast and BLS are quite different, which may partly explain why the highest EC fluxes are not
421 matched by the BLS. Specifically, the area to the south and south-west of the EC mast has a
422 particularly high proportion of built and impervious surfaces and little vegetation, whilst the BLS
423 source area always includes open green spaces. Thus when the EC footprint is over the least
424 vegetated sector (180-240°), the measured Q_{H_EC} tends to be larger compared to other wind sectors
425 around the flux mast as well as to the scintillometer results. This effect would be amplified when
426 surface water is scarce. During summertime, when the wind is from the south, both Q_{H_LAS} and
427 Q_{H_BLS} are lower than Q_{H_EC} (Fig. 6). For more westerly winds (240-270°) the EC source area contains
428 more vegetation and there is closer agreement between Q_{H_EC} and Q_H from the scintillometers.

429 However, the remaining curvature in Fig. 6a, but not seen in Fig. 6b, most likely indicates
430 saturation affecting the BLS (5.5 km path) but not the LAS on the shorter path. Despite having
431 corrected the scintillometers for saturation (Sect. 2.2), a comparison of the distribution of C_T^2 values
432 from the BLS and LAS suggests that the highest BLS fluxes are still affected: whilst the LAS provides
433 C_T^2 values up to about $0.03 \text{ K}^2 \text{ m}^{-2/3}$, the BLS distribution drops off sharply at around $0.009 \text{ K}^2 \text{ m}^{-2/3}$.
434 Recently, Wood et al. (2013) found an upper C_T^2 threshold of $0.02 \text{ K}^2 \text{ m}^{-2/3}$ for their shorter path
435 length of 4.2 km. Other studies have also suggested that the effects of saturation may still be
436 observed above commonly-used thresholds (Kohsiek et al. 2006).

437 During night and transition times, the agreement between the datasets is poorer (r^2 decreases to
438 around 0.4 for $K_\downarrow \leq 5 \text{ W m}^{-2}$). This is to be expected for several reasons. Firstly, the limitations in
439 instrument performance are reached when fluxes are small, for both EC and scintillometry.
440 Secondly, the time of stability transition may vary with location, even along the scintillometer paths,
441 so that the three values of Q_H obtained for a given time period may not have the same sign. Data
442 points in the second and fourth quadrants indicate when scintillometer and EC derived Q_H have
443 opposite signs. The stability may also change more than twice per day which would mean the
444 scintillometer data are processed assuming the wrong stability regime. Thirdly, the corrections for
445 the influence of humidity fluctuations on C_T^2 and L_{Ob} are generally larger at these times (when β is

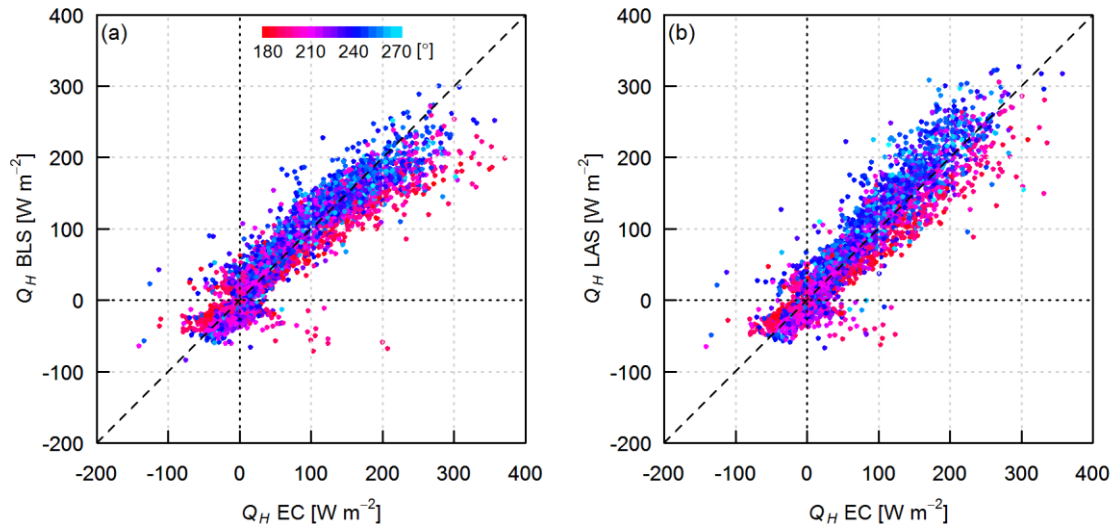
446 small). The Bowen ratio correction to C_T^2 introduces the larger error of these two approximations;
 447 neglecting the buoyancy correction to the Obukhov length (e.g. Green et al. (2001)) is thought to
 448 lead to a slight underestimation in Q_H of $\approx 0.5 \text{ W m}^{-2}$. Finally, near-neutral to stable atmospheric
 449 conditions do not always satisfy the assumptions required for the measurement theory (e.g. weak
 450 turbulence, non-stationarity, poorer performance of similarity functions). Removing the night time
 451 data causes the regression slopes in Fig. 5 to decrease slightly to 0.77 (BLS) and 0.94 (LAS), and the
 452 intercepts to increase to 13 W m^{-2} (BLS) and 9 W m^{-2} (LAS). For night time data only, the intercepts
 453 are similar in size but of opposite sign. These intercepts are thought to result from the
 454 overestimation of small fluxes by the similarity functions. Considering all data together (Fig. 5) the
 455 lack of small Q_H values from the scintillometers can be identified around zero. Using functions of a
 456 conventional form (such as Equations 2 and 3) appears to under represent Q_H values close to zero
 457 and overestimates Q_H in neutral conditions (f_{MO} is too small so the T_* obtained is too large).
 458 Investigation into the scaling of C_T^2 with stability is presented in more detail elsewhere (Ward et al.
 459 in preparation a) and Lagouarde et al. (2006) also noted an overestimation (15 W m^{-2}) of small night
 460 time Q_H values using An88 and DB93 (unstable forms). Although this effect is undesirable, the small
 461 size of the fluxes at these times means that absolute errors are small.

462



463

464 **Fig. 5** Comparison of 30 min sensible heat fluxes derived from the scintillometers (BLS, LAS) and eddy covariance (EC) for all
 465 available data.



466

467 **Fig. 6** As for Fig. 5 but for summertime (May-Sep 2011-12) data only and for wind directions 180-270° (colours).

468

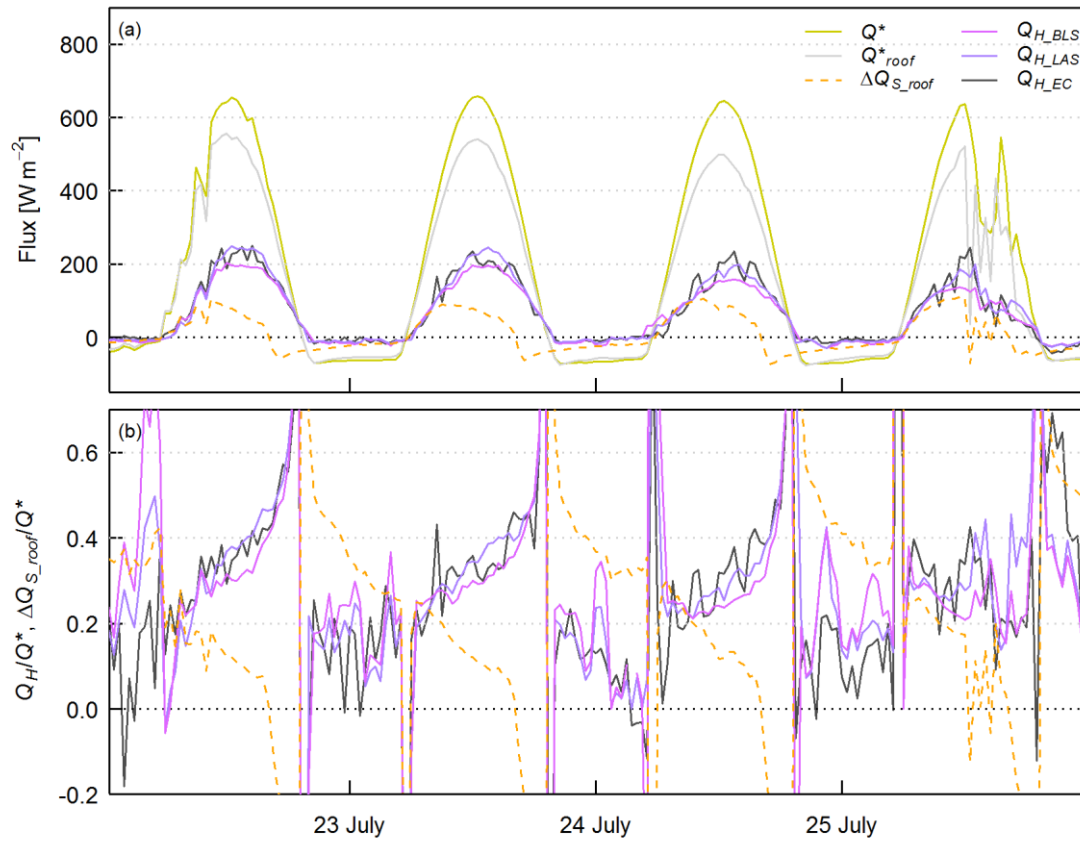
469 The diurnal course of Q_H obtained from the three systems follow each other closely: example
 470 days from July 2012 are shown in Fig. 7. No rainfall was observed during these mostly clear-sky days
 471 although the influence of cloud cover can be seen on the morning of 22 July and afternoon of 25
 472 July. On 22 July the fluxes respond consistently to changes in the net radiation and the peaks and
 473 troughs are closely matched between EC, LAS and BLS observations. Data from MET_{roof},
 474 approximately 3 km southwards (Fig. 1), closely matches the variation in Q^* measured at the EC site.
 475 Time-lapse photography reveals fairly uniform, almost full cloud cover at sunrise which clears
 476 throughout the morning. On the afternoon of 25 July, however, the situation is quite different.
 477 Rapidly changing patchy cloud cover creates spatial variability in the radiation balance components.
 478 The responses of the two radiometers are less well correlated (compare Q^* and Q^*_{roof} in Fig. 7a) and
 479 Q_H is seen to respond differently across the different measurement scales. Not surprisingly, $Q_{H,EC}$
 480 most closely matches Q^* as both are measured at the same location and have more similarly sized
 481 and at least partially coincident source areas. In general, the scintillometers yield a more smoothly
 482 varying diurnal course than EC, often attributed to the greater spatial averaging by scintillometers
 483 (e.g. Lagouarde et al. (2006), Guyot et al. (2009)). The BLS appears to vary more smoothly than the
 484 LAS (e.g. 24 July) which is consistent with the size of their source areas.

485 For clear days, the phase of Q_H is lagged relative to Q^* . At the three scales Q_H peaks after Q^* and
 486 remains positive later into the evening than Q^* . One component of the urban net heat storage flux is
 487 approximated by a heat flux plate installed under the roof covering at MET_{roof} ($\Delta Q_{S,roof}$ in Fig. 7a).
 488 This flux increases earlier in the day and becomes negative long before Q^* . In this way, release of

489 stored energy enables Q_H to remain positive even when Q^* is negative (Oke and Cleugh 1987;
490 Lemonsu et al. 2004). Normalising these fluxes by the net radiation clearly demonstrates the
491 opposing hysteresis patterns of Q_H compared to ΔQ_{S_roof} (Fig. 7b). The proportion of Q^* directed into
492 sensible heat increases throughout the day whereas the proportion of energy used to heat the
493 surface decreases. Strong hysteresis is evident on clear days but it tends to be less obvious on
494 cloudier days. Similar patterns have been observed at other urban sites at the local-scale (Grimmond
495 and Cleugh 1994; Grimmond and Oke 2002; Grimmond et al. 2004). Here we demonstrate that the
496 phase lag between Q_H and Q^* is observed right across the urban environment, from the local-scale
497 up to the city-scale. The shift in peak Q_H around midday and into early afternoon can also be seen to
498 some extent in the average monthly values (Fig. 4), particularly in spring and early summer 2011.

499 Other than under conditions of rapidly changing Q^* , and its associated high spatial variability, the
500 diurnal patterns in Q_H derived from EC and the scintillometers match those of Q^* measured at the
501 EC site (Fig. 8). On 21, 22 and 27 July 2011 the sudden drop in Q^* during the middle of the day is also
502 seen in Q_H . The day-to-day variation in these two quantities is also very similar. For example Q^* and
503 Q_H steadily increase to reach over 600 W m^{-2} and $200\text{-}300 \text{ W m}^{-2}$, respectively, on 25 July when peak
504 Q_{H_BLS} is about 2/3 of Q_{H_LAS} . Both Q^* and Q_H are lower during the following few days until 29 July
505 when the net radiation remained very small throughout the day ($< 100 \text{ W m}^{-2}$) and conditions were
506 mostly near-neutral. On this day the agreement in the shape of the diurnal cycle between the
507 scintillometers and EC is poorer, although the fluxes show some agreement in responding to the dip
508 in Q^* in the afternoon. Under these near-neutral conditions it is likely that the stability transitions
509 occur more often than twice daily as prescribed by the algorithm used to determine the sign of
510 scintillometric Q_H . Indeed, Q_{H_EC} is seen to change sign several times during the afternoon and
511 evening.

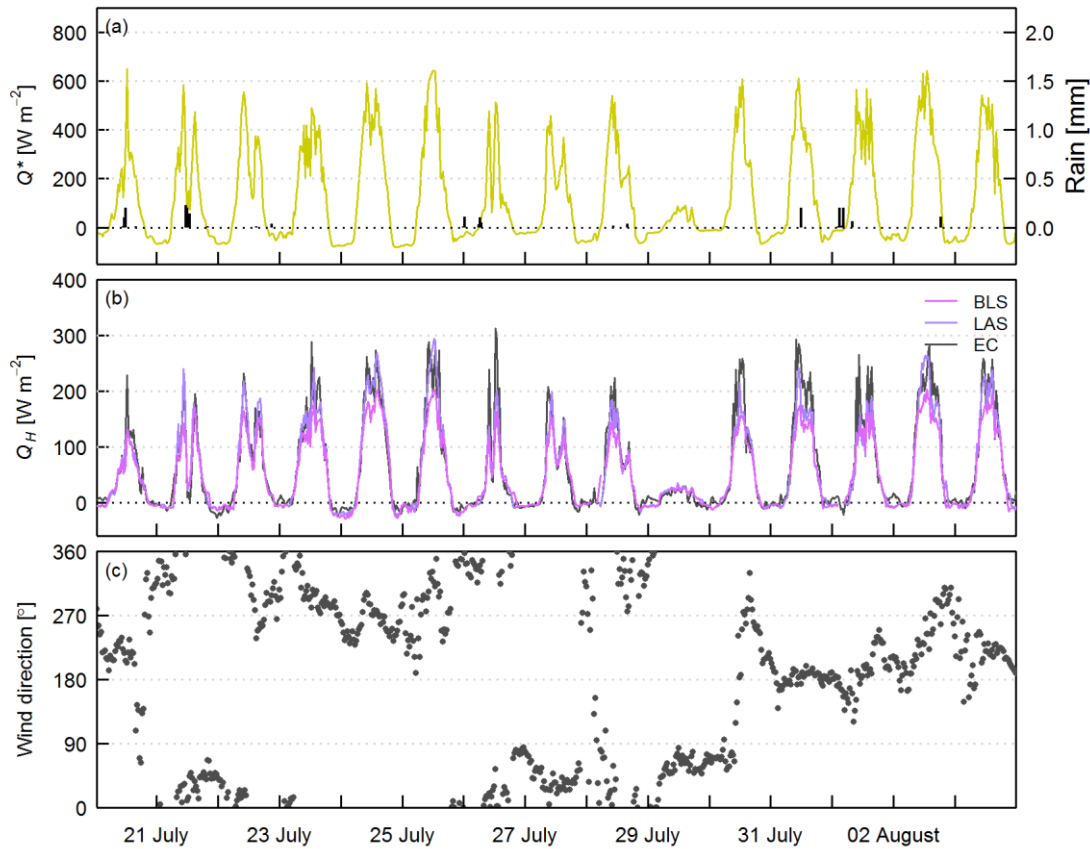
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513

514 **Fig. 7** Diurnal variation in sensible heat fluxes (Q_H) and net all-wave radiation (Q^*) for four days in July 2012. Data from a
 515 heat flux plate installed on a rooftop, representing one component of the storage heat flux ($\Delta Q_{S_{roof}}$) and a second
 516 radiometer located on the rooftop (Q^*_{roof}) are also shown. In (b) the fluxes have been normalized by the net all-wave
 517 radiation measured at the EC site (Q^*).

518



519

520 **Fig. 8** Sensible heat fluxes from EC and the scintillometers alongside net all-wave radiation from the EC site (Q^*), rainfall
 521 and wind direction (also measured at the EC site) for two weeks in July-August 2011.

522

523 The sign of the scintillometer sensible heat flux must be assigned during processing. Here, the
 524 stability was assumed to change from stable to unstable at the first minimum in C_n^2 on each day, and
 525 from unstable to stable at the second minimum, providing these transitions occurred within the
 526 likely time frames for sunrise and sunset. Additionally, the net radiation can be used to check
 527 whether the minima identified are likely to indicate stability transitions rather than sudden increases
 528 in cloud cover, for example. For each 24 h period the algorithm always results in some stable and
 529 some unstable data and the proportion of each depends on the observed behaviour of C_n^2
 530 (effectively on the time between the morning and evening minima). As is evident from the data, this
 531 method generally performs well in Swindon, where EC data suggests Q_H tends to be positive for
 532 some duration around midday and negative at night (Ward et al. 2013a). However, there are some
 533 days when the stability transition does not occur and either unstable conditions prevail throughout
 534 the night or stable conditions throughout the day. In these cases the sign of the fluxes from the

535 scintillometers may be incorrect but these occasions are observed infrequently and the size of the
536 fluxes tends to be small so the likely impact is minimal.

537 The day-to-day (night-to-night) changes in amplitude are usually captured (e.g. decreasing
538 magnitude of nocturnal Q_H 24-27 July 2011 in Fig. 8b) and for some days the evolution of Q_H
539 throughout the night is similar (e.g. decreasing 20-21, increasing 25-26 and 26-27 July 2011, Fig. 8b).
540 This clear relation between the scintillometer and EC fluxes gives confidence that the measurement
541 heights are suitable; in particular that the scintillometers are not measuring above the surface layer.
542 In the winter months, occasionally there are periods of a few hours to days when the shallow surface
543 layer means the scintillometer measurements cannot be related to surface fluxes via MOST (Braam
544 et al. 2012). The EC data further supports these findings with very few cases of strongly stable
545 stratification observed ($\zeta_{EC} < 0.1$ for 89% of data).

546 **3.3. Influence of the surface**

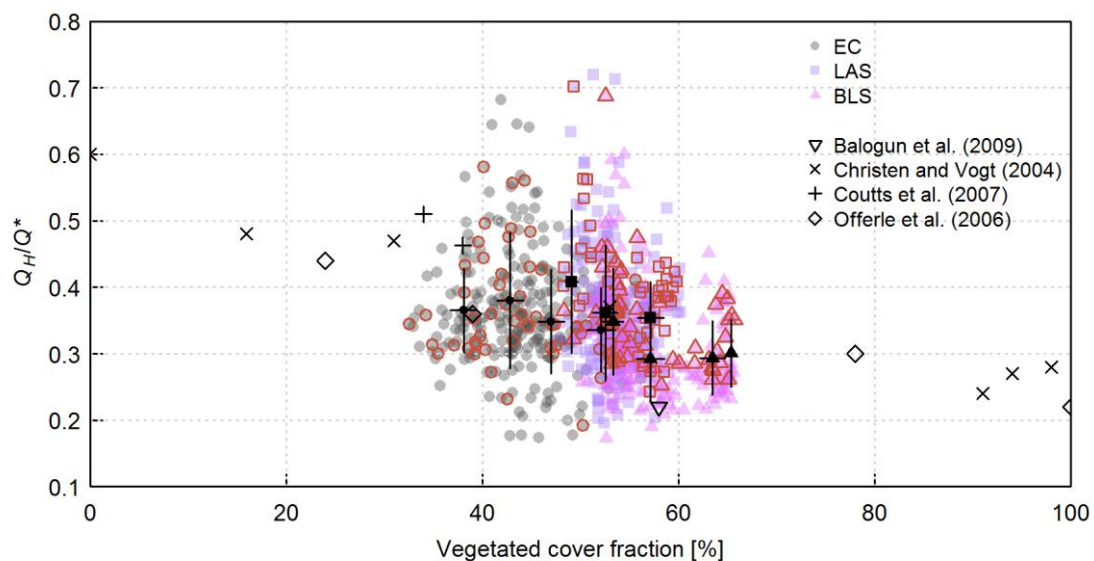
547 Comparing the relative sizes of the fluxes can offer insight into key controls on suburban energy
548 partitioning. Towards the end of the case study in Fig. 8 (30 July-01 August 2011), $Q_{H_{EC}}$ peaks at
549 larger values than either of the scintillometers, whilst $Q_{H_{LAS}}$ is generally largest near the beginning
550 of the period (21-25 July). The wind direction (Fig. 8c) provides a partial explanation due to the
551 variation in source areas. For westerly to northerly winds, $Q_{H_{LAS}}$ tends to be largest. All three fluxes
552 become similar during northerly winds, when there is a greater vegetation fraction within the source
553 area of each instrument. For the scintillometers the footprint will extend to include some of the rural
554 farmland beyond the edge of the suburbs; at the EC site the increased vegetation is due to more
555 gardens to the north of the mast (Ward et al. 2013a).

556 The period shown in Fig. 9 (21 May – 31 July 2012) coincides with sudden vegetation growth in
557 response to warm, sunny conditions at the end of May, completing the leaf-out period to reach
558 maturity. Vegetation is then fully active throughout June and July. In this period a range of synoptic
559 conditions (cloudy, mixed and clear days), frequent rainfall and a wide distribution of wind directions
560 (although south-westerly was still dominant) occurred.

561 Footprint calculations for each 30 min period reveal an overall ranking of the vegetation fraction
562 for each instrument that is in accordance with broad expectations given their respective sitings (EC <
563 LAS < BLS). The mean vegetation fractions (\pm standard deviations) are 44.1 (± 5.0) %, 53.9 (± 2.9) %
564 and 56.9 (± 4.5) % for EC, LAS and BLS, respectively, for the data shown in Fig. 9. The standard
565 deviation is largest for the EC site, as might be expected (a) given the far smaller size of the source
566 area and (b) the differences in surface cover with wind sector around the mast. The vegetation

567 fraction ranges between 32.6% and 56.8% according to the EC footprint estimation for this period.
 568 The LAS source area characteristics are much less variable (minimum 47.7%, maximum 60.2%). The
 569 retail park to the west of the path (Fig. 1) constitutes a small proportion of the total source area and
 570 for westerly wind directions there is only a small increase in the built and impervious fractions.
 571 Despite having the largest area, the BLS footprint shows appreciable variability (48.3% – 65.7%),
 572 mostly associated with southerly or northerly winds when the town centre and nearby industrial
 573 areas (Fig. 1) or rural surroundings are included in the footprint. For small changes in wind direction
 574 the BLS source area composition hardly changes, whereas the EC source area composition can vary
 575 considerably (particularly for the 180-270° sector). In addition to the directional aspect of the
 576 surface heterogeneity, the total area included in the scintillometer footprint is smaller when the
 577 wind direction is parallel, as opposed to perpendicular, to the scintillometer path (Meijninger et al.
 578 2002b). In this case, the spatial integration occurs over a smaller area so the footprint composition,
 579 and observed fluxes, may be expected to be more variable.

580



581

582 **Fig. 9** Ratio of observed sensible heat flux to net all-wave radiation versus the proportion of vegetation within the flux
 583 footprint of the EC station, LAS and BLS in Swindon. Points are 30 min values around midday (1100-1500 UTC) for the
 584 period 21 May – 31 July 2012. Data are excluded for times during and ≤ 2 h after rainfall and when $K_d \leq 200 \text{ W m}^{-2}$. Black
 585 symbols with error bars represent the mean \pm standard deviation of the respective observed values binned in 5% intervals
 586 of the vegetated cover fraction (bins with > 10 data points are plotted). Those data collected more than 2 days since
 587 rainfall are outlined in red. Average summertime values from various sites in the literature are shown for comparison (see
 588 references for details).

589

590 The ratio of Q_H to Q^* decreases as the proportion of vegetation within each instrument's source
591 area increases (Fig. 9). Normalising the turbulent fluxes by an indicator of the energy available
592 largely removes the otherwise often dominant dependence on insolation. Additionally, to moderate
593 the influence of the diurnal hysteresis pattern (Fig. 7), only data around midday (1100-1500 UTC)
594 have been included in Fig. 9. The observed relation between vegetation cover and partitioning of
595 energy into Q_H is in agreement with other published studies, including summertime data from
596 Kansas City (Balogun et al. 2009), seven sites in Basel (Christen and Vogt 2004), two sites (high and
597 medium density) in Melbourne (Coutts et al. 2007) and four sites in Łódź (Offerle et al. 2006). Use of
598 the scintillometers in Swindon enables this comparison to be extended to larger scales.

599 Relations between land cover and energy partitioning have mostly been developed for summer
600 months, when the majority of field campaigns have taken place and do not account for differences
601 in surface or synoptic conditions. Whilst there is generally good agreement between summertime
602 datasets across a range of sites, those studies extending to winter demonstrate very different
603 behaviour of Q_H/Q^* . In dense urban areas, the anthropogenic heat flux and much larger storage flux
604 can sustain a positive sensible heat flux all year round (Goldbach and Kuttler 2013; Kotthaus and
605 Grimmond in press-a). In these locations, building density may be a more appropriate variable to use
606 than vegetation fraction and the effect of the anthropogenic heat flux can result in Q_H that is
607 significantly greater than Q^* . The few campaigns spanning multiple seasons indicate temporal
608 evolution of daytime Q_H/Q^* , e.g. between about 0.30 (winter) and 0.55 (summer) in Melbourne
609 (Coutts et al. 2007), and between 0.29 (December) and 0.49 (July) in Tokyo (Moriwaki and Kanda
610 2004). The data presented here reveal daytime Q_H/Q^* peaks in spring between 0.4 and 0.5 and
611 drops to about 0.2 in winter for Swindon. These seasonal changes incorporate multiple effects. The
612 anthropogenic influences already mentioned, vegetative activity and the amount of incoming
613 radiation are major factors, but do not account for inter-annual variability in meteorological
614 conditions or rainfall. In February 2012 the limited moisture availability likely contributed to an
615 atypically high Q_H/Q^* of around 0.4.

616 At shorter time scales, the meteorological conditions and local stability both have an influence.
617 Reduced availability of moisture constrains the latent heat flux and allows the sensible heat to rise.
618 Following rainfall, the surface dries out and the ratio Q_H/Q^* tends to increase (outlined points in Fig.
619 9 represent data collected following more than 2 days without rainfall). Inter-annual variations in
620 rainfall can lead to differences in the size of the fluxes from year to year that cannot only be
621 attributed to variations in Q^* (Fig. 3). Although normalising by Q^* removes much of the dependence

622 on the radiative energy, whether conditions are clear or cloudy can affect the response of the
623 surface. Some studies have stratified results by cloud cover conditions (Grimmond and Oke 1995;
624 Balogun et al. 2009) although the effect on Q_H/Q^* is small. In Fig. 9, data are excluded for $K_d \leq 200$
625 $W m^{-2}$ and most of the remaining points greater than 0.6 occur under low insolation. For large K_d
626 values the scatter is further reduced; this likely to be a result of differing conditions within the
627 instruments' source areas under variable cloud cover. The sensible heat flux is dependent on the
628 amount of energy stored and released, which itself depends on the season (Offerle et al. 2005),
629 surface wetness (Kawai and Kanda 2010) and cloud cover (Grimmond and Oke 1995). The ability of
630 the surface to store or dissipate heat depends primarily on the physical properties of the constituent
631 materials, but may also be affected by changes in surface conditions, for example a wet surface may
632 have a lower albedo than when dry (e.g. in Cairo (Frey et al. 2011)) and soil moisture affects its
633 conductivity. Different materials respond differently to direct and diffuse radiation (Kotthaus and
634 Grimmond in press-b). In combination with surface morphology and changing solar elevation with
635 latitude and time of year, this determines the impact of shadowing. To account for shading patterns
636 in energy flux parameterization schemes Loridan and Grimmond (2012) propose an 'active' built
637 index. The latent heat flux also depends on these, and other, factors. To further develop
638 understanding of such processes and interactions it will be necessary to focus more attention on the
639 interdependencies between energy fluxes and how these are affected by surface conditions in urban
640 areas.

641 Finally, although the Bowen ratio correction has not been applied to the data here, the biggest
642 impact of the correction would be at small β . For $\beta = 0.5$, scintillometric Q_H is overestimated by 9%
643 which would result in mean Q_H/Q^* being overestimated by 0.04. Implementing the β correction
644 would act to further decrease Q_H/Q^* with vegetation fraction. As β itself has been shown to depend
645 on the vegetation fraction, smaller β at larger vegetation fraction again acts to amplify rather than
646 reduce the trend.

647 **4. Conclusions**

648 This work demonstrates the applicability of large aperture scintillometry for making spatially
649 integrated observations over urban areas. With selection of a suitable path, adequately sited
650 auxiliary meteorological measurements and knowledge of the land surface, sensible heat flux
651 estimates are obtained that are representative of several neighbourhoods or across the settlement.
652 Whilst EC measurements are representative of the local-scale ($0.5 km^2$), the scintillometer data in
653 this study have much larger source areas: 3.0 and $7.5 km^2$ (95% contribution) for the LAS and BLS,
654 respectively.

655 Remarkable temporal agreement is observed across the three different areal extents for both
656 short-term variability (e.g. the response to radiation patterns over a few hours to days) and seasonal
657 trends. Differences in magnitudes of the fluxes between sites are attributed primarily to the role of
658 vegetation and reveal the influence of anthropogenic materials on surface-atmosphere interactions.
659 Empirical relations between land cover and fluxes often underpin urban energy models and are
660 valuable for gauging the likely partitioning of energy, and hence the environmental conditions
661 (including thermal comfort and moisture availability), in cities where measurements have not been
662 made.

663 Comparison of the EC dataset with large-area fluxes at the city-scale provides some context to
664 the results and confirms that the EC site selection was appropriate. The scintillometer fluxes tend to
665 be smoother as a result of the greater spatial averaging. The large-scale flux measurements are also
666 much less sensitive to source area variability, for example due to changing wind direction over
667 heterogeneous surfaces. As they encompass a larger proportion of the study area, these large-area
668 fluxes are more representative and suffer less from sampling bias, whereas EC measurements are
669 easily influenced by spatially variable land cover or surface characteristics around the mast. The
670 effect can be decreased by measuring at a greater height, but in general the land cover must be
671 carefully examined for each wind sector before drawing conclusions on the representativeness of
672 data from a single EC site.

673 For many purposes we are interested in fluxes at large scales, whether the application is input
674 data for, or evaluation of, land-surface models or numerical weather prediction, assessment of
675 satellite remote sensing products or representative observational datasets to characterize a
676 particular environment. Scintillometry offers a promising way forward, but there are still limitations.
677 A major source of uncertainty arises from the MOST functions. This is an area that would benefit
678 from further attention for all land cover types and has implications beyond improving the accuracy
679 of fluxes from scintillometry. Single-wavelength scintillometry may be best suited to urban areas
680 with little vegetation as the higher the Bowen ratio the smaller the error due to neglecting the β -
681 correction (Moene 2003). Given the potential for saturation, particularly if the sensible heat flux is
682 large, it is recommended that an extra-large aperture scintillometer is considered for long paths (e.g.
683 > 4 km, for paths of similar height and fluxes of similar magnitude). Future work will likely focus on
684 the development of the scintillometry technique and the application for routine monitoring at large-
685 scales, e.g. Kleissl et al. (2009a). Such observational networks would offer valuable data for
686 assimilation into models that assess e.g. air quality or heat stress, both highly relevant to human
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696

697 **References**

- 698 Andreas EL (1988) Estimating C_n^2 over snow and sea ice from meteorological data. *J Opt Soc Am* 5:
699 481-495.
- 700 Andreas EL (1989) Two-wavelength method of measuring path-averaged turbulent surface heat
701 fluxes. *J Atmos Ocean Technol* 6: 280-292.
- 702 Balogun A, Adegoke J, Vezhapparambu S, Mauder M, McFadden J and Gallo K (2009) Surface energy
703 balance measurements above an exurban residential neighbourhood of Kansas City,
704 Missouri. *Boundary-Layer Meteorol* 133: 299-321. doi: 10.1007/s10546-009-9421-3
- 705 Bergeron O and Strachan IB (2010) Wintertime radiation and energy budget along an urbanization
706 gradient in Montreal, Canada. *Int J Climatol* 32: 137-152. doi: 10.1002/joc.2246
- 707 Beyrich F, Bange J, Hartogensis O, Raasch S, Braam M, van Dinter D, Gräf D, van Kesteren B, van
708 den Kroonenberg A, Maronga B, Martin S and Moene A (2012) Towards a Validation of
709 Scintillometer Measurements: The LITFASS-2009 Experiment. *Boundary-Layer Meteorol* 144:
710 83-112. doi: 10.1007/s10546-012-9715-8
- 711 Beyrich F, De Bruin HAR, Meijninger WML, Schipper JW and Lohse H (2002) Results from one-year
712 continuous operation of a large aperture scintillometer over a heterogeneous land surface.
713 *Boundary-Layer Meteorol* 105: 85-97.
- 714 Braam M, Bosveld F and Moene A (2012) On Monin–Obukhov Scaling in and Above the Atmospheric
715 Surface Layer: The Complexities of Elevated Scintillometer Measurements. *Boundary-Layer*
716 *Meteorol* 144: 157-177. doi: 10.1007/s10546-012-9716-7
- 717 Chehbouni A, Watts C, Kerr YH, Dedieu G, Rodriguez JC, Santiago F, Cayrol P, Boulet G and Goodrich
718 DC (2000a) Methods to aggregate turbulent fluxes over heterogeneous surfaces: application
719 to SALSA data set in Mexico. *Agric For Meteorol* 105: 133-144.
- 720 Chehbouni A, Watts C, Lagouarde JP, Kerr YH, Rodriguez JC, Bonnefond JM, Santiago F, Dedieu G,
721 Goodrich DC and Unkrich C (2000b) Estimation of heat and momentum fluxes over complex
722 terrain using a large aperture scintillometer. *Agric For Meteorol* 105: 215-226.
- 723 Cheinet S, Beljaars A, Weiss-Wrana K and Hurtaud Y (2011) The Use of Weather Forecasts to
724 Characterise Near-Surface Optical Turbulence. *Boundary-Layer Meteorol* 138: 453-473. doi:
725 10.1007/s10546-010-9567-z
- 726 Christen A and Vogt R (2004) Energy and radiation balance of a central European city. *Int J Climatol*
727 24: 1395-1421. doi: 10.1002/joc.1074
- 728 Clifford SF, Ochs GR and Lawrence RS (1974) Saturation of optical scintillation by strong turbulence. *J*
729 *Opt Soc Am* 64: 148-154.

730 Coutts AM, Beringer J and Tapper NJ (2007) Impact of increasing urban density on local climate:
731 Spatial and temporal variations in the surface energy balance in Melbourne, Australia. *J Appl*
732 *Meteorol Climatol* 46: 477-493. doi: 10.1175/jam2462.1

733 De Bruin HAR, Kohsiek W and Van den Hurk BJM (1993) A verification of some methods to
734 determine the fluxes of momentum, sensible heat, and water-vapour using standard-
735 deviation and structure parameter of scalar meteorological quantities. *Boundary-Layer*
736 *Meteorol* 63: 231-257.

737 Detto M, Montaldo N, Albertson JD, Mancini M and Katul G (2006) Soil moisture and vegetation
738 controls on evapotranspiration in a heterogeneous Mediterranean ecosystem on Sardinia,
739 Italy. *Water Resour Res* 42: 16. doi: 10.1029/2005wr004693

740 Evans JG (2009) Long-Path Scintillometry over Complex Terrain to Determine Areal-Averaged
741 Sensible and Latent Heat Fluxes. Soil Science Department, The University of Reading, PhD,
742 181 pp

743 Evans JG, McNeil DD, Finch JW, Murray T, Harding RJ, Ward HC and Verhoef A (2012) Determination
744 of turbulent heat fluxes using a large aperture scintillometer over undulating mixed
745 agricultural terrain. *Agric For Meteorol* 166-167: 221-233.

746 Ezzahar J, Chehbouni A and Hoedjes JCB (2007) On the application of scintillometry over
747 heterogeneous grids. *J Hydrol* 334: 493-501. doi: 10.1016/j.jhydrol.2006.10.027

748 Frey CM, Parlow E, Vogt R, Harhash M and Abdel Wahab MM (2011) Flux measurements in Cairo.
749 Part 1: in situ measurements and their applicability for comparison with satellite data. *Int J*
750 *Climatol* 31: 218-231. doi: 10.1002/joc.2140

751 Garratt JR (1978) Transfer characteristics for a heterogeneous surface of large aerodynamic
752 roughness. *Q J R Meteorol Soc* 104: 491-502. doi: 10.1002/qj.49710444019

753 Garratt JR (1992) *The Atmospheric Boundary Layer*, Cambridge University Press, 316 pp

754 Goldbach A and Kuttler W (2013) Quantification of turbulent heat fluxes for adaptation strategies
755 within urban planning. *Int J Climatol* 33: 143-159. doi: 10.1002/joc.3437

756 Gouvea ML and Grimmond CSB (2010) Spatially integrated measurements of sensible heat flux using
757 scintillometry. Ninth Symposium on the Urban Environment, Keystone, Colorado, 2nd-6th
758 August 2010

759 Green AE, Astill MS, McAneney KJ and Nieveen JP (2001) Path-averaged surface fluxes determined
760 from infrared and microwave scintillometers. *Agric For Meteorol* 109: 233-247.

761 Grimmond CSB and Cleugh HA (1994) A Simple Method to Determine Obukhov Lengths for Suburban
762 Areas. *J Appl Meteorol* 33: 435-440.

763 Grimmond CSB, King TS, Roth M and Oke TR (1998) Aerodynamic roughness of urban areas derived
764 from wind observations. *Boundary-Layer Meteorol* 89: 1-24.

765 Grimmond CSB and Oke TR (1995) Comparison of Heat Fluxes from Summertime Observations in the
766 Suburbs of Four North American Cities. *J Appl Meteorol* 34: 873-889. doi: 10.1175/1520-
767 0450

768 Grimmond CSB and Oke TR (1999) Aerodynamic properties of urban areas derived from analysis of
769 surface form. *J Appl Meteorol* 38: 1262-1292.

770 Grimmond CSB and Oke TR (2002) Turbulent heat fluxes in urban areas: Observations and a local-
771 scale urban meteorological parameterization scheme (LUMPS). *J Appl Meteorol* 41: 792-810.

772 Grimmond CSB, Salmond JA, Oke TR, Offerle B and Lemonsu A (2004) Flux and turbulence
773 measurements at a densely built-up site in Marseille: Heat, mass (water and carbon dioxide),
774 and momentum. *J Geophys Res (Atmos)* 109: D24101. doi: D2410110.1029/2004jd004936

775 Grimmond CSB, Souch C and Hubble MD (1996) Influence of tree cover on summertime surface
776 energy balance fluxes, San Gabriel Valley, Los Angeles. *Climate Res* 06: 45-57. doi:
777 10.3354/cr006045

778 Guyot A, Cohard J-M, Anquetin S, Galle S and Lloyd CR (2009) Combined analysis of energy and
779 water balances to estimate latent heat flux of a Sudanian small catchment. *J Hydrol* 375:
780 227-240.

781 Hartogensis OK, Watts CJ, Rodriguez JC and De Bruin HAR (2003) Derivation of an effective height for
782 scintillometers: La Poza experiment in Northwest Mexico. *J Hydrometeorol* 4: 915-928.

783 Hill RJ, Bohlander RA, Clifford SF, McMillan RW, Priestly JT and Schoenfeld WP (1988) Turbulence-
784 induced millimeter-wave scintillation compared with micrometeorological measurements.
785 *IEEE Trans Geosci Remote Sens* 26: 330-342.

786 Hill RJ, Clifford SF and Lawrence RS (1980) Refractive-index and absorption fluctuations in the
787 infrared caused by temperature, humidity, and pressure fluctuations. *J Opt Soc Am* 70: 1192-
788 1205.

789 Hill RJ, Ochs GR and Wilson JJ (1992) Measuring surface-layer fluxes of heat and momentum using
790 optical scintillation. *Boundary-Layer Meteorol* 58: 391-408. doi: 10.1007/bf00120239

791 Hiller RV, McFadden JP and Kljun N (2011) Interpreting CO₂ Fluxes Over a Suburban Lawn: The
792 Influence of Traffic Emissions. *Boundary-Layer Meteorol* 138: 215-230. doi: 10.1007/s10546-
793 010-9558-0

794 Hoedjes JCB, Chehbouni A, Ezzahar J, Escadafal R and De Bruin HAR (2007) Comparison of large
795 aperture scintillometer and eddy covariance measurements: Can thermal infrared data be
796 used to capture footprint-induced differences? *J Hydrometeorol* 8: 144-159. doi:
797 10.1175/jhm561.1

798 Hoedjes JCB, Zuurbier RM and Watts CJ (2002) Large aperture scintillometer used over a
799 homogeneous irrigated area, partly affected by regional advection. *Boundary-Layer*
800 *Meteorol* 105: 99-117.

801 Hsieh CI, Katul G and Chi T (2000) An approximate analytical model for footprint estimation of scalar
802 fluxes in thermally stratified atmospheric flows. *Adv Water Resour* 23: 765-772.

803 Järvi L, Grimmond CSB and Christen A (2011) The Surface Urban Energy and Water Balance Scheme
804 (SUEWS): Evaluation in Los Angeles and Vancouver. *J Hydrol* 411: 219-237.

805 Järvi L, Nordbo A, Junninen H, Riikonen A, Moilanen J, Nikinmaa E and Vesala T (2012) Seasonal and
806 annual variation of carbon dioxide surface fluxes in Helsinki, Finland, in 2006-2010. *Atmos*
807 *Chem Phys* 12: 8475-8489. doi: 10.5194/acp-12-8475-2012

808 Järvi L, Rannik U, Mammarella I, Sogachev A, Aalto PP, Keronen P, Siivola E, Kulmala M and Vesala T
809 (2009) Annual particle flux observations over a heterogeneous urban area. *Atmos Chem*
810 *Phys* 9: 7847-7856.

811 Kanda M, Moriwaki R, Roth M and Oke T (2002) Area-averaged sensible heat flux and a new method
812 to determine zero-plane displacement length over an urban surface using scintillometry.
813 *Boundary-Layer Meteorol* 105: 177-193.

814 Kawai T and Kanda M (2010) Urban Energy Balance Obtained from the Comprehensive Outdoor
815 Scale Model Experiment. Part I: Basic Features of the Surface Energy Balance. *J Appl*
816 *Meteorol Climatol* 49: 1341-1359. doi: 10.1175/2010jamc1992.1

817 Keogh S, Mills G and Fealy R (2012) The energy budget of the urban surface: two locations in Dublin.
818 *Irish Geography* 45: 1-23. doi: 10.1080/00750778.2012.689182

819 Kleissl J, Gomez J, Hong SH, Hendrickx JMH, Rahn T and Defoor WL (2008) Large aperture
820 scintillometer intercomparison study. *Boundary-Layer Meteorol* 128: 133-150. doi:
821 10.1007/s10546-008-9274-1

822 Kleissl J, Hartogensis O and Gomez J (2010) Test of Scintillometer Saturation Correction Methods
823 Using Field Experimental Data. *Boundary-Layer Meteorol* 137: 493-507. doi:
824 10.1007/s10546-010-9540-x

825 Kleissl J, Hong SH and Hendrickx JMH (2009a) New Mexico scintillometer network supporting remote
826 sensing and hydrologic and meteorological models. *Bull Am Meteorol Soc* 90: 207-218. doi:
827 10.1175/2008bams2480.1

828 Kleissl J, Watts CJ, Rodriguez JC, Naif S and Vivoni ER (2009b) Scintillometer Intercomparison Study-
829 Continued. *Boundary-Layer Meteorol* 130: 437-443. doi: 10.1007/s10546-009-9352-z

830 Kohsiek W and Herben MHAJ (1983) Evaporation derived from optical and radio-wave scintillation.
831 *Appl Opt* 22: 2566-2570.

832 Kohsiek W, Meijninger WML, De Bruin HAR and Beyrich F (2006) Saturation of the Large Aperture
833 Scintillometer. *Boundary-Layer Meteorol* 121: 111-126. doi: 10.1007/s10546-005-9031-7

834 Kotthaus S and Grimmond CSB (in press-a) Energy exchange in a dense urban environment - Part I:
835 temporal variability of long-term observations in central London. *Urban Climate*. doi:
836 10.1016/j.uclim.2013.10.002

837 Kotthaus S and Grimmond CSB (in press-b) Energy exchange in a dense urban environment – Part II:
838 impact of spatial heterogeneity of the surface. *Urban Climate*. doi:
839 10.1016/j.uclim.2013.10.001

840 Lagouarde JP, Irvine M, Bonnefond JM, Grimmond CSB, Long N, Oke TR, Salmond JA and Offerle B
841 (2006) Monitoring the sensible heat flux over urban areas using large aperture
842 scintillometry: Case study of Marseille city during the ESCOMPTE experiment. *Boundary-*
843 *Layer Meteorol* 118: 449-476. doi: 10.1007/s10546-005-9001-0

844 Lemonsu A, Grimmond CSB and Masson V (2004) Modeling the surface energy balance of the core of
845 an old Mediterranean city: Marseille. *J Appl Meteorol* 43: 312-327.

846 Liu SM, Xu ZW, Zhu ZL, Jia ZZ and Zhu MJ (2013) Measurements of evapotranspiration from eddy-
847 covariance systems and large aperture scintillometers in the Hai River Basin, China. *J Hydrol*
848 487: 24-38. doi: <http://dx.doi.org/10.1016/j.jhydrol.2013.02.025>

849 Loridan T and Grimmond CSB (2012) Characterization of Energy Flux Partitioning in Urban
850 Environments: Links with Surface Seasonal Properties. *J Appl Meteorol Climatol* 51: 219-241.
851 doi: 10.1175/jamc-d-11-038.1

852 Maronga B, Moene AF, Dintner D, Raasch S, Bosveld FC and Gioli B (2013) Derivation of Structure
853 Parameters of Temperature and Humidity in the Convective Boundary Layer from Large-
854 Eddy Simulations and Implications for the Interpretation of Scintillometer Observations.
855 *Boundary-Layer Meteorol* 148: 1-30. doi: 10.1007/s10546-013-9801-6

856 Maronga B and Raasch S (2013) Large-Eddy Simulations of Surface Heterogeneity Effects on the
857 Convective Boundary Layer During the LITFASS-2003 Experiment. *Boundary-Layer Meteorol*
858 146: 17-44. doi: 10.1007/s10546-012-9748-z

859 Meijninger WML, Beyrich F, Lüdi A, Kohsiek W and De Bruin HAR (2006) Scintillometer-based
860 turbulent fluxes of sensible and latent heat over a heterogeneous land surface - A
861 contribution to LITFASS-2003. *Boundary-Layer Meteorol* 121: 89-110. doi: 10.1007/s10546-
862 005-9022-8

863 Meijninger WML and De Bruin HAR (2000) The sensible heat fluxes over irrigated areas in western
864 Turkey determined with a large aperture scintillometer. *J Hydrol* 229: 42-49.

865 Meijninger WML, Green AE, Hartogensis OK, Kohsiek W, Hoedjes JCB, Zuurbier RM and De Bruin HAR
866 (2002a) Determination of area-averaged water vapour fluxes with large aperture and radio
867 wave scintillometers over a heterogeneous surface - Flevoland field experiment. *Boundary-*
868 *Layer Meteorol* 105: 63-83.

869 Meijninger WML, Hartogensis OK, Kohsiek W, Hoedjes JCB, Zuurbier RM and De Bruin HAR (2002b)
870 Determination of area-averaged sensible heat fluxes with a large aperture scintillometer
871 over a heterogeneous surface - Flevoland field experiment. *Boundary-Layer Meteorol* 105:
872 37-62.

873 Mestayer P, Bagga I, Calmet I, Fontanilles G, Gaudin D, Lee JH, Piquet T, Rosant J-M, Chancibault K,
874 Lebouc L, Letellier L, Mosini M-L, Rodriguez F, Rouaud J-M, Sabre M, Tétard Y, Brut A, Selves
875 J-L, Solignac P-A, Brunet Y, Dayau S, Irvine M, Lagouarde J-P, Kassouk Z, Launeau P, Connan
876 O, Defenouillère P, Goriaux M, Hébert D, Letellier B, Mario D, Najjar G, Nerry F, Quentin C,
877 Biron R, Cohard J-M, Galvez J and Klein P (2011) The FluxSAP 2010 hydroclimatological
878 experimental campaign over an heterogeneous urban area. 11th EMS Annual Meeting,
879 Berlin, Germany, 12th-16th September 2011

880 Moene AF (2003) Effects of water vapour on the structure parameter of the refractive index for
881 near-infrared radiation. *Boundary-Layer Meteorol* 107: 635-653.

882 Moriwaki R and Kanda M (2004) Seasonal and diurnal fluxes of radiation, heat, water vapor, and
883 carbon dioxide over a suburban area. *J Appl Meteorol* 43: 1700-1710.

884 Mustchin J, Pauscher L, Ward HC, Kotthaus S, Gouvea M, Morrison W and Grimmond CSB (2013)
885 Comparison of Three Large Aperture Scintillometer Models Over London. Tübingen
886 Atmospheric Physics Symposium "Scintillometers and Applications", Tübingen, Germany,
887 7th-9th October 2013

888 Nordbo A, Järvi L, Haapanala S, Moilanen J and Vesala T (2013) Intra-City Variation in Urban
889 Morphology and Turbulence Structure in Helsinki, Finland. *Boundary-Layer Meteorol* 146:
890 469-496. doi: 10.1007/s10546-012-9773-y

891 Offerle B, Grimmond CSB and Fortuniak K (2005) Heat storage and anthropogenic heat flux in
892 relation to the energy balance of a central European city centre. *Int J Climatol* 25: 1405-
893 1419. doi: 10.1002/koc.1198

894 Offerle B, Grimmond CSB, Fortuniak K and Pawlak W (2006) Intraurban differences of surface energy
895 fluxes in a central European city. *J Appl Meteorol Climatol* 45: 125-136.

896 Oke TR and Cleugh HA (1987) Urban heat storage derived as energy balance residuals. *Boundary-
897 Layer Meteorol* 39: 233-245. doi: 10.1007/bf00116120

898 Pasquill F (1974) *Atmospheric Diffusion*, Wiley, 429 pp

899 Pauscher L (2010) *Scintillometer Measurements above the Urban Area of London*. Department of
900 Micrometeorology, University of Bayreuth, Diploma, 104 pp

901 Roberts SM, Oke TR, Grimmond CSB and Voogt JA (2006) Comparison of Four Methods to Estimate
902 Urban Heat Storage. *J Appl Meteorol Climatol* 45: 1766-1781. doi: 10.1175/jam2432.1

903 Roth M, Salmond JA and Satyanarayana ANV (2006) Methodological considerations regarding the
904 measurement of turbulent fluxes in the urban roughness sublayer: The role of
905 scintillometry. *Boundary-Layer Meteorol* 121: 351-375. doi: 10.1007/s10546-006-9074-4

906 Samain B, Defloor W and Pauwels VRN (2012) Continuous Time Series of Catchment-Averaged
907 Sensible Heat Flux from a Large Aperture Scintillometer: Efficient Estimation of Stability
908 Conditions and Importance of Fluxes under Stable Conditions. *J Hydrometeorol* 13: 423-442.
909 doi: 10.1175/jhm-d-11-030.1

910 Samain B, Ferket BVA, Defloor W and Pauwels VRN (2011a) Estimation of catchment averaged
911 sensible heat fluxes using a large aperture scintillometer. *Water Resour Res* 47: W05536.
912 doi: 10.1029/2009wr009032

913 Samain B, Simons GWH, Voogt MP, Defloor W, Bink N-J and Pauwels VRN (2011b) Consistency
914 between hydrological model, large aperture scintillometer and remote sensing based
915 evapotranspiration estimates for a heterogeneous catchment. *Hydrol Earth Syst Sci* 8:
916 10863-10894. doi: 10.5194/hessd-8-10863-2011

917 Schmid HP (1994) Source areas for scalars and scalar fluxes. *Boundary-Layer Meteorol* 67: 293-318.
918 doi: 10.1007/bf00713146

919 Schmid HP, Cleugh HA, Grimmond CSB and Oke TR (1991) Spatial variability of energy fluxes in
920 suburban terrain. *Boundary-Layer Meteorol* 54: 249-276. doi: 10.1007/bf00183956

921 Steeneveld GJ, Tolk LF, Moene AF, Hartogensis OK, Peters W and Holtslag AAM (2011) Confronting
922 the WRF and RAMS mesoscale models with innovative observations in the Netherlands:
923 Evaluating the boundary layer heat budget. *J Geophys Res (Atmos)* 116: D23114. doi:
924 10.1029/2011jd016303

925 Stull RB (1988) *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, 666 pp

926 Thiermann V and Grassl H (1992) The measurement of turbulent surface-layer fluxes by use of
927 bichromatic scintillation. *Boundary-Layer Meteorol* 58: 367-389.

928 Van Kesteren B and Hartogensis O (2011) Analysis of the Systematic Errors Found in the Kipp &
929 Zonen Large-Aperture Scintillometer. *Boundary-Layer Meteorol* 138: 493-509. doi:
930 10.1007/s10546-010-9564-2

931 Vesala T, Järvi L, Launiainen S, Sogachev A, Rannik Ü, Mammarella I, Siivola E, Keronen P, Rinne J,
932 Riikonen ANU and Nikinmaa E (2008) Surface–atmosphere interactions over complex urban
933 terrain in Helsinki, Finland. *Tellus B* 60: 188-199. doi: 10.1111/j.1600-0889.2007.00312.x
934 Ward HC, Evans JG and Grimmond CSB (2013a) Multi-season eddy covariance observations of
935 energy, water and carbon fluxes over a suburban area in Swindon, UK. *Atmos Chem Phys* 13:
936 4645-4666. doi: 10.5194/acp-13-4645-2013
937 Ward HC, Evans JG, Hartogensis OK, Moene AF, De Bruin HAR and Grimmond CSB (2013b) A critical
938 revision of the estimation of the latent heat flux from two-wavelength scintillometry. *Q J R*
939 *Meteorol Soc* 139: 1912-1922. doi: 10.1002/qj.2076
940 Weber S and Kordowski K (2010) Comparison of atmospheric turbulence characteristics and
941 turbulent fluxes from two urban sites in Essen, Germany. *Theor Appl Climatol* 102: 61-74.
942 doi: 10.1007/s00704-009-0240-8
943 Wesely ML (1976) Combined effect of temperature and humidity fluctuations on refractive-index. *J*
944 *Appl Meteorol* 15: 43-49.
945 Wood CR and Järvi L (2012) An overview of urban climate observations in Helsinki. *Magazine of the*
946 *Finnish Air Pollution Prevention Society*: 30-33
947 Wood CR, Kouznetsov RD, Gierens R, Nordbo A, Järvi L, Kallistratova MA and Kukkonen J (2013) On
948 the Temperature Structure Parameter and Sensible Heat Flux over Helsinki from Sonic
949 Anemometry and Scintillometry. *J Atmos Ocean Technol* 30: 1604-1615. doi: 10.1175/JTECH-
950 D-12-00209.1
951 Wood N and Mason P (1991) The influence of static stability on the effective roughness lengths for
952 momentum and heat transfer. *Q J R Meteorol Soc* 117: 1025-1056. doi:
953 10.1002/qj.49711750108
954 Wyngaard JC (1973) On surface-layer turbulence. *Workshop on micrometeorology*, American
955 *Meteorological Society*
956 Zieliński M, Fortuniak K and Pawlak W (2012) Turbulent sensible heat flux in Łódź obtained from
957 scintillometer measurements - comparison of free and mix algorithms. *Contemporary Trends*
958 *Geosci* 1: 109-117.
959 Zilitinkevich SS, Mammarella I, Baklanov AA and Joffre SM (2008) The effect of stratification on the
960 aerodynamic roughness length and displacement height. *Boundary-Layer Meteorol* 129:
961 179-190. doi: 10.1007/s10546-008-9307-9

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