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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 km<sup>2</sup>, whilst the long path extends from the rural outskirts to the town centre and has a source area of around 5-10 km<sup>2</sup>. 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 km<sup>2</sup> (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 ( $\beta$ ) correction given by Wesely (1976) (see Moene (2003)  
105 for full details and a discussion) is not implemented in Equation 1 because  $\beta$  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  $\zeta$  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  $\kappa_v$  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  $\rho$  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  $Q_{H\_EC}$ .

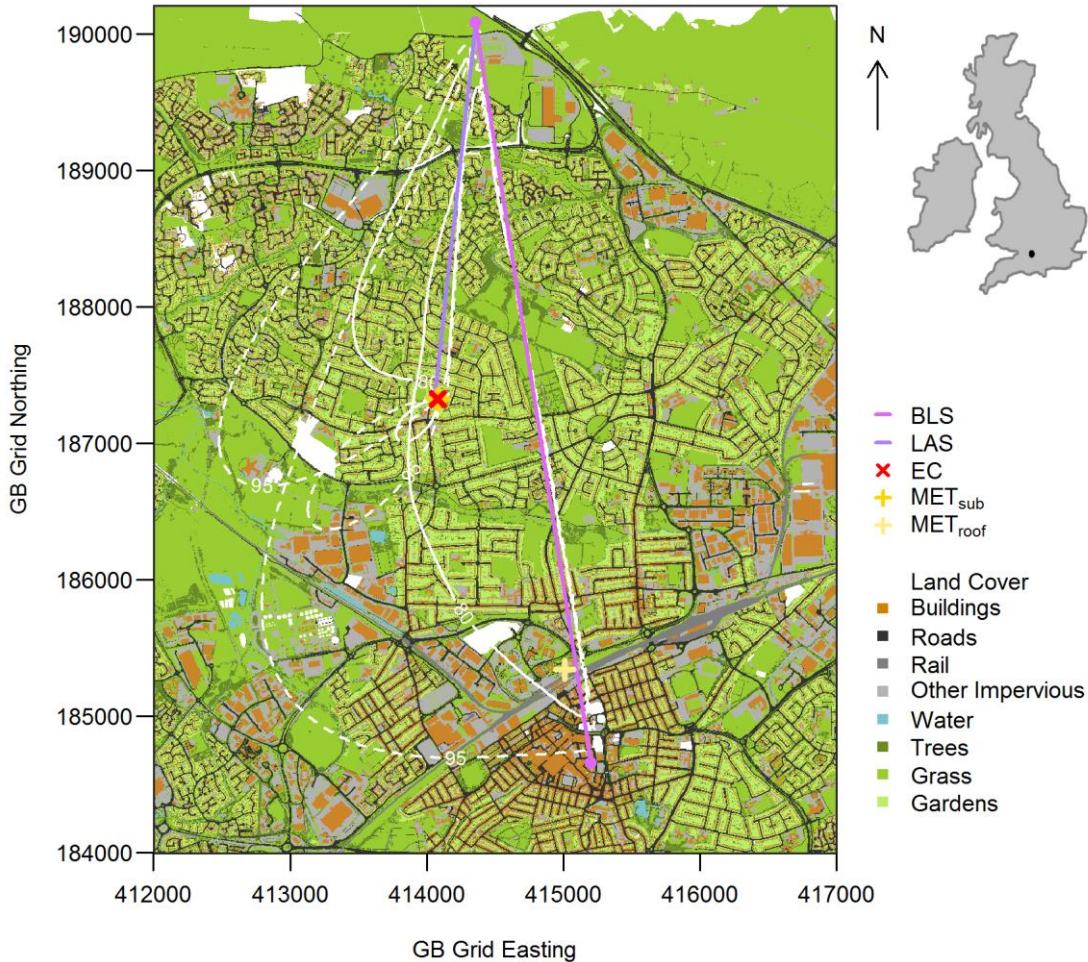
133 One drawback of scintillometry is that the sign of the heat flux is unknown and must be assigned  
 134 based on other information. Following a comparison of possible algorithms, Samain et al. (2012)  
 135 recommended using an algorithm based on the minima in the diurnal cycle of  $C_n^2$  to indicate 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>sub</sub> and MET<sub>roof</sub>). Example footprints for typical atmospheric conditions (wind direction = 225°,  
 157  $L_{Ob} = -200$  m,  $u_* = 0.5$  m s<sup>-1</sup> and  $\sigma_v = 0.9$  m s<sup>-1</sup>) 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<sup>-1</sup> and standard deviation of  
186 lateral wind  $\sigma_v = 0.9$  m s<sup>-1</sup>). 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 km<sup>2</sup> (0.5, 3.0 and 7.5 km<sup>2</sup>) 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

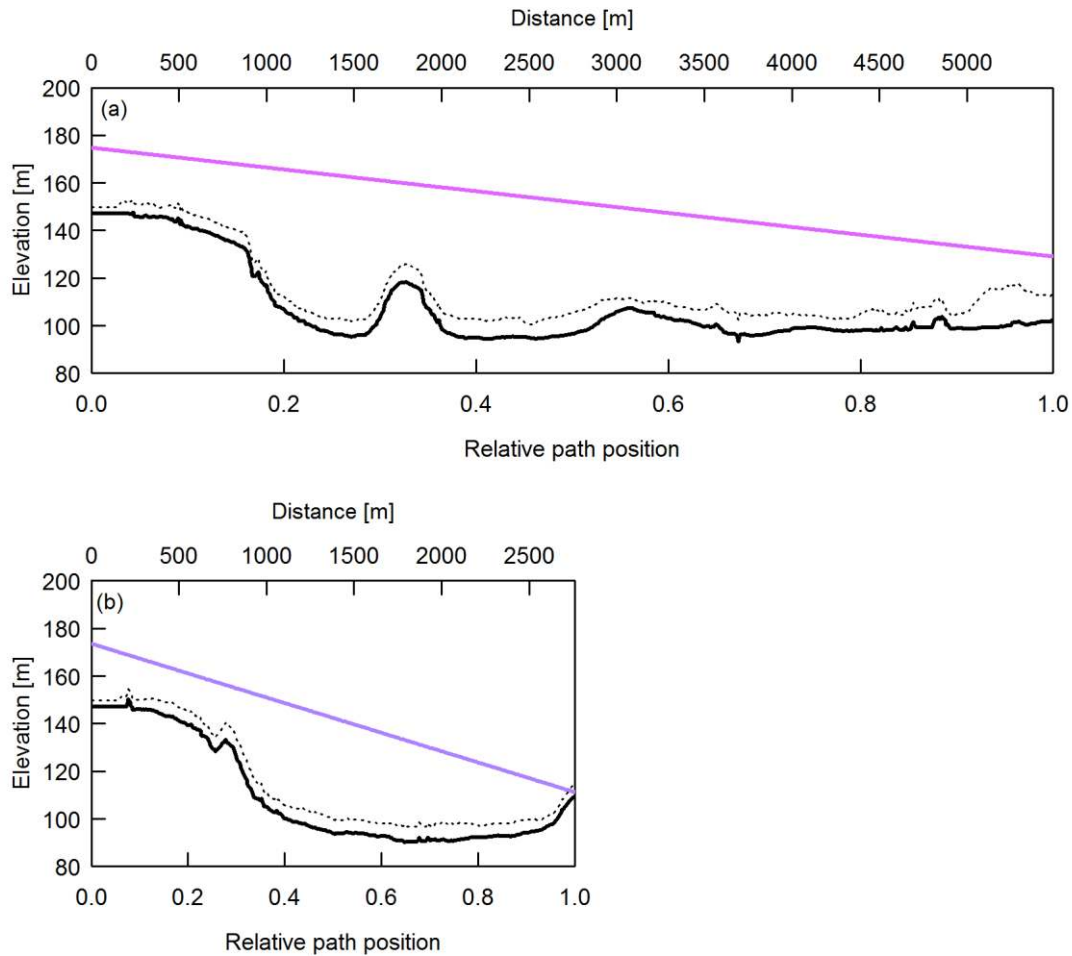
198 for the LAS path, when winds are from the west or north-west and in stable conditions, as this recent  
199 development has not yet been incorporated in the spatial database.

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,  $z_{d0}$ , 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>sub</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 <sub>roof</sub> *	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<sub>roof</sub> 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>sub</sub> and unadjusted MET<sub>roof</sub> 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  $\beta$  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 ( $\Delta Q_s$ ) 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  $\beta$  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  $\beta$  (Meijninger and De Bruin  
299 2000). When  $\beta$  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<sub>roof</sub> was adjusted to produce  
310 the combined dataset with optimum availability of input data. Concurrent  $Q_H$  values calculated using  
311 the MET<sub>sub</sub> wind speed or the adjusted MET<sub>roof</sub> 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<sup>-2</sup>).

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>sub</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  $K_1 > 5 \text{ W m}^{-2}$ , 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 England<sup>1</sup>. 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.

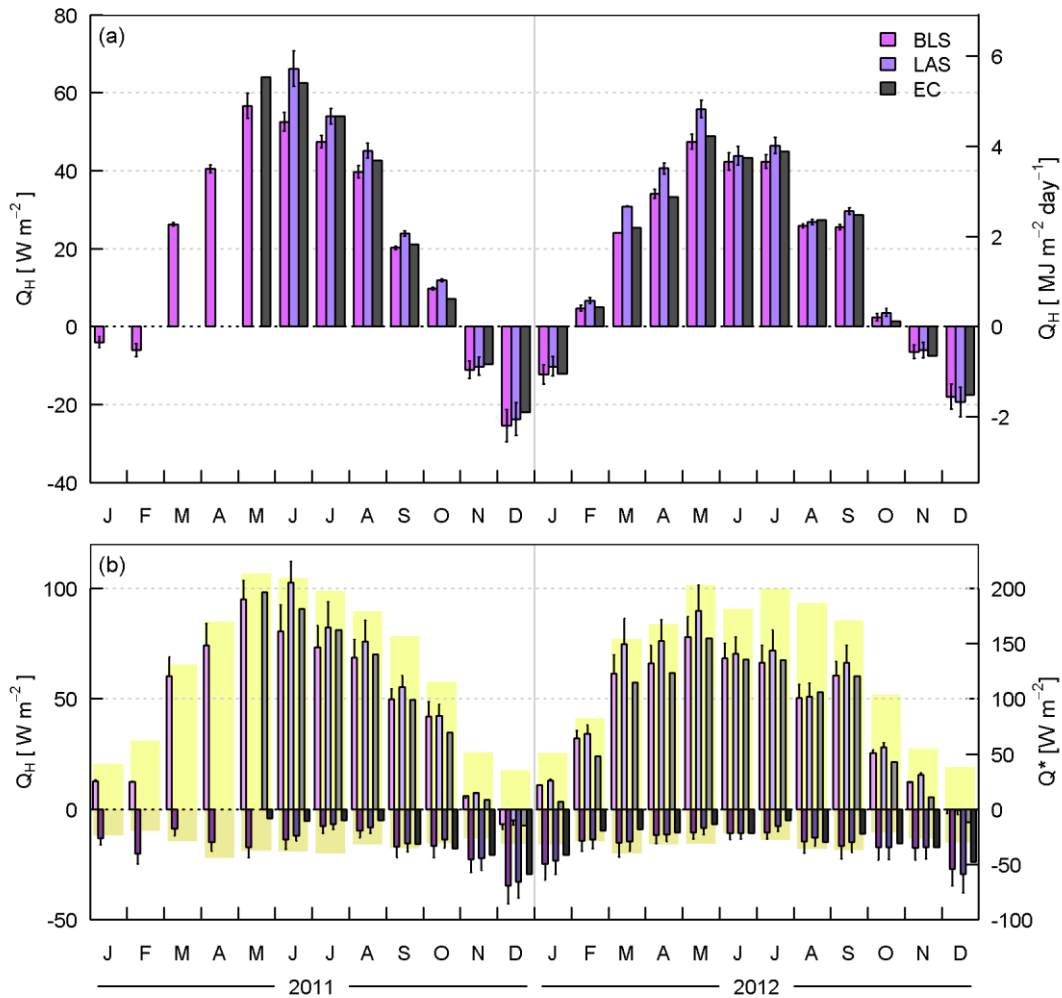
347 June 2012 was particularly wet and cloudy (sunshine hours were only 70% of normal<sup>1</sup>; mean  
348 daytime  $K_{\downarrow}$  was  $174 \text{ W m}^{-2}$  in 2012 compared to  $212 \text{ W m}^{-2}$  in 2011). Monthly mean daily  $Q_H$  was  
349 19%, 34% and 31% lower than in June 2011 for 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

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



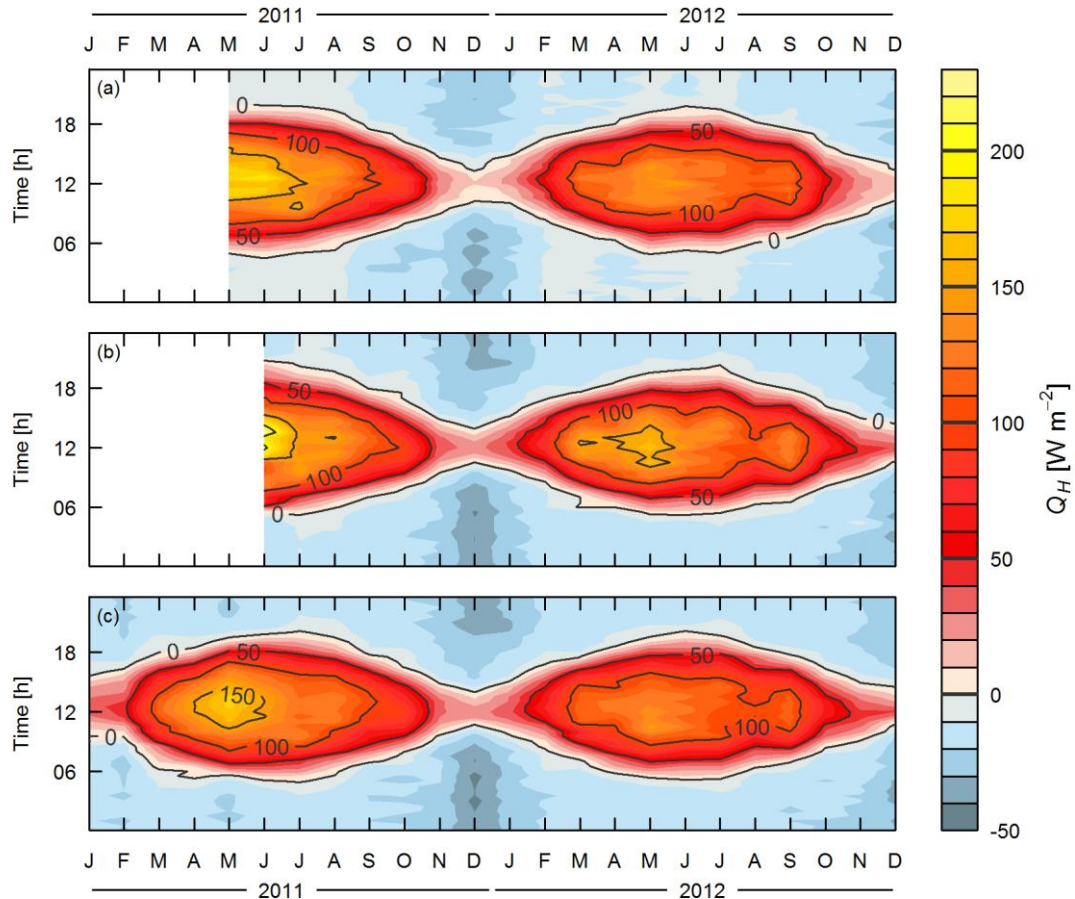


357

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 ( $K_t > 5 W m^{-2}$ ) 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  $\pm 0.2$   
 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  $150 \text{ W m}^{-2}$ , 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  $\pm 0.2$  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  $z_{ef}$  ( $\pm 2.25$  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

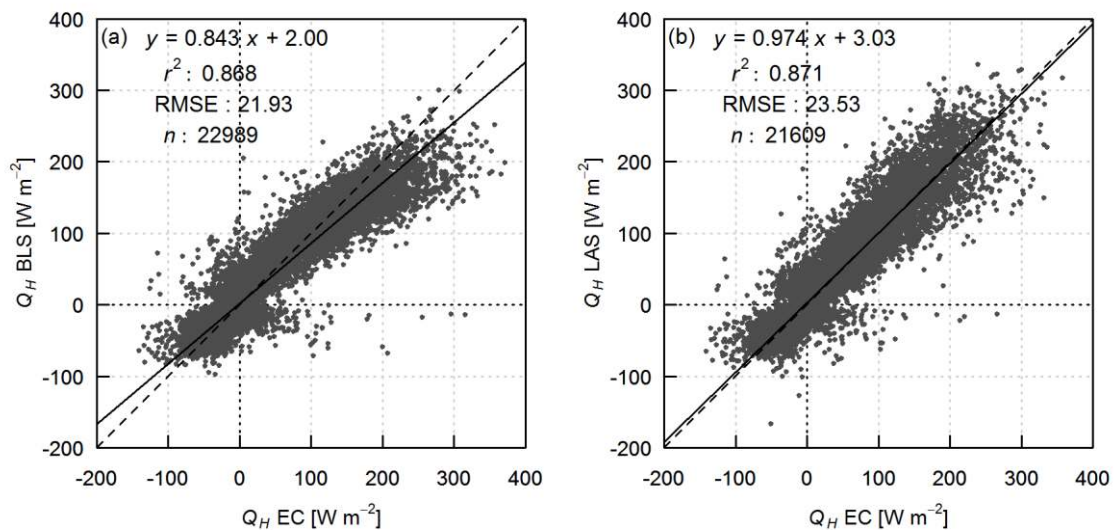
414 Direct comparison of 30 min sensible heat fluxes obtained from scintillometry and EC (Fig. 5)  
415 indicates reasonably good agreement between the measurement techniques and across the scales  
416 with strong correlation ( $r^2 \approx 0.87$ ). The slope of the regression between  $Q_{H\_LAS}$  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  $\beta$  is

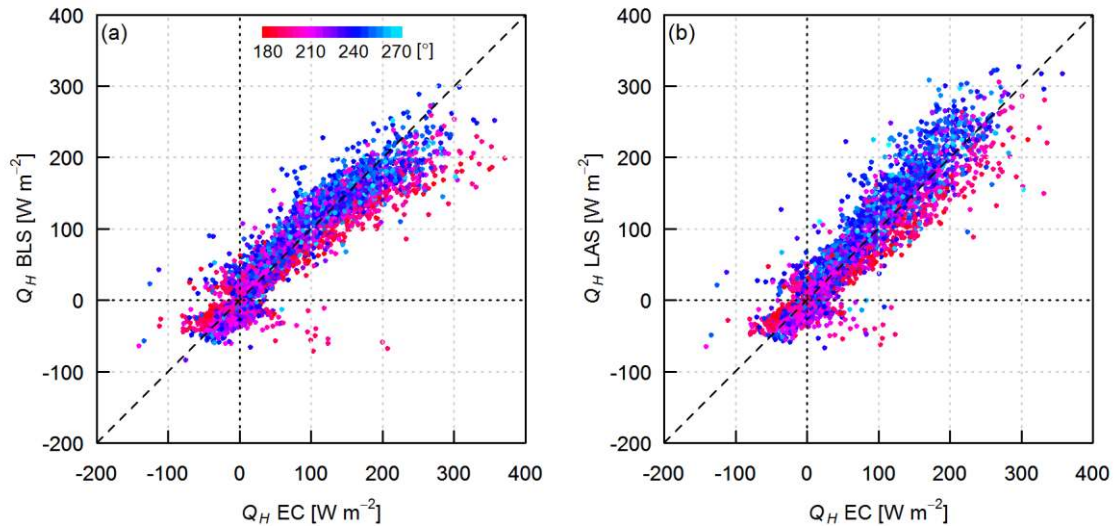
446 small). The Bowen ratio correction to  $C_T^2$  introduces the larger error of these two approximations;  
 447 neglecting the buoyancy correction to the Obukhov length (e.g. Green et al. (2001)) is thought to  
 448 lead to a slight underestimation in  $Q_H$  of  $\approx 0.5 \text{ W m}^{-2}$ . 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  $13 \text{ W m}^{-2}$  (BLS) and  $9 \text{ W m}^{-2}$  (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 ( $15 \text{ W m}^{-2}$ ) 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  $\text{MET}_{\text{roof}}$ ,  
 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  $Q^*_{\text{roof}}$  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.

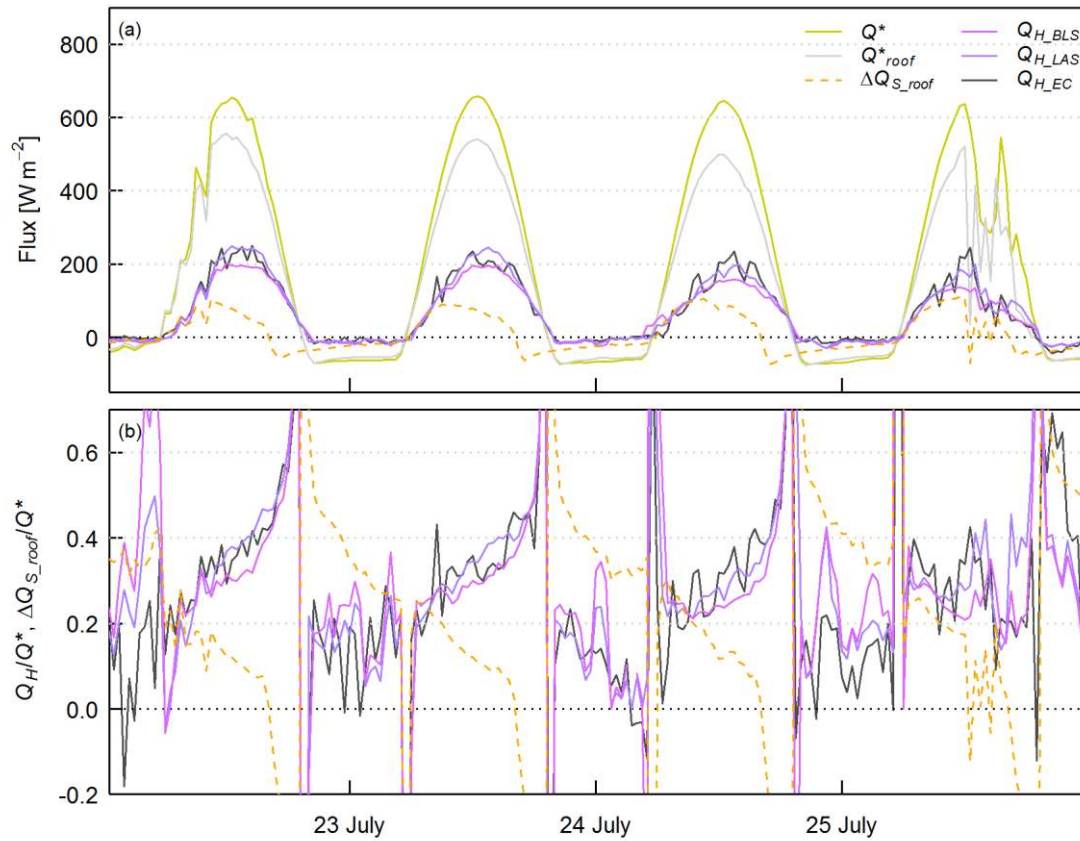
485 For clear days, the phase of  $Q_H$  is lagged relative to  $Q^*$ . At the three scales  $Q_H$  peaks after  $Q^*$  and  
 486 remains positive later into the evening than  $Q^*$ . One component of the urban net heat storage flux is  
 487 approximated by a heat flux plate installed under the roof covering at  $\text{MET}_{\text{roof}}$  ( $\Delta Q_{S, \text{roof}}$  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  $\Delta Q_{S\_roof}$  (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  $600 \text{ W m}^{-2}$  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.

512



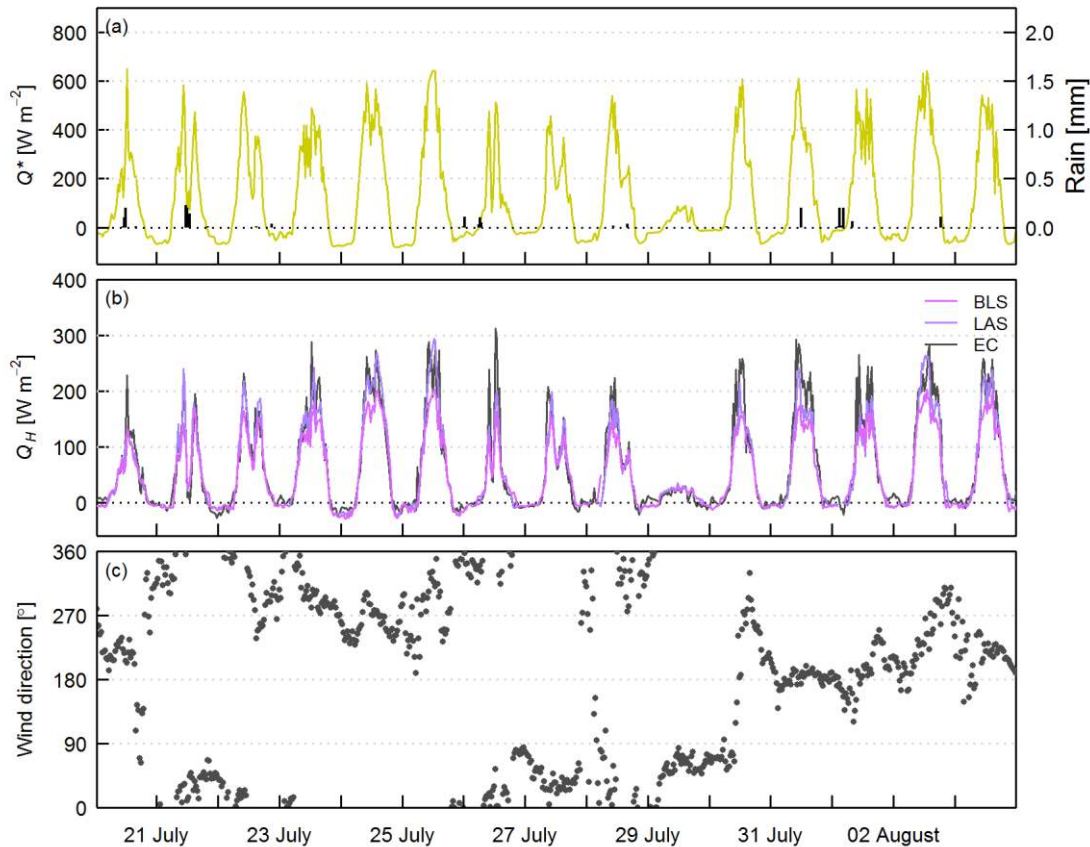


513

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**

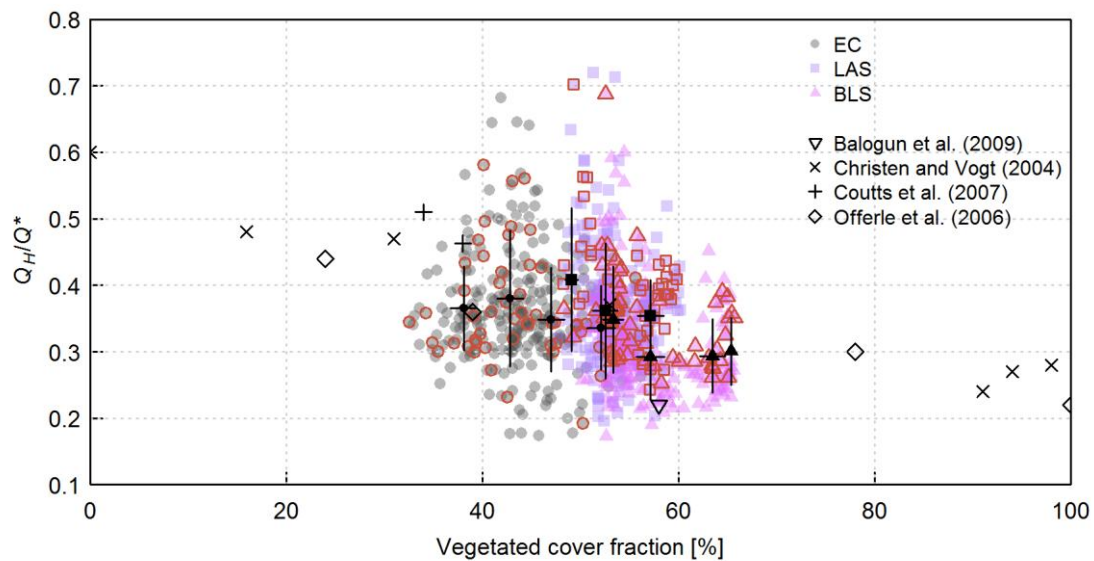
547 Comparing the relative sizes of the fluxes can offer insight into key controls on suburban energy  
548 partitioning. Towards the end of the case study in Fig. 8 (30 July-01 August 2011),  $Q_{H\_EC}$  peaks at  
549 larger values than either of the scintillometers, whilst  $Q_{H\_LAS}$  is generally 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 ( $\pm 5.0$ ) %, 53.9 ( $\pm 2.9$ ) %  
564 and 56.9 ( $\pm 4.5$ ) % 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  $\leq 2$  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  $\beta$ . 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  $\beta$  correction  
644 would act to further decrease  $Q_H/Q^*$  with vegetation fraction. As  $\beta$  itself has been shown to depend  
645 on the vegetation fraction, smaller  $\beta$  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  $\beta$ -  
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  
687 health and well-being.

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696

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