

amt-2014-321: Response to reviews

We are very grateful for the appraisals of this two-part study, particularly given the time required to assess both papers together. We thank the reviewers for their positive feedback and valuable suggestions for improving the manuscripts. All comments have been taken into account. Detailed responses to each point are provided below (in bold type), followed by the revised manuscript with the changes indicated.

Interactive comment on “Infrared and millimetre-wave scintillometry in the suburban environment – Part 2: Large-area sensible and latent heat fluxes” by H. C. Ward et al.

B. van Kesteren (Referee)

The authors present a two-part study in which they present the results of the first long-term application of an optical-microwave scintillometer system over Swindon, UK. In the first part, they present the results in terms of structure parameters and in the second part they present the results in terms of the heat fluxes.

Indeed, both manuscripts present research novel in many aspects. The application of a combined optical-microwave scintillometer system has been presented before, but never for such an extensive time period, nor over the city centre. This first part addressed many technical issues, whereas the second part focuses more on the retrieval of turbulent fluxes and environmental aspects. The authors have shown a great competence and insight in the methods and understanding of scintillometry at the one hand and the urban environment at the other hand. The manuscript is generally of a high scientific quality, presenting innovative results, and very well written, so that I recommend publication after some minor revisions.

Some comments from Part 1 were found to be relevant here as well and are simply copied.

P 11222, line 3 and elsewhere – “evaporation” seems to be used throughout this paper as a synonym for “evapotranspiration”, but not always. For accuracy, I would prefer the term “evapotranspiration” where applicable, or a definition at the beginning of the paper explaining what the authors think of when using the word “evaporation”.

- **‘Evapotranspiration’ is now used throughout. (Note that Brutsaert (1982) and others indicate that ‘evaporation’ can cover both terms.)**

P 11222, line 4 – to what does “this technique” refer?

- **The text now reads ‘this ‘two-wavelength’ technique’.**

P 11223, line 23 – “refraction”, it results from diffraction. Rewrite.

- **Changed to ‘diffraction’.**

P 11223, line 21-25 – this is a very long and complex sentence. Please simplify.

- **The text now reads, ‘The beam intensity varies in time due to diffraction by eddies of different densities, dependent on their temperature and humidity content. Changes in**

temperature and humidity are expressed as the temperature and humidity structure parameters, which are converted to fluxes of heat and water vapour using similarity theory.'

P 11224, line 23 – it seems RPG sells the microwave scintillometers by now.

- **The text has been updated to read, 'although a commercially available system has recently been developed'**

P 11225, last paragraph – the time frame of the experiment should be mentioned in the introduction, as well as the notion that seasonal variability is addressed in the paper. This introduction much better gives the objectives of this paper, than was the case in Part I. Nevertheless, the authors should better present the research themes.

- **Seasonal variability and the length of the dataset are now given in the Introduction.**

P 11226, Eq. (2) – please, give a reference for this equation.

- **A reference to Green et al. (2000) has been added.**

P 11226, line 20-21 – the authors should give some more information on their methodology regarding the retrieval of the friction velocity. This is a very general statement. Probably, the Kansas functions were used (Businger-Dyer)?

- **Yes, the Businger-Dyer functions were used and this is now mentioned in the text.**

P 11227, line 2 – Braam et al. (2014) also gives a very useful assessment on methodology, measurement height, instrumentation and other aspects influencing the similarity functions.

- **We agree and have added the reference to the text.**

P 11227, Eq. (5) – Ward et al., (2013b) gives a different definition in their Eq. (17). What happened to the $1/(1-q)$ term here?

- **The $(1-q)^{-1}$ multiplier makes a very small difference of <1% (0.7% on average), so can be reasonably approximated by 1.**

P 11228, line 13 – the authors could give a reference to Part I here.

- **We decided not to reference Part 1 here as the information is given here.**

P 11229, line 9-20 – there is rather much repetition here as compared to Part I. Could it be shortened? In any case remains the question whether the authors could elaborate on the issue regarding the meteorological measurements being scaled to fit the scintillometer effective height?

- **This section has been shortened and a reference added to Part 1. As mentioned in the response to reviews for Part 1, the height of the wind speed measurement was accounted for but it is not necessary to adjust temperature, pressure or humidity over these distances.**

P 11230, line 27 – add a comma after “fluxes” for readability.

- **Done.**

P 11232, line 21 – recommend to change “two-wavelength structure parameters have been” to “the two-wavelength method has been”

- **The sentence now reads, ‘For this reason, structure parameters obtained via the two-wavelength method have been used to calculate the scintillometric fluxes presented below.’**

P 11236, section 4.1.3 – at latest here, it would be good to mention that scintillometry is an indirect method for measuring fluxes (Wyngaard and Clifford, 1978).

- **This is now mentioned in Section 2.**

P 11236, line 6-8 – the Meijninger studies did rely on absolute humidity instead of specific humidity and hence probably made some error (see Ward et al., 2013). Furthermore, Meijninger 2002 uses De Bruin similarity functions, whereas in 2006 they used the mean value of the Andreas and De Bruin functions; therefore, comparing these studies is a bit tricky. Lastly, they ignored the humidity effect on the Obukhov length. To conclude, analysing of these values must be done with care, even though the authors are right in addressing the uncertainty in the EC values.

- **A note has been added that the scintillometry data were not processed identically in these two studies. Nevertheless, the common result that scintillometer fluxes exceed EC fluxes was found in both cases.**

P 11237, line 1 – so, the authors rule out the effect of the anthropogenic flux?

- **Yes, the estimated anthropogenic heat flux is too small ($10\text{-}15\text{ W m}^{-2}$) to fully account for these offsets.**

P 11237, line 13-15 – the values of DB93 and An88 are smaller than observed. Interesting to observe here is that Thiermann and Grassl (1992) seem to fit much better for neutral conditions. They derived their formulation from the variance-budget equations, see e.g. Wyngaard and Kosovic (1994) or Andreas (1988) – his Eq. 4.30. Assuming $\phi_{iT} = \phi_{iM} = 1$, yields for $z/L = 0$, the value 6.37. This value has some clearly defined theoretical assumptions behind it (e.g. horizontal homogeneity, no advection ...). Hence, it would be worth mentioning and discussing some of these details I think.

- **The observed humidity scaling mostly lies between TG92 and An88/ DB93 for slightly stable conditions; for slightly unstable conditions TG92 is too large (Figure A1). For temperature and for non-neutral conditions TG92 is not a good match to the observations. We decided to limit the discussion to the similarity functions used in the paper. It would be beyond the scope of these papers to discuss details of the derivations and assumptions for other similarity functions.**

P 11239 – line 5-10 – “rejection of QE when IRGA windows are wet results in underestimated EC fluxes” and “(b) suffers a bias to “count” $QE < 0$ (dewfall) as $QE > 0$ ”. Are not the IRGA windows wetted as well during dewfall? This would lead to an overestimation of QE in case these situations are omitted from the analysis, wouldn’t it?

- Yes, EC is expected to underestimate dewfall ($Q_E < 0$), which translates into an overestimate of evapotranspiration ($Q_E > 0$). This has been clarified by adding the following text, '(except when dewfall wets the IRGA windows and it is $Q_E < 0$ that is not measured)'.

Interactive comment on “Infrared and millimetre-wave scintillometry in the suburban environment – Part 2: Large-area sensible and latent heat fluxes” by H. C. Ward et al.

M. Irvine (Referee)

This paper is the second of a two part study. The first part dealing with structure parameters and this paper (the second part) dealing with the important practical question of transforming measured structure parameter values to evaporation (the sum of surface evaporation and evapotranspiration) at footprint scales in phase with land use scales and satellite observations. This is done using optical and radio scintillometry combining one, two and bichromatic wavelength methods over a suburban landscape with seasonal timescales. As such this study is both original and important to the scientific community demonstrating an operation method of observing evaporation at this important land use scale. Furthermore the authors discuss in detail potential advantages and short comings of the method allowing the reader to evaluate its potential for their use.

Here are a couple of comments:

P11233 line 23 I think you can add the bichromatic method along with the two-wavelength method.

- **We used ‘two-wavelength’ scintillometry here following the decision to use the two-wavelength (rather than bichromatic) structure parameters to calculate fluxes (due to the inherent variability of the bichromatic technique).**

P11234 lines 26 and 27 Why if saturation is a problem it possible to have Sensible Heat values on some days that are higher than the ‘saturation limit’?

- **As there is no distinct cut-off or limit for saturation (the effect increases the more saturated the signal), it is possible to have QH values affected by saturation (i.e. QH that is underestimated) whilst still having higher QH values at other times (that are underestimated to a greater extent). Discussion of saturation is clearly unhelpful here so it has been deleted; the differences are most likely due to the spatial sampling issues described.**

P11236 line 15 large-scale circulations. It is probable that the scintillometry ‘sees’ more large scale eddies on its path. It is perhaps useful to mention this.

- **The following text has been added, ‘(for example, scintillometers have a much larger spatial sampling volume)’.**

A comment to finish the transformation from structure parameter to flux, especially for water, is probably the weak link.

- **The text, ‘as the conversion of structure parameters to fluxes is accompanied by substantial uncertainties, especially for humidity’ has been added to the Conclusions.**

Interactive comment on “Infrared and millimetre-wave scintillometry in the suburban environment – Part 2: Large-area sensible and latent heat fluxes” by H. C. Ward et al.

Anonymous Referee #3

Single review of both of the companion papers:

----- Overall comments / thoughts: -----

* A positive contribution to land-surface interactions, micro-meteorology, and scintillometry. This paper will certainly move science forward.

* Excellent quality figures (science and presentation).

* A very thorough work.

* In particular, Fig1 in the second paper is very important and nicely laid out.

* Language is almost flawless.

* It is a rare pleasure to review work of both high quality science and presentation.

----- Suggestions for improvements in general throughout the manuscripts: -----

* Can the uniqueness (a world first) of this work be more upfront, e.g. in the Highlights?

- **The Introduction has been modified to more clearly state the objectives and contributions of this work (please see responses to other comments).**

Some specific comments:

PAPER-A: ---

- **Please see Part 1 response.**

PAPER-B: ---

Figure 1 » Commendably excellent in terms of content and presentation.

11229/10 » More info needed? e.g. WXT-510...

- **The automatic weather station was upgraded from a WXT 510 to a WXT 520 during the study period. The text has now been changed to read, ‘WXT 510/520’ in both papers.**

Interactive comment on “Infrared and millimetre-wave scintillometry in the suburban environment – Part 2: Large-area sensible and latent heat fluxes” by H. C. Ward et al.

J.-M. Cohard (Referee)

H. Ward et al. present a paper series called “Infrared and millimetre-wave scintillometry in the suburban environment” containing 2 parts. – Part 1 is about the different ways to obtain structure parameters for temperature and specific humidity from scintillometers at different wave lengths. The part 2 is about the way to derive average turbulent fluxes from these structure parameters. The first part evaluates the performance of 3 methods, namely the single wave length method, the bichromatic method and the 2 wave length method. The second part develops objectively advantages and limitations of the scintillometry techniques. Both parts analyse a 14 months data time series obtained from July 2011 to December 2012 above Swindon (UK).

Theoretical backgrounds are clearly exposed highlighting the assumptions and limitations of the techniques deployed during this experiment. Results give a complete and detailed panorama of what is to be done when using Infra Red and Microwave scintillometers. It is based on the longest time series ever obtained for such technique. This huge amount of results and remarks will be very useful for any one wants to apply scintillometry techniques in the future. Urban surface Bowen ratios are finally presented and compared to previous studies. This last part will certainly require further analysis, but it is clearly not the main objective of these papers.

Finally, this matches very well with the AMT journal and has to be published after minor corrections.

Some comments on both parts are listed below.

Part I : Structure parameters

- **Please see Part 1 response.**

Part II : Large-area sensible and latent heat fluxes

11222 : “” This is a classical result. For a highlight, it would be better to announce “Energy partitioning land cover dependencies of urban areas”

- **Changed to ‘Land cover influences on urban energy partitioning’**

11224 –L22 :MW scintillometer are now available at RPG in Germany.

- **The text has been updated to read, ‘although a commercially available system has recently been developed’**

11227 L12 : u^* was not introduced before. Define it and explain how you estimate it at scintillometer scale.

- **u^* is introduced after Equation 2 and more information has now been provided in accordance with other reviewer’s suggestions too.**

11233 - L 4 : “ ... whereas EC is usually capable of providing fairly continuous Q_H “ I would not say that. If sonic anemometers are able to provide continuous measurements during rainfall it is not straight forward to interpret these covariance measurements to be related to surface fluxes.

- **Unlike EC systems comprising open-path gas analysers, one of the often cited advantages of EC systems comprising closed-path gas analysers is that they are often able to provide fluxes during and directly after rainfall (e.g. Haslwanter et al. 2009; Burba et al. 2010). The literature suggests that Q_H values are not necessarily removed from EC data during rainfall, unless the rainfall is intense (e.g. Evans et al. 2012). The design of the sonic is another consideration; some models are less affected by rainfall than others. The wording has been altered to reflect the fact that Q_H values obtained during rainfall are often used ('EC usually provides fairly continuous Q_H measurements except during heavy rainfall'), without making a statement about whether this is valid or not. Spikes are seen in the sonic temperature when rainfall interferes with the measurement; here a threshold on the standard deviation of temperature (> 0.9 K) is used to identify and reject these data.**

11235 : L5 & L26 : Generalities on Q^* are not welcomed ! First the footprint of Q^* and Q_{H_EC} are not really similar even above 10m turbulent fluxes are wind direction dependent but not radiative budget. Secondly, radiative budget is different from a land cover to another. Compensation could occur but it's far from a general behaviour. You don't need to say that to convince the readers. Figure 5 is enough!

You'd better develop this idea considering this is still an issue to obtain radiative budget at scintillometer scale until we can't trust in remote sensing products.

- **The explanation on page 11235 has been rewritten as follows: '...the EC system and radiometer are located on the same mast, so their footprints are located in approximately the same area, whereas the footprint of the scintillometer system is larger and in a different location. These differences are particularly relevant when considering how the surface responds to patchy cloud cover across scales of 10-100 m.'**
- **Regarding the second points, the text has been modified to provide a more balanced perspective and a second references has been added: 'There may also be differences in Q^* between the source areas, although studies have suggested that the radiation budget may not vary between surfaces as much as might be expected because the relevant properties (albedo and radiative temperature) tend to have compensating effects on the outgoing shortwave and longwave radiative fluxes (Schmid et al. 1991; Christen and Vogt 2004). Nevertheless, spatial variability in cloud cover still makes it challenging to obtain Q^* measurements representative of scintillometer source areas.'**

11235 & 11236 L20: A scatter plot comparing Q^* with $Q_E + Q_H$ for the all observation period would be very helpful to follow the discussion.

- **To avoid making the paper any longer we decided not to add additional plots to the paper, but have included them here for 30-min (Figure AC1) and daily averages (Figure AC2). Note that the statistics provided in the paper have been updated (corrected) in accordance with those shown here.**

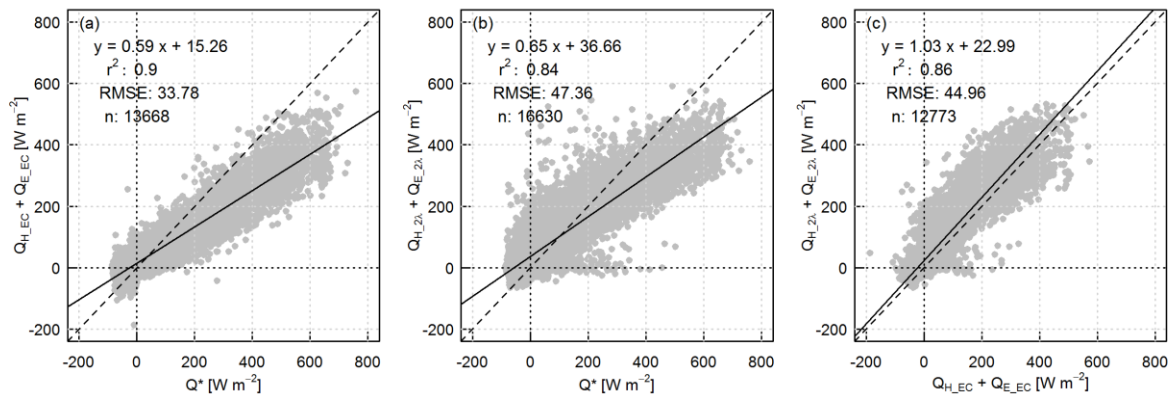


Figure AC1 Scatter plots of 30-min flux data. The solid line is the fitted linear regression; the dashed line is 1:1.

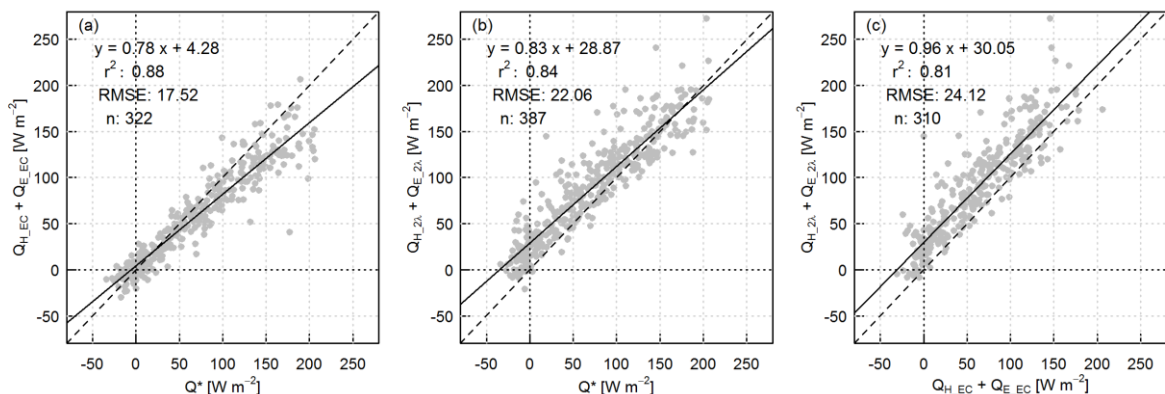


Figure AC2 Scatter plots of daily average fluxes (excluding days with < 50% data available). The solid line is the fitted linear regression; the dashed line is 1:1.

11239 L 5 – 18 : This paragraph is much more a conclusion and should be displaced.

- **We feel it is important to summarise the uncertainties and limitations of the methods used here, before going on to interpret the results in terms of seasonality and other sites. We therefore decided to leave this paragraph where it is.**

11239 L25 : Difficult to conclude on the relation between latent heat fluxes and rain as Q^* is also much higher in 2012. Remarks on bowen ratio are much convincing.

- **This sentence has been deleted.**

11242 :L 6 – 13. This part of the conclusion doesn't refer completely to what has been developed in the paper. The control by available energy and water on flux partitioning is not a strong conclusion. Unfortunately I found it difficult to get a general conclusion on processes at this stage. Figure 9 gives a kind of tendency but with large scatter. Indeed this certainly depends on urban morphology at least. These data required certainly further investigation. I suggest you insist more on the scintillometer techniques and again displaced in the conclusion the concluding paragraph from page 11239.

- This part of the conclusion has been modified to better reflect the content of the paper. The conclusion begins, ‘The first observations of large-area heat fluxes using the two-wavelength scintillometry technique are presented for the urban environment. Higher evapotranspiration rates (and lower β) from the BLS-MWS (1-3 mm day⁻¹ on average) compared with the EC measurements (0.5-2 mm day⁻¹) are partly attributed to the greater proportion of vegetation typically within the BLS-MWS source area. In winter, vegetation plays a smaller role (β is more similar between BLS-MWS and EC datasets) and the available energy is a crucial factor so Q_H is often negative as a consequence of energy being directed mainly into Q_E' before going on to summarise the methodological differences.

Fig 2 : footprint areas not shaded enough.

- The footprint areas are now more clearly marked.

Limiting stabilities ? precise.

- The lower limit is for free convection conditions and the upper limit is for neutral conditions (e.g. see Figure 3 of Hartogensis et al. (2003)). The wording of the Table 1 caption has been changed and this part now reads ‘the range in effective height represents the variation with stability’.

References

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Infrared and millimetre-wave scintillometry in the suburban environment – Part 2: large-area sensible and latent heat fluxes

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Abstract

A millimetre-wave scintillometer was paired with an infrared scintillometer enabling estimation of large-area ~~evaporation~~evapotranspiration across northern Swindon, a suburban area in the UK. Both sensible and latent heat fluxes can be obtained using this 'two-wavelength' technique, as it is able to provide both temperature and humidity structure parameters, offering a major advantage over conventional single-wavelength scintillometry. The first paper of this two-part series presented the measurement theory and results of the structure parameters. In this second paper, heat fluxes are obtained and analysed. These fluxes, estimated using two-wavelength scintillometry over an urban area, are the first of their kind. Source area modelling suggests the scintillometric fluxes are representative of 5-10 km². For comparison, local-scale (0.05-0.5 km²) fluxes were measured by an eddy covariance station. Similar responses to seasonal changes are evident at the different scales but the energy partitioning varies between source areas. The response to moisture availability is explored using data from two consecutive years with contrasting rainfall patterns (2011-2012). This extensive dataset offers insight into urban surface-atmosphere interactions and demonstrates the potential for two-wavelength scintillometry to deliver fluxes over mixed land cover, typically representative of an area 1-2 orders of magnitude greater than for eddy covariance measurements. Fluxes at this scale are extremely valuable for hydro-meteorological model evaluation and assessment of satellite data products.

Keywords: bichromatic correlation; energy balance; ~~evaporation~~evapotranspiration; spatially-integrated fluxes; two-wavelength scintillometry; urban

Highlights

- Observed large-area sensible and latent heat fluxes for an urban area
- Multi-seasonal comparison of eddy covariance and scintillometry techniques
- Interpretation of two-wavelength fluxes aided by bichromatic-correlation data
- ~~Energy partitioning strongly dependent on land cover~~
- Land cover influences on urban energy partitioning
- Suburban ~~evaporation~~evapotranspiration exceeds 3 mm day^{-1} for vegetated areas

1. Introduction

There is considerable demand for large-area estimates of ~~evaporation~~evapotranspiration, or its energy equivalent, the latent heat flux. Observations of catchment-scale ~~evaporation~~evapotranspiration are required for hydrological modelling, both to evaluate model performance and as forcing data for flood forecasting and for real-time river flow and water balance models. For rural environments knowledge of ~~evaporation~~evapotranspiration is important for irrigation scheduling, crop management and crop yield prediction – applications which will become increasingly important with the demands of food and water security as the world's population continues to grow. The latent heat flux has been shown to be a significant component of the energy and water balance in urban areas, particularly for vegetated neighbourhoods (e.g. Grimmond and Oke 1995; 2002). Accurate measurement and prediction of urban ~~evaporation~~evapotranspiration is important for assessing the merits of urban design options (such as green roofs), water management schemes (e.g. irrigation bans) and strategies for sustainable urban drainage (Xu and Chen 2005; Mitchell et al. 2008), as well as for better understanding of thermal comfort and flood risk.

As a tool for routine monitoring of heat fluxes, scintillometry offers several advantages: measurements are spatially representative, of high temporal resolution (30 min or shorter) and continuous (i.e. not limited to cloud-free days as for some satellite products), with the ability to inherently cope with heterogeneity; systems are practical to install and low maintenance (e.g. Kleissl et al. 2009). Scintillometers measure the intensity of an electromagnetic beam transmitted through the turbulent atmosphere. ~~Changes in intensity due to refraction by eddies of differing densities are related to changes in temperature and humidity, expressed as the temperature and humidity structure parameters, from which the fluxes of heat and water vapour are obtained using similarity theory. The beam intensity varies in time due to diffraction by eddies of different densities, dependent on their temperature and humidity content. Changes in temperature and humidity are expressed as the temperature and humidity structure parameters, which are converted to fluxes of heat and water vapour using similarity theory.~~ At infrared (or optical) wavelengths, temperature fluctuations dominate, so these instruments are suitable for deriving the sensible heat flux. Longer wavelengths (e.g. microwaves, radiowaves) are more sensitive to humidity fluctuations so that, in combination with infrared, both sensible and latent heat fluxes can be obtained more directly (Hill et al. 1988; Andreas 1989); with a single infrared instrument estimating the latent heat flux relies on closure of the energy balance.

Hill et al. (1988) outlined the two-wavelength theory and demonstrated the viability of the technique by comparison with structure parameters and fluxes from other micrometeorological methods at a very homogeneous agricultural site. The technique has since been used to estimate heat fluxes over a vineyard (Green et al. 2000), pasture (Green et al. 2001), mixed agricultural landscapes (Meijninger et al. 2002a) and mixed agriculture with complex topography (Evans et al. 2010). The heavily-instrumented LITFASS campaigns (Beyrich and Mengelkamp 2006) focus on heterogeneous land cover, mainly mixed agriculture. During LITFASS-2003, heat fluxes from aggregated eddy covariance (EC) data compared with two-wavelength scintillometry estimates indicated generally good performance over the 11-day measurement period (Meijninger et al. 2006).

In addition, the bichromatic-correlation method was developed and tested (Beyrich et al. 2005; Lüdi et al. 2005). This extension to the two-wavelength method enables a path-averaged measurement of the temperature-humidity correlation coefficient, thus removing the need to assume its value as with the traditional two-wavelength method. In the overview paper of LITFASS-2009 (Beyrich et al. 2012) structure parameters from two example days, 12-13 July 2009, are presented. Two-wavelength scintillometry remains a specialist technique at present, as only a few instruments of longer wavelength exist, although ~~development of a~~ commercially available systems has recently been developed-is underway (Hartogensis et al. 2013). A three-wavelength method has also been proposed as a solution to obtaining the combined temperature-humidity fluctuations, but would require at least three scintillometers and sensitivity analyses suggest results may not be significantly improved over the two-wavelength method (Andreas 1990).

Single-wavelength (large aperture) scintillometry is now a fairly well-established technique deployed in a variety of locations, although its use in urban environments has only developed recently. A three week campaign in Marseille demonstrated good agreement between scintillometer and EC sensible heat fluxes over the ‘reasonably homogeneous’ built surface (Lagouarde et al. 2006). A much longer campaign in Łódź looks at diurnal and seasonal variability (Zieliński et al. 2012). Results from Swindon using the single-wavelength method (i.e. infrared scintillometers only) are presented in a separate paper (Ward et al. 2014a). Other urban sites include London (Gouvea and Grimmond 2010), Toulouse (Masson et al. 2008), Nantes (Mestayer et al. 2011) and Helsinki (Wood et al. 2013). These studies are concerned with the sensible heat flux.

Here, we report on the first large-area sensible and latent heat fluxes obtained from a two-wavelength scintillometer system installed over the urban environment. Results are analysed alongside EC measurements representative of a much smaller scale. An extensive dataset spanning 14 months enables the seasonal variability of the fluxes to be investigated, as well as differences between years. Following the theoretical (Section 2) and experimental (Section 3) details, the

performance of the techniques is critically examined (Section 4.1). Three approaches are considered here: the single-wavelength, two-wavelength and bichromatic-correlation methods. Important physical processes determining the energy partitioning are then explored using the two-wavelength and EC fluxes. For each wavelength (or combination of wavelengths) the conversion of the observed refractive index structure parameters to temperature (C_T^2) and humidity (C_q^2) structure parameters and the temperature-humidity cross-structure parameter (C_{Tq}) is described in Part 1 (Ward et al. 2014b).

2. Scintillometry theory: obtaining fluxes

Here the goal is to relate the structure parameters of temperature and humidity from scintillometry to the surface fluxes of heat and water vapour. Briefly, the two-wavelength scintillometer system provides three refractive index structure parameters (C_n^2), denoted C_{n1n1} from the optical scintillometer, C_{n2n2} from the millimetre-wave scintillometer and C_{n1n2} from the correlation between optical and millimetre-wave signals. Conversion to the temperature and humidity structure parameters involves either the single-wavelength, two-wavelength or bichromatic-correlation method. For the two-wavelength method C_{n1n1} and C_{n2n2} are combined to give C_T^2 and C_q^2 , which also requires an assumption about the temperature-humidity correlation coefficient, r_{Tq} . The assumption used in this study is $r_{Tq} = \pm 0.8$. The bichromatic-correlation method additionally measures the cross-structure parameter C_{n1n2} to remove the need for the r_{Tq} assumption. Knowing the three refractive index structure parameters (C_{n1n1} , C_{n2n2} , C_{n1n2}) enables the three meteorological structure parameters (C_T^2 , C_q^2 , C_{Tq}) to be found. A summary is given in Figure 1 and the reader is referred to Part 1 for full details.

The structure parameters of temperature, T , or specific humidity, q , can be related to surface fluxes using Monin-Obukhov similarity theory (MOST). For example (Wyngaard et al. 1971),

$$\frac{C_T^2(z_m - z_d)^{2/3}}{T_*^2} = \frac{C_q^2(z_m - z_d)^{2/3}}{q_*^2} = f_{MO} \left(\frac{z_m - z_d}{L_{Ob}} \right), \quad (1)$$

where T^* and q^* are the scaling variables of temperature and humidity respectively; z_m is the measurement height, z_d the displacement height, L_{Ob} the Obukhov length and f_{MO} is a similarity function describing the height dependence as a function of stability. Thus, scintillometry is an indirect method for obtaining fluxes. For the path-averaged quantities obtained from scintillometry, the effective height, z_{ef} , is used in place of $(z_m - z_d)$ as described in Hartogensis et al. (2003). The stability parameter, ζ , is defined as $(z_m - z_d)/L_{Ob}$ for the EC station and z_{ef}/L_{Ob} for the scintillometer system. The Obukhov length is calculated from (e.g. Green et al. 2000)

$$L_{Ob} = \frac{u_*^2 T}{g \kappa_v T_* (1 + 0.07 / \beta)} \quad (2)$$

where g is the acceleration due to gravity, κ_v is von Kármán's constant and β is the Bowen ratio. The required friction velocity (u_*) input is ~~usually~~ obtained from a point measurement of wind speed and an estimate of the roughness length (z_0) using the Businger-Dyer functions. The scaling variables, stability and effective height are determined by iteration (e.g. Moene et al. 2004).

Several forms of the similarity functions exist in the literature. ~~and u~~ Useful discussions can be found Braam et al. (2014), in Braam et al. (2012) and Beyrich et al. (2012) in the context of scintillometry, and in Kanda et al. (2002) for consideration of urban environments. The choice of similarity function for this dataset is investigated in Appendix A. As in other scintillometry studies, identical functions for T and q are assumed here. The widely-used forms with the constants suggested by Andreas (1988) are used,

$$f_{MO}(\zeta) = c_{T1} (1 - c_{T2} \zeta)^{-2/3} \quad (\zeta < 0) \quad (3a)$$

$$f_{MO}(\zeta) = c_{T1} (1 + c_{T3} \zeta^{2/3}) \quad (\zeta > 0) \quad (3b)$$

with $c_{T1} = 4.9$, $c_{T2} = 6.1$ and $c_{T3} = 2.2$ (hereafter An88).

The sensible heat flux is calculated using

$$Q_H = -\rho c_p u_* T_*, \quad (4)$$

where ρ is the density of air and c_p the specific heat capacity at constant pressure. The latent heat flux is calculated following Ward et al. (2013b),

$$Q_E = -\rho L_v u_* q_*, \quad (5)$$

where L_v is the latent heat of vaporisation. Equations 4 and 5 define the scaling variables. When q_* is not known (as for the single-wavelength method), Q_E may be estimated as the residual of the surface energy balance if all other terms are known, but the complexity of energy partitioning in urban areas makes this very difficult. The urban energy balance can be written (Oke 1987):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S \quad (6)$$

where Q^* is the net all-wave radiation, Q_F the anthropogenic heat flux and ΔQ_S the net storage heat flux. The Bowen ratio, β , is expressed in terms of the fluxes as Q_H/Q_E .

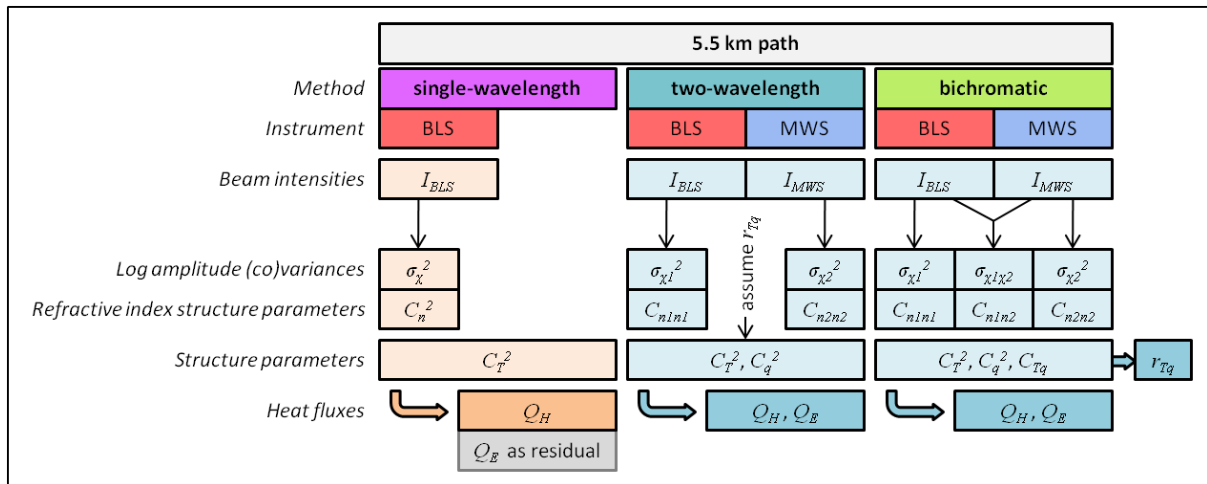


Figure 1 Methods to obtain heat fluxes from scintillometry as applicable to the experimental setup in Swindon. See Section 3 for details of the instrumentation, including an optical large aperture scintillometer (BLS) and a millimetre-wave scintillometer (MWS). Notation is defined in the text.

3. Observational details

A two-wavelength scintillometer system was deployed on a 5.5 km path over a suburban area of Swindon, UK. This system comprises an infrared scintillometer, the BLS900 (Scintec, Rottenburg, Germany), and a 94 GHz millimetre-wave scintillometer (Evans 2009). Near the centre of the scintillometer path an EC station was installed at a height of 12.5 m in the garden of a residential property. The instrument locations and typical source areas of the fluxes are shown in Figure 2.

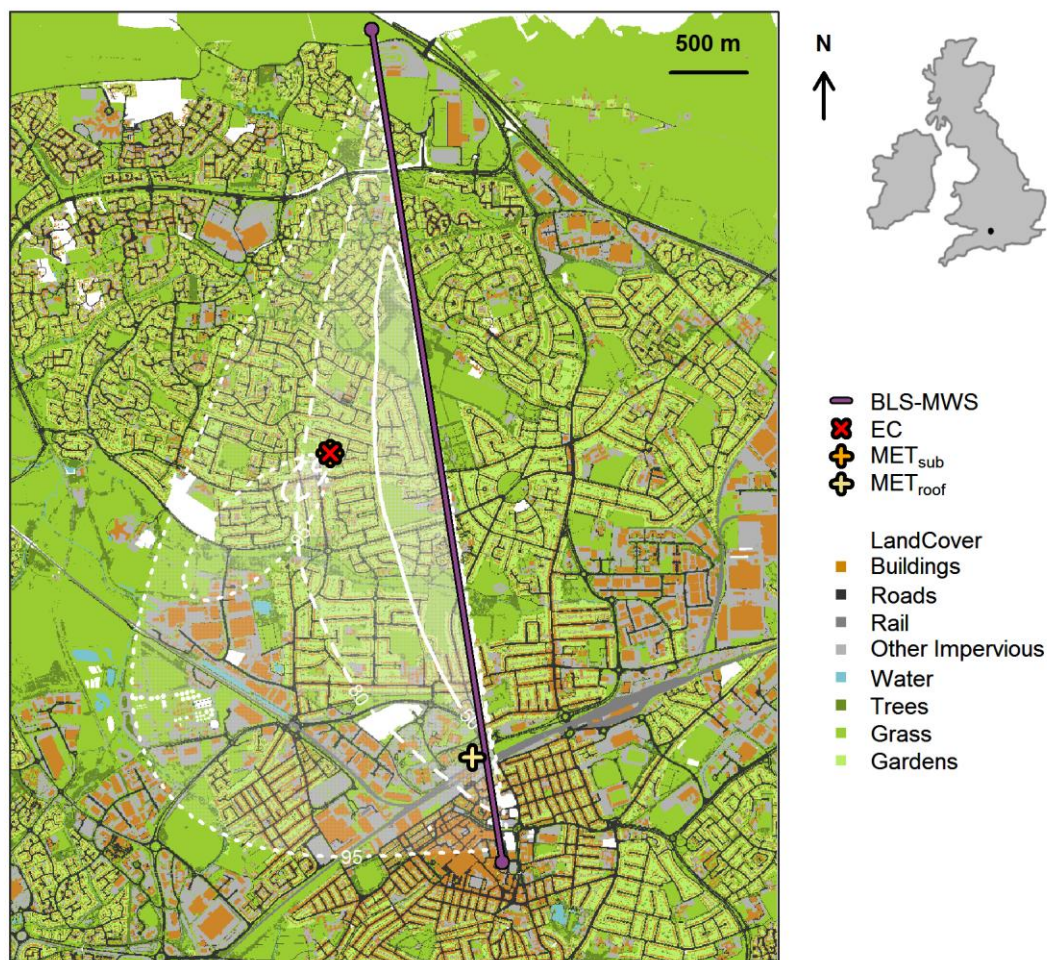


Figure 2 Land cover map of the study area showing the two-wavelength scintillometer path (BLS-MWS) and locations of the eddy covariance station (EC) and two meteorological stations (MET_{sub} , MET_{roof}). Land cover classification was based on a geodatabase (OS MasterMap 2010 © Crown Copyright), lidar data (2007, ©Infoterra Ltd) and aerial photography (2009, ©GeoPerspectives). Where data were unavailable areas are left unclassified (white). Example footprints indicate the area

contributing 50%, 80% and 95% of the observed fluxes for typical unstable atmospheric conditions and southwesterly wind (see text for details). The location of Swindon within the British Isles is shown (top right).

Table 1 summarises the instrumental setup and site characteristics. The effective height of the scintillometer system is given as the effective height of the BLS according to Equation 15 of Hartogensis et al. (2003) and includes the displacement height. A single value for the displacement height and roughness length were based on the mean height of buildings and trees (z_H) (within 500 m of the EC site and 1000 m of the scintillometer path) and the relations $z_0 = 0.1z_H$, $z_d = 0.7z_H$ (Garratt 1992; Grimmond and Oke 1999).

Source area estimation combines an analytical model (Hsieh et al. 2000) with the scintillometer path weighting (e.g. Meijninger et al. 2002b). The values in Table 1 and used for Figure 2 are for typical atmospheric conditions: southwesterly wind (225°), $u_* = 0.5 \text{ m s}^{-1}$, standard deviation of lateral wind $\sigma_v = 0.9 \text{ m s}^{-1}$ and $L_{Ob} = -200 \text{ m}$ (200 m for stable conditions).

Variation in surface cover composition with wind direction and stability is shown in Figure 3 for typical EC and BLS-MWS footprints (normalised to give a total of 100%). The source area composition is more variable for EC than the BLS-MWS, owing to the greater spatial sampling of the BLS-MWS and the distribution of land cover surrounding the EC mast: paved areas, buildings and roads to the southwest and large gardens to the northeast. The relative contribution of vegetation to the EC source area is lowest for southwesterly winds (32% for 225°) and highest for northeasterly winds (53% for 45°). The BLS-MWS footprint always has a significant contribution from vegetation, partly due to the large nature reserve near the centre of the path (Figure 2). For unstable conditions the BLS-MWS footprint comprises 56% vegetation cover on average. For stable conditions, the BLS-MWS source area is larger and contains a greater contribution from the town centre to the south and industrial areas to the east and southwest. For northerly winds and stable conditions, the source area extends beyond suburban Swindon and over the rural areas. At these times the footprint extends considerably beyond the edges of the land cover map (Figure 2), thus the land cover

composition (and source area size) is less reliable – an even larger contribution from vegetation is expected than suggested by Figure 3. Note that the size of the source area depends on the wind direction; it is smallest when winds are near parallel to the scintillometer path.

Instrumentation	Location	Height [m]	z_0 [m]	z_d [m]	Approx. source area [km ²]		
					95%	80%	50%
BLS-MWS scintillometer system	51°36'33.9" N						
	1°47'38.6" W (Tx)	45.0*	0.7	4.9	7.5	3.0	0.9
	51°33'38.1" N	[39.0-45.0]	[0.5- 1.1]	[4.4-5.4]	(10.2)	(6.9)	(3.2)
	1°46'55.3" W (Rx)						
Eddy covariance station	51°35'4.6" N	12.5	0.5	3.5	0.5	0.06	0.007
	1°47'53.2" W		[0.4-0.9]	[3.0-4.0]	(0.7)	(0.1)	(0.01)

Table 1 Details of the scintillometer and eddy covariance systems. Tx denotes transmitter; Rx denotes receiver. *The height of the scintillometer system is given as the effective height of the BLS. Values in square brackets represent the probable range of each quantity: for the range in effective height these are the limiting stabilities represents the variation with stability; for z_0 and z_d these are based on the literature (e.g. Grimmond and Oke (1999)). See text for details of the source area estimation.

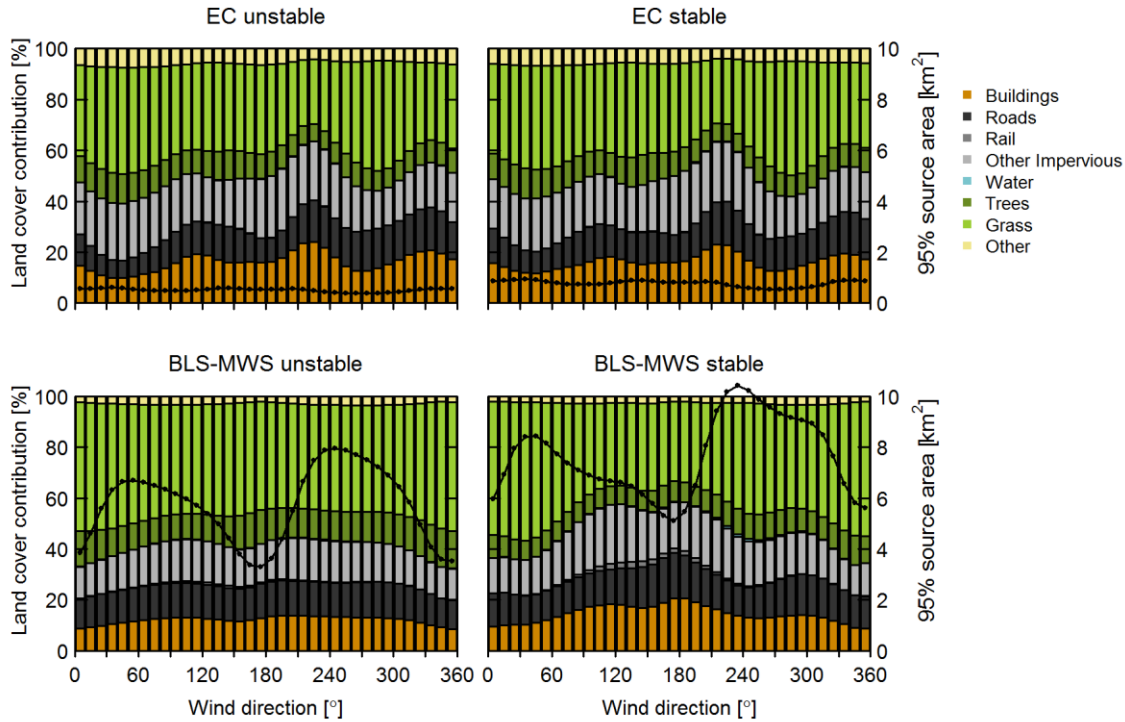


Figure 3 Contribution of land cover types to the EC and BLS-MWS source areas by wind direction for typical atmospheric conditions ($u_* = 0.5 \text{ m s}^{-1}$, $\sigma_v = 0.9 \text{ m s}^{-1}$, $L_{Ob} = \pm 200 \text{ m}$). Black lines indicate the approximate size of the source area contributing 95% of the flux (right-hand axis).

Other meteorological instrumentation was also installed at the EC site (denoted MET_{sub}). An automatic weather station (WXT [510/520](#), Vaisala, Finland) at a height of 10.6 m provides the temperature, pressure, humidity and wind speed inputs required to process the scintillometry data. A four-component radiometer (NR01, Hukseflux, The Netherlands) at 10.1 m provides incoming and outgoing shortwave ($K_{\downarrow}$, $K_{\uparrow}$) and longwave ($L_{\downarrow}$, $L_{\uparrow}$) radiation and the net all-wave radiation. A tipping bucket rain gauge (0.2 mm tip, Casella, Bedford, UK) is situated near the base of the EC mast. Data from a second ~~similarly instrumented~~ meteorological station on a rooftop near the town centre (MET_{roof} , Figure 2) were ~~linearly adjusted and~~ used to gap-fill MET_{sub} to provide a more complete set of continuous input variables, ~~though these were only required in a few cases (mainly to cover power failure at MET_{sub}). Less than 2% of the combined dataset consisted of the adjusted MET_{roof} data (see Part 1).~~

The EC sensible and latent heat fluxes were calculated for every 30-min interval. Raw data were collected from a sonic anemometer (R3, Gill Instruments, Lymington, UK) and an open-path infrared gas analyser (IRGA) (LI-7500, LI-COR Biosciences, Lincoln, USA) at 20 Hz (CR3000, Campbell Scientific Ltd., Loughborough, UK). Flux processing included despiking of raw data; correction for angle of attack; time-lag compensation; double co-ordinate rotation; corrections for sonic temperature (Schotanus et al. 1983), high and low frequency losses (Moncrieff et al. 1997) and gas densities (Webb et al. 1980). The open source EddyPro software (v5-00, LI-COR Biosciences) was used to implement these stages. Quality control excluded data during times of instrumental fault or when rain could adversely affect readings and data were subject to physically reasonable range checking. More information about the EC system can be found in Ward et al. (2013a).

A CR5000 datalogger (Campbell Scientific Ltd.) sampled the BLS and MWS signal intensities at 100 Hz. Raw signals were digitally bandpass filtered between 0.06 Hz and 20 Hz for the calculation of C_{n2n2} and C_{n1n2} . Quality control comprised raw data despiking, rejection of data during rain or fog, threshold checking of C_n^2 and removal of data strongly affected by saturation. The remaining BLS data were corrected for saturation (Clifford et al. 1974). The MWS data were well below the saturation threshold (Clifford et al. 1974) and no correction was applied to the MWS data or the BLS-MWS cross-correlation. For further discussion see Part 1.

The calculation of fluxes from scintillometry proceeds as described in Section 2. During daytime hours between minima in C_{n1n1} , the similarity functions for unstable conditions were used; at other times stable conditions were assumed. The two-wavelength results were calculated assuming positive r_{Tq} during unstable conditions (i.e. assuming $Q_H > 0$, $Q_E > 0$) and negative r_{Tq} under stable conditions (i.e. assuming $Q_H < 0$, $Q_E > 0$). Clearly the two-wavelength method will suffer a positive bias in Q_E resulting from these assumptions, i.e. dewfall ($Q_E < 0$) is never identified. The bichromatic-correlation method, in principle, provides more information than the two-wavelength method. Initially, unstable conditions during daytime and stable conditions at night are assumed. Then for

cases of observed $r_{Tq} < 0$ during daytime (between C_{nlnl} minima) Q_E is assumed to remain positive but Q_H to switch to being negative, so the stable similarity function is used. This may be expected to occur following rainfall when surfaces are wet. During the night it is more difficult to determine the correct stability regime, as $r_{Tq} > 0$ can indicate either stable conditions and dewfall ($Q_H < 0$, $Q_E < 0$) or unstable conditions and ~~evaporation~~evapotranspiration ($Q_H > 0$, $Q_E > 0$). Because r_{Tq} only describes the relative sign of the fluxes, these two situations cannot be distinguished by the bichromatic-correlation method, although it does indicate the occurrence of either of the two situations. Here, nocturnal $r_{Tq} > 0$ is taken to indicate dewfall. A time-step of 10 min was used for two-wavelength C_T^2 and C_q^2 , yielding Q_H and Q_E also at 10 min. To reduce the variability of the bichromatic-correlation method (Part 1), the corresponding fluxes were calculated at 30-min intervals using 30-min mean C_T^2 and C_q^2 . For the single-wavelength method no Bowen ratio correction has been applied.

In the following, the subscript ‘EC’ is used to refer to quantities derived from the eddy covariance measurements and ‘BLS-MWS’ from scintillometry. Where results have used structure parameters calculated using the single-wavelength, two-wavelength or bichromatic-correlation methods, these are subscripted ‘1 λ ’, ‘2 λ ’ and ‘bc’ respectively. Data are presented for 14 months when all instrumentation was functioning: July-December 2011 and May-December 2012.

4. Results and discussion

4.1. Comparison of methods

Sensible and latent heat fluxes obtained from scintillometry (bichromatic-correlation and two-wavelength methods) and eddy covariance are shown in Figure 4. The sensible heat flux calculated using the single-wavelength method is also plotted. To our knowledge Figure 4 includes the first fluxes derived from structure parameters where the measured combined temperature-humidity fluctuations have been incorporated via the bichromatic-correlation method.

Differences in sensible heat fluxes from the three scintillometry techniques are small. The scintillometry values match the EC values reasonably well, despite the different measurement

footprints. Notable differences can be seen during the early morning of 30 September 2012 when Q_H from the scintillometers is more negative than Q_{H_EC} until around 0900 UTC. During the middle of the day on 11 May 2012 Q_{H_EC} is 50-100 W m⁻² larger than the scintillometry results; possibly $Q_{H_BLS-MWS}$ is limited by saturation here (see Ward et al. (2014a) for discussion). Although the Q_H values are fairly similar in magnitude, Q_E from the scintillometers tends to be larger than from EC.

Differences between the bichromatic fluxes and two-wavelength fluxes are mostly small, as observed r_{Tq_bc} values are mostly similar to the assumed $r_{Tq_2\lambda}$ values (± 0.8). At times when measured r_{Tq} deviates from the assumed values, the fluxes differ accordingly. Q_E is affected more than Q_H . Comparison with Q^* suggests that the lower bichromatic fluxes are sometimes more realistic given the available energy, e.g. on the morning of 21 August 2011 (Q_{H_bc} and Q_{E_bc}) and 11 May 2012 (Q_{H_bc}). The expected diurnal cycle of r_{Tq} is usually observed (positive during daytime, negative at night) and generally there is good agreement between r_{Tq_EC} and r_{Tq_bc} . On 21 August 2011, for example, r_{Tq} changes sign at the evening transition, but also changes sign again a few hours later. Both EC and bichromatic-correlation methods capture this behaviour. The EC data reveal negative Q_E as r_{Tq} becomes positive, indicating dewfall. The bichromatic-correlation method is also able to identify this dew event, which is ignored by the two-wavelength assumptions ($Q_{E_2\lambda}$ always remains positive overnight, Section 3). At other times, the bichromatic results appear less reasonable. Firstly, there are incidences of $|r_{Tq_bc}| > 1$, which do not have a meaningful physical interpretation but point to measurement limitations. Secondly, large fluctuations in r_{Tq_bc} sometimes lead to sudden spikes in the fluxes. Such variability results in fluxes that are at times almost certainly unduly influenced by the performance of the method. As discussed in Part 1, the small signal-to-noise ratio of the cross-structure parameter C_{n1n2} and the accumulation of uncertainties in r_{Tq} can contribute to large errors associated with individual measurements. For this reason, ~~two-wavelength~~ structure parameters obtained via the two-wavelength method have been used to calculate the scintillometric fluxes presented below.

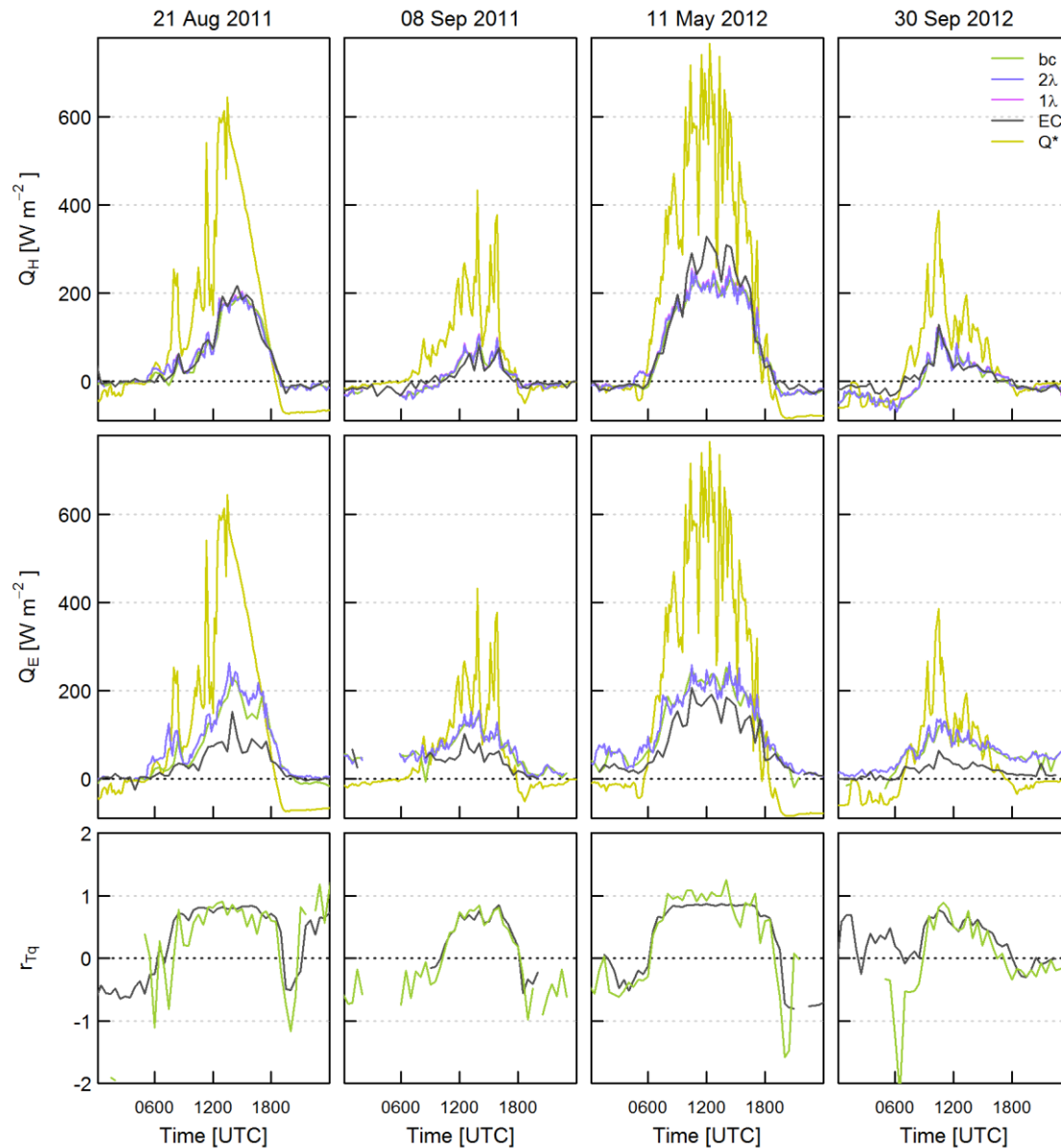


Figure 4 Sensible and latent heat fluxes and net all-wave radiation (Q^*) and the temperature-humidity correlation coefficient for selected days. Single-wavelength and two-wavelength results are for 10-min intervals; EC and bichromatic statistics are at 30-min intervals (structure parameters for the same days are shown in Figure 8 of Part 1).

4.1.1. ~~Evaporation~~Evapotranspiration following rainfall

Two-wavelength scintillometry has the potential to provide fluxes directly following rainfall, when water droplets on open-path gas analyser windows may preclude Q_E measurements by eddy covariance. Note that closed-path IRGAs permit flux measurements during or soon after rainfall, but have their own issues including water droplets wetting filters and high relative humidity causing

condensation in the sample tubing. Scintillometer measurements can be made as soon as the propagation path is clear following a rain shower even when the land surface (or IRGA window) has not had time to dry. The drawback is that neither Q_H nor Q_E can be reliably obtained while the scintillometer path is obstructed, whereas EC ~~is usually capable of providing~~ fairly continuous Q_H measurements except during ~~very~~ heavy rainfall. Fluxes from three days in July 2012 are shown in Figure 5. Q_{H_EC} and $Q_{H_2\lambda}$ are closely matched and clearly respond to the energy available, primarily net all-wave radiation. Out of the 72 h shown, scintillometer data are available for 56.7 h, Q_{H_EC} for 66.5 h and Q_{E_EC} for only 32.5 h. Rainfall in the evening of 11 July meant the IRGA windows remained wet throughout the night. The BLS-MWS system shows an increase in Q_E after rainfall and non-zero ~~evaporation~~evapotranspiration through the night (0.6 mm between 2130 and 0800 on 12 July; no Q_{E_EC} data were available during this time). Very high rates of ~~evaporation~~evapotranspiration can be observed when surface water is abundant and there is considerable energy input from Q^* , such as in the middle of the day on 11 July. Latent heat fluxes exceeded 500 W m^{-2} and the variability seen in Q_E is a response to incoming radiation. Short averaging times for the scintillometer fluxes (10 min) are an advantage in capturing the rapid response of the drying surface. Total ~~evaporation~~evapotranspiration may be significantly underestimated by the EC method because of missing measurements following rainfall (Heusinkveld et al. 2008). Using an urban canopy model at a site on a university campus, Ramamurthy and Bou-Zeid (2014) estimated that nearly 5% of total ~~evaporation~~evapotranspiration was missed due to wet IRGA windows. Two-wavelength scintillometry may provide a method to estimate fluxes that overcomes this issue.

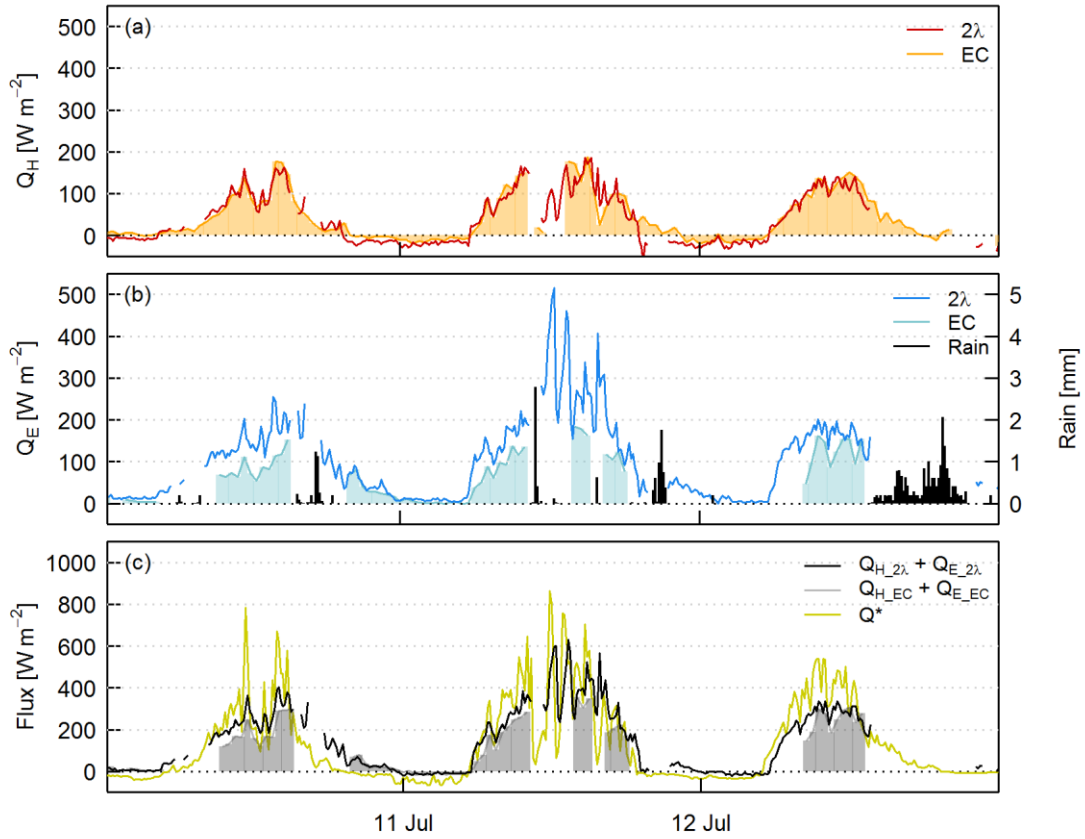


Figure 5 Response of (a) sensible and (b) latent heat fluxes to rainfall (right-hand axis) and (c) net all-wave radiation. Shading indicates availability of EC data. EC data are at 30-min intervals; all other data are at 10-min intervals.

4.1.2. Source area characteristics

Flux footprints are variable in time due to changing atmospheric conditions, primarily stability and wind direction (e.g. Schmid 1994; Hsieh et al. 2000). Due to the distribution of surface cover around the EC mast (Figure 3), differences in the carbon balance with wind direction are seen (Ward et al. 2013a). Large-scale scintillometer measurements are generally less susceptible to variation in land cover sampled – an advantage in terms of obtaining representative datasets. The land cover composition of the BLS-MWS footprint offers greater potential for transpiration than the impervious surfaces around the EC mast. Footprint differences between the systems are further enhanced considering that the EC source area is more built-up for the prevailing southwesterly wind (Section 3). The influence of land cover on fluxes is explored in the following case study.

Towards the end of May 2012 (after very wet and cloudy weather since early April), there was an extended period of warm and sunny weather during which vegetation quickly developed and leafed-out (22-28 May). Increased insolation on 22 May encouraged photosynthesis, Q_E increased rapidly and β decreased as transpiration rates rose (Figure 6). The highest rates of ~~evaporation~~evapotranspiration were observed on 25-27 May when conditions were warm and windy (reaching 25°C and 6 m s⁻¹ on 25-26 May) with a high vapour pressure deficit (20 hPa) and plenty of available energy and moisture. The EC-measured carbon dioxide flux also indicates strong photosynthetic uptake on these days (not shown). On 25-26 May winds are northeasterly and the EC source area contains a large proportion of active vegetation; more energy is directed into Q_{E_EC} than Q_{H_EC} . Once the wind direction becomes more southwesterly again β_{EC} increases and continues to increase as the urban surface dries out, peaking on 31 May. Once rain arrives and the wind direction changes on 1 June, β_{EC} drops again. Meanwhile, a consistently high proportion of vegetation in the scintillometer source area maintains low $\beta_{2\lambda}$ throughout this period.

The similarity between Q_{H_EC} and $Q_{H_2\lambda}$ is remarkable. EC and scintillometry are often in good agreement, even during night-time when both datasets have larger associated uncertainties (e.g. large negative Q_H observed on 25-26 and 26-27 May, Figure 6b). On 23, 27 and 29 May, clouds give rise to sudden changes in Q^* . Q_{H_EC} rapidly adjusts, particularly the sharp peak on 29 May, while for the scintillometer system the radiation patterns are replicated to a lesser extent. ~~It is possible that saturation may be a partial explanation for these differences, but higher $Q_{H_2\lambda}$ values are reached on other days with similar Q_{H_EC} . More likely, it is~~This is likely due to spatial sampling. Firstly, area-averaging tends to result in smoother diurnal cycles for scintillometry fluxes than EC (Lagouarde et al. 2006; Guyot et al. 2009). Secondly, the EC system and radiometer are located on the same mast, so their footprints are located in approximately the same area, whereas the footprint of the scintillometer system is larger and in a different location. These differences are particularly relevant when considering how the surface responds to patchy cloud cover across scales of 10-100 m.~~more~~

similar to each other than the footprint of the scintillometer system. It is therefore expected that Q^* would correlate better with Q_{H_EC} than $Q_{H_2\lambda}$.

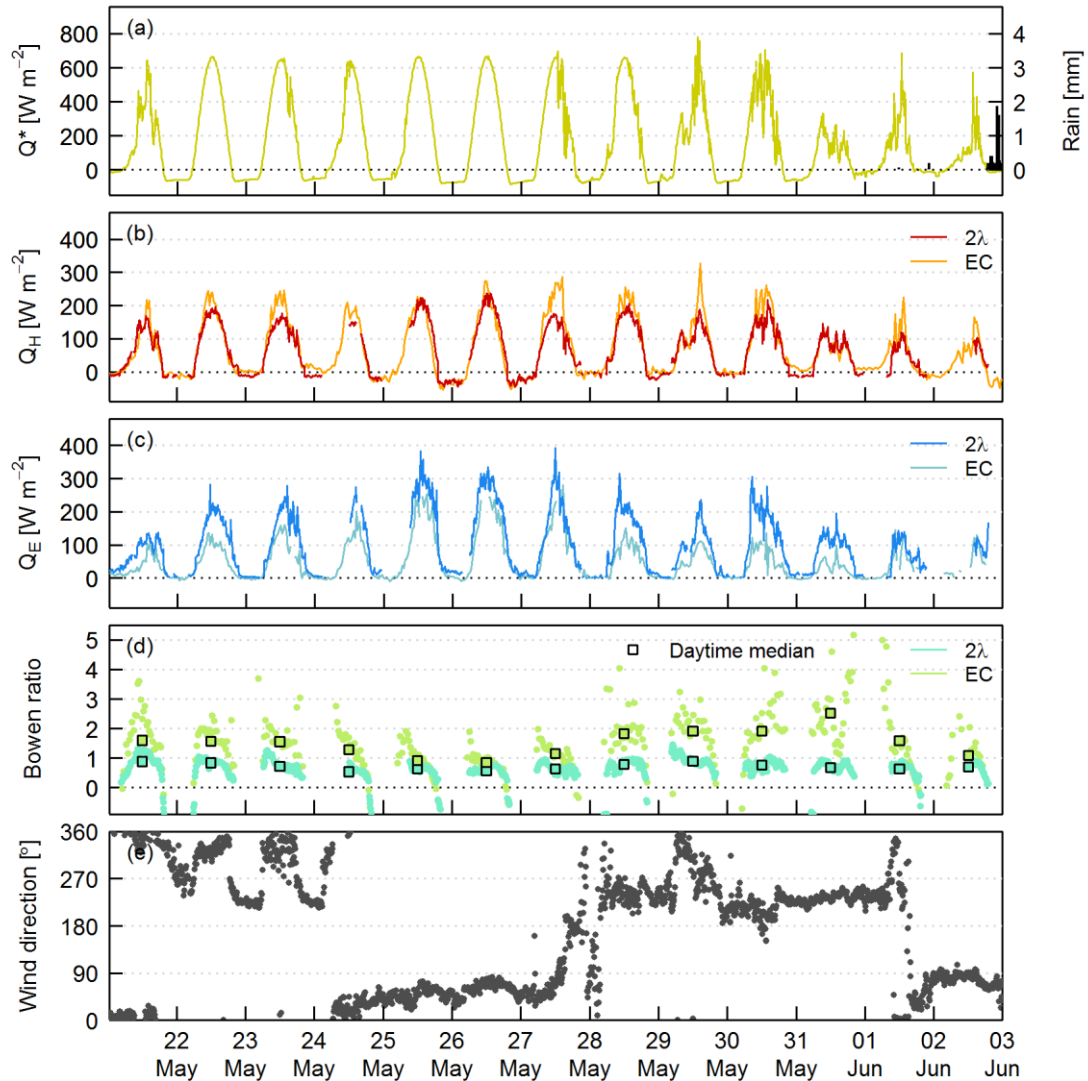


Figure 6 Energy partitioning according to eddy covariance and scintillometry during a warm, dry period in spring 2012. In (d) only daytime data are shown.

Despite the close agreement in Q_H , the latent heat flux from the scintillometers often exceeds that from EC. Average daily ~~evaporation~~evapotranspiration from the BLS-MWS is 1.5-3 times larger than from EC (Figure 7). Thus not only does the energy partitioning (β) differ between EC and BLS-MWS datasets, but the sum of the turbulent fluxes ($Q_H + Q_E$) is greater for the BLS-MWS system than for the EC system.

To some extent, the degree of urbanisation in the source areas could contribute to differences in $Q_H + Q_E$. Anthropogenic and net storage heat fluxes are non-negligible contributions to the urban energy budget (Equation 6). Both of these terms tend to increase with urban density, as energy demand increases with population density and large thermal masses made from anthropogenic materials (e.g. buildings) effectively absorb and release heat. Therefore the EC footprint is likely associated with a slightly higher Q_F than the BLS-MWS footprint. Conversely to what is observed, this would provide more energy for $Q_H + Q_E$, not less. However, such differences are estimated to be small given the size of Q_F : peak values are estimated at about $10\text{-}15 \text{ W m}^{-2}$ for suburban Swindon (Ward et al. 2013a) which is within the expected range for similar environments (e.g. Christen and Vogt 2004; Bergeron and Strachan 2010). The EC footprint probably has a larger associated ΔQ_S , which corresponds to smaller $Q_H + Q_E$, when $\Delta Q_S > 0$. Whilst ΔQ_S may be a contributing factor to observed differences between EC and BLS-MWS datasets, if it was the main explanation one would expect other suggestions that this is the case, for example in the shape of the diurnal cycle of Q_H (Q_{H_EC} would lag $Q_{H_2\lambda}$), which are not seen. There may also be ~~small~~ differences in Q^* between the source areas, although studies have suggested that the radiation budget may not vary between surfaces as much as might be expected because the relevant properties ~~of different surfaces~~ (albedo and radiative temperature) tend to have compensating effects on the outgoing shortwave and longwave radiative fluxes (Schmid et al. 1991; Christen and Vogt 2004). Nevertheless, spatial variability in cloud cover still makes it challenging to obtain Q^* measurements representative of scintillometer source areas. Other reasons for differences between EC and scintillometry results (aside from source area characteristics) are considered in the next section.

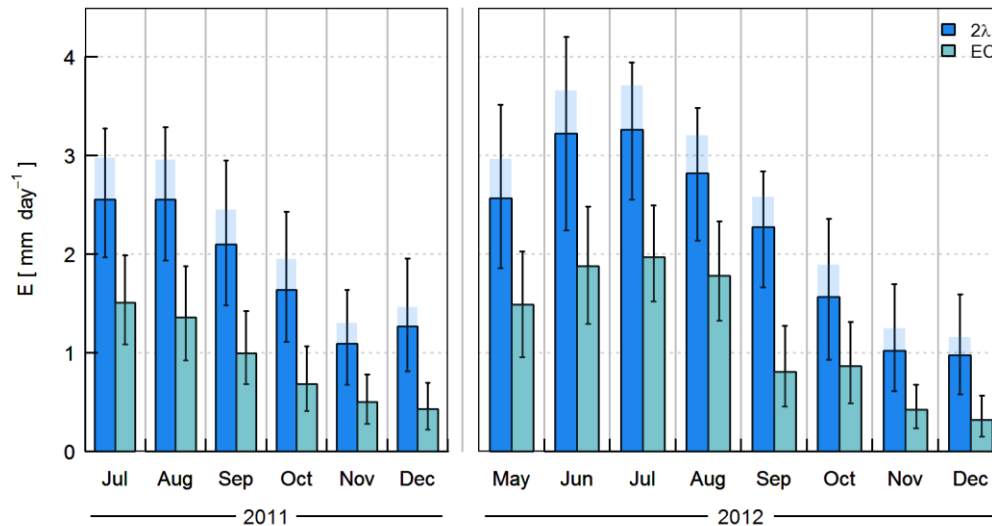


Figure 7 Average daily ~~evaporation~~evapotranspiration by month: bars represent the sum over the median daily cycle of ~~evaporation~~evapotranspiration for each month; error bars indicate the upper and lower quartiles; shading indicates the impact of using the De Bruin et al. (1993) similarity function.

4.1.3. Consideration of uncertainties

Studies that have made direct comparisons between EC and scintillometry have generally found reasonable agreement within experimental uncertainties, though two-wavelength estimates of Q_E are often quite large. Meijninger et al. (2002a) found a difference of 8% between $Q_{E_2\lambda}$ and Q_{E_EC} . Meijninger et al. (2006) found $Q_{E_2\lambda}$ (using *in situ* r_{Tq} from EC) was 26% larger than Q_E from EC data aggregated over the source area. The corresponding $Q_{H_2\lambda}$ overestimated Q_{H_EC} by 7%, and for low fluxes ($< 150 \text{ W m}^{-2}$) $Q_{H_2\lambda} + Q_{E_2\lambda}$ was larger than the estimated available energy. (Note that the scintillometry data were not processed identically in these two studies.) Underestimation of turbulent fluxes by EC may partly explain these differences; under-closure of the energy balance is widely documented and can commonly be as much as 10-20% (Wilson et al. 2002; Frank et al. 2013). A variety of explanations have been suggested, including instrumental limitations (Kochendorfer et al. 2012), large-scale circulations (Foken 2008) and inadequate accounting for other terms in the energy balance (Leuning et al. 2012). As these factors are unlikely to affect scintillometry in the same

way (for example, scintillometers have a much larger spatial sampling volume), it should perhaps be expected that EC fluxes are smaller.

In Swindon, Q_E from the BLS-MWS is almost always higher than that from EC, whilst Q_H is similar during the day and more negative at night (Figure 8). Regression of 30-min $Q_H + Q_E$ against Q^* yields slopes of 0.675 (2λ) and 0.59 (EC) with substantial offsets of 37 W m^{-2} (2λ) and 15 W m^{-2} (EC). A small positive offset is expected given the contribution of the anthropogenic heat flux (Equation 6; Section 4.1.2). For regressions of daily average $Q_H + Q_E$ against Q^* (excluding days with < 50% data available), the slopes increase and offsets decrease (to 0.863 and 29 W m^{-2} (2λ), and 0.78 and 4 W m^{-2} (EC)). Regression of $Q_{H_{2\lambda}} + Q_{E_{2\lambda}}$ with $Q_{H_{EC}} + Q_{E_{EC}}$ gives slopes and intercepts of 1.036 and 23 W m^{-2} (30 min), and 0.969 and 340 W m^{-2} (daily average). This non-negligible offset between techniques seems to be related to overestimation of BLS-MWS fluxes by the similarity functions.

In general, there is a tendency for similarity functions to overestimate very small fluxes. Large scatter during stable and neutral times demonstrates the limitation of similarity theory scaling and cautions that flux estimates are less reliable at these times. This may partly explain the large magnitude of wintertime fluxes from scintillometry (Figure 8a, c) and the corresponding high ~~evaporation~~evapotranspiration rates for December 2011 and 2012 (Figure 7). The general shape of the observed temperature and humidity scaling, based on EC values, is described by similarity functions given in the literature (Appendix A). Agreement is often quite good in unstable conditions (e.g. for An88 and De Bruin et al. (1993) (DB93)) but the fits are poorer in near neutral and stable conditions as the data become more scattered. For neutral stability there are differences in the behaviour of temperature and humidity. While the temperature scaling diverges, the humidity scaling tends towards an approximately constant value which appears to be larger than suggested by An88 or DB93. These features will result in overestimation of the magnitude of Q_H and Q_E under these conditions. In Figure 7 the average daily ~~evaporation~~evapotranspiration calculated using DB93 is shown (shaded) in comparison to the values derived using An88 (bars). The impact of the choice of

similarity function can alter the daily ~~evaporation~~evapotranspiration by 0.20-0.45 mm, i.e. approximately 15-20% or more.

Compared to the uncertainty associated with similarity functions, other uncertainties in the derivation of fluxes are mostly small. Out of the required input quantities, uncertainties in the beam height, z_0 and wind speed are most important; the long path length reduces the impact of inaccuracies in estimating its length and sensitivity to the other meteorological input variables is small (Hartogensis et al. 2003; Ward et al. 2014a). Using the range of z_0 given in Table 1, Q_H and Q_E would decrease by 7% or increase by 14%. The displacement height is incorporated in the effective height, and as a change in z_d of ± 0.5 m is minor compared to z_{ef} itself, it has negligible impact ($< 1\%$) on the fluxes. The range of z_{ef} given in Table 1 is for the limiting cases of free convection and near neutral stability (according to Equations 13 and 14 of Hartogensis et al. (2003)). Using these values of z_{ef} results in fluxes that are 6% smaller or 3% larger. Fluxes calculated using the full iterative procedure to account for stability in determination of z_{ef} (Section 2; Equation 12, Hartogensis et al. (2003)), yield a much smaller range of z_{ef} (42.8-43.5 m).

Determination of wintertime and night-time fluxes presents challenges for both EC and scintillometry. The (usually) smaller magnitude of these fluxes (a) may be close to the detection limit of the instruments and (b) means that relative uncertainties can be large. Weak turbulence and non-stationarity violate the assumptions required for both EC and scintillometry measurement theory and MOST. A shallow boundary layer may mean measurements are made outside the surface layer and may no longer relate to the surface fluxes (e.g. Braam et al. 2012). However, the rough suburban surface helps to maintain turbulent mixing and there were very few occasions observed when comparisons between scintillometer and EC data suggested the scintillometers were above the surface layer.

The two-wavelength method cannot distinguish times of dewfall and ‘counts’ these instances of negative Q_E as positive Q_E (Section 3). According to the EC data, dewfall ($Q_E < 0$) was recorded for

8% of the study period, amounting to 4.9 mm in total. Based on this, the total ~~evaporation~~evapotranspiration from the two-wavelength method may be overestimated by ≈ 10 mm for the whole study period. When there is heavy dewfall, however, this will often settle on the IRGA windows leading to those data being rejected, so the EC data are also expected to underestimate dewfall. An advantage of the bichromatic-correlation method is that the relative sign of the fluxes is given by r_{Tq_bc} , so that positive r_{Tq} during night-time implies either $Q_H > 0$, $Q_E > 0$ or $Q_H < 0$, $Q_E < 0$.

Reduced sensitivity of the MWS around the region of minimum C_{n2n2} at $\beta \approx 2-3$ (Leijnse et al. 2007; Ward et al. 2013b) may also introduce a bias towards larger Q_E . As discussed in Part 1, the instrumental noise floor and experimental limitations are thought to widen the region of reduced sensitivity beyond the theoretical prediction of the position of the minimum. The two-wavelength method tends to give Bowen ratios less than about 1.3. The bichromatic results suggest higher β for about 3% of data. Although this represents a small proportion of the total dataset, it could have a more substantial effect in drier conditions and may restrict the ability of two-wavelength datasets to capture changing energy partitioning as conditions increase above $\beta \approx 1.3$. It is likely that the bichromatic-correlation results are also somewhat affected by problematic C_{n2n2} .

In summary, many of the issues affecting EC and scintillometry techniques lead to underestimated EC fluxes and overestimated scintillometry fluxes, more so for Q_E than Q_H . Under-closure of the energy balance and rejection of Q_E when IRGA windows are wet result in underestimated EC fluxes (except when dewfall wets the IRGA windows and it is $Q_E < 0$ that is not measured). Two-wavelength scintillometry: (a) is able to capture large Q_E following rain; (b) suffers a bias to 'count' $Q_E < 0$ (dewfall) as $Q_E > 0$; (c) relies on MOST to obtain fluxes, the limitations of which are thought to cause overestimation of the magnitudes of the fluxes; and (d) has limited sensitivity at moderate β which probably leads to overestimates of Q_E . Furthermore, in this setup, the source area composition also favours lower β for the BLS-MWS. On the other hand, saturation causes underestimation of Q_H from scintillometry. Analysis of results from both techniques enables

investigation into the limitations of each and provides a more complete picture of the behaviour of the environment. In the next sections, seasonal behaviour of the energy partitioning is analysed and results are set in context against other studies.

4.2. Analysis of seasonal patterns

Seasonal trends and substantial inter-annual variability are evident in the Swindon fluxes (Figure 8). Average annual rainfall for southern England is 780 mm (1971-2000 normal, Met Office (2013)). Rainfall was below average in 2011 with an annual total of 530 mm, and above average in 2012 (1020 mm), with over 900 mm between April and December 2012. Contrasts in water availability are reflected in the energy partitioning: β is significantly smaller in 2012 than 2011. ~~Latent heat fluxes tend to be larger and sensible heat fluxes smaller comparing similar months in 2012 and 2011, particularly in summer.~~ September 2012 deviates from the general trend of decreasing β from summer to winter. EC averages for this month are less representative than for other months due to lower data availability, but both datasets suggest a larger β than might be expected. This can mainly be attributed to a lack of freely available surface water and near-surface soil moisture, and fairly sunny weather during the first half of the month. By 23 September near-surface soil moisture had reached its lowest value for the period studied in 2012 (data not shown). The effect of dry impervious surfaces on the September 2012 EC observations is further enhanced due to predominantly southwesterly winds, which kept the footprint over the least vegetated areas (Section 3). Across the dataset as a whole, the variability in daytime energy partitioning (i.e. β) is smaller for the BLS-MWS than EC (e.g. Figure 6d, Figure 8d).

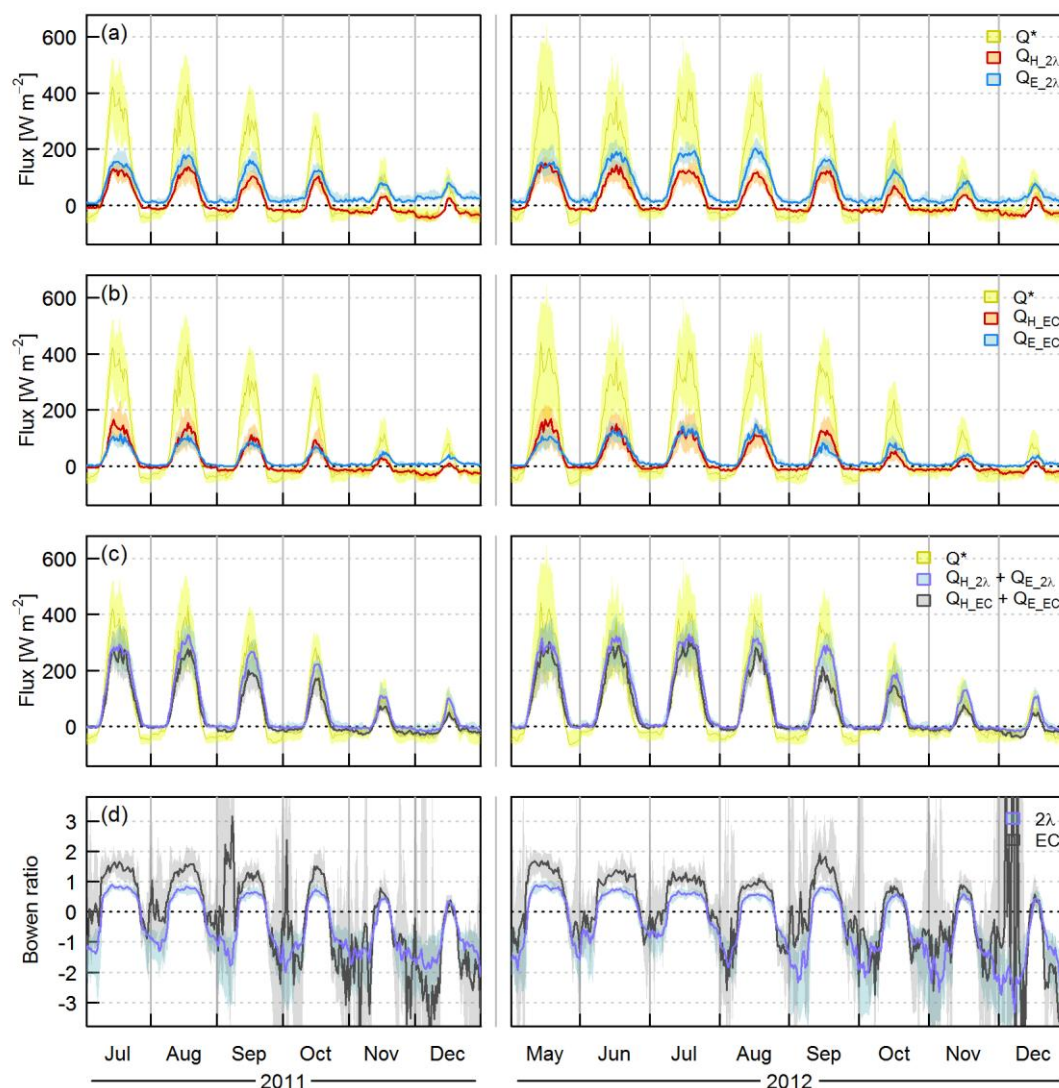


Figure 8 Monthly median diurnal cycles (lines) and inter-quartile ranges (shading) of sensible and latent heat fluxes determined using (a) two-wavelength scintillometry and (b) eddy covariance; (c) sum of the turbulent fluxes; and (d) Bowen ratio. The net all-wave radiation is also shown.

4.3. Comparison with other sites

The Swindon results are in good agreement with the North American studies of Grimmond and Oke (1995), in that frequent rainfall during summer reduces the expected Bowen ratio from 1.0-1.5 to 0.8-1.0. The observed inter-annual variation highlights the advantage of multi-year datasets to obtain representative data, both in terms of assessing the climatology of a region and for selecting appropriate parameters for modelling studies. The UK climate, with frequent rainfall, means

~~evaporation~~evapotranspiration continues from wet surfaces and pervious areas all year round, resulting in negative Q_H for much of the day if energy is limited. Similar energy partitioning has been noted at other suburban sites (e.g. Goldbach and Kuttler 2013) in contrast to city centre studies where typically the water availability is reduced and the energy input is supplemented by a larger anthropogenic component (Kotthaus and Grimmond 2014). Zieliński et al. (2012) present several months of Q_H data from scintillometry in Łódź. While the broad seasonal trends observed are similar to those in Swindon, Q_H is larger, particularly in wintertime, which is not surprising given the higher density of buildings at their city centre site (Fortuniak et al. 2013).

The BLS-MWS provides measurements that are representative of a considerable area of suburban Swindon. These results suggest that vegetated suburban areas are able to support high rates of ~~evaporation~~evapotranspiration ($\approx 3 \text{ mm day}^{-1}$). For comparison, summertime daily ~~evaporation~~evapotranspiration rates from UK woodlands are around $4\text{--}5 \text{ mm day}^{-1}$ (Roberts et al. 2005; Thomas et al. 2011). ~~Evaporation~~Evapotranspiration rates from residential and recreational areas in suburban Minneapolis-Saint Paul, Minnesota are around 3 mm day^{-1} in summer (Peters et al. 2011), comparable to the BLS-MWS results shown here, but near zero in winter (conditions are much colder and drier). The Swindon results are thus comparable to other published findings, but to obtain concurrent Q_H and Q_E at this scale is rare.

Low β from the BLS-MWS system is similar to other highly vegetated sites, such as Kansas City, Missouri (58% vegetation cover) – the observed daytime Bowen ratio of 0.47 for the August study period (Balogun et al. 2009) is one of the lowest among urban campaigns. For Swindon, average $\beta_{2\lambda}$ is 0.5–0.6 around midday in August 2012, but larger in 2011 (≈ 0.8); daytime averages are smaller due to the shape of the diurnal cycle (Figure 8d). In Kansas City, as for many of the North American studies (Grimmond and Oke 2002), automated irrigation supplements water availability, particularly those with warm dry summers. However the wet weather in Swindon during summer 2012 was accompanied by reduced insolation, limiting ~~evaporation~~evapotranspiration despite abundant

moisture (June 2012 was particularly cloudy). During winter β_{EC} and $\beta_{2\lambda}$ are more similar than during summer, as there is less contrast between vegetated and non-vegetated surfaces compared to when plants are actively transpiring (Offerle et al. 2006). The need to incorporate seasonality into model parameterisations is discussed in Loridan and Grimmond (2012) and Best and Grimmond (2013).

Observations of decreasing β with increasing vegetation fraction are mostly based on summertime observations (Grimmond and Oke 2002; Christen and Vogt 2004). Average daytime β for summer and winter are plotted for Swindon and other sites in the literature in Figure 9. Despite considerable scatter, clearly β decreases as the vegetation fraction increases. Notably high β at the rural site in Melbourne is attributed to drought conditions (Coutts et al. 2007). Values for winter months are more scattered and have a larger spread. This may be partly due to the shorter day length during winter – i.e. mean daytime β contains a wider range of values (Figure 8d), but it also reflects the changing role of vegetation depending on whether transpiration is occurring. For both Swindon and Montreal, where there are data for more than one summer and winter season, there is often a substantial difference between values in different years, again highlighting the importance of long-term observations.

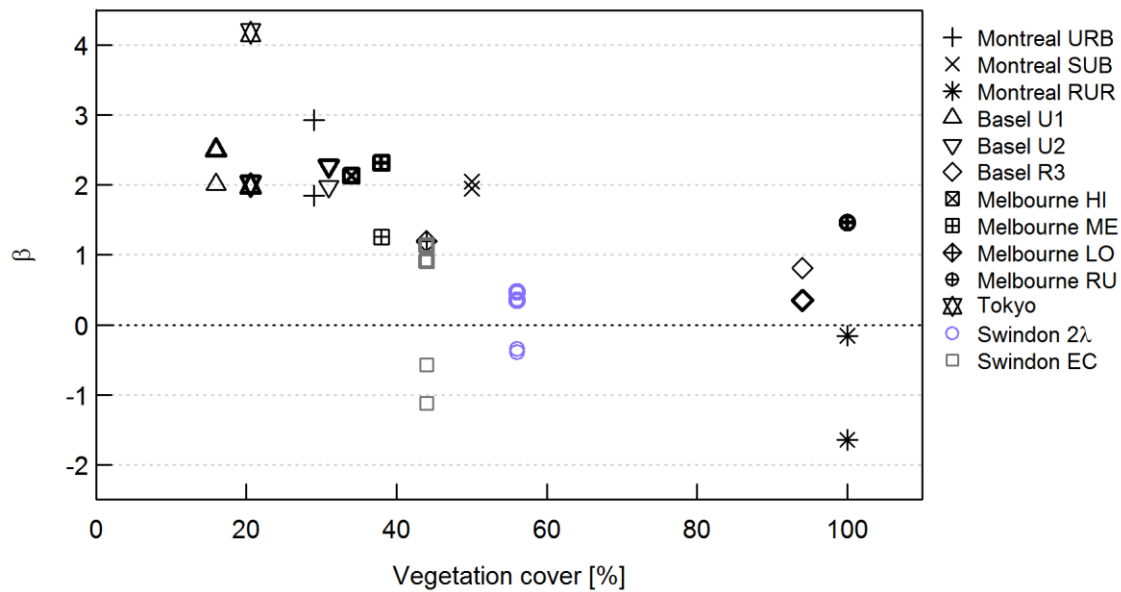


Figure 9 Observed daytime Bowen ratios for summer (**bold**) and winter months versus plan area vegetation cover at sites in Montreal (Bergeron and Strachan 2010), Basel (Christen and Vogt 2004), Melbourne (Coutts et al. 2007), Tokyo (Moriwaki and Kanda 2004) and Swindon (this study). See references for details of the sites.

5. Conclusions

The first observations of large-area heat fluxes using the two-wavelength scintillometry technique are presented for the urban environment. ~~Contrasting conditions between the two summer-to-winter periods studied highlight the importance of making long-term observations in order to capture seasonal and inter-annual variability. Water availability is a key control on the energy partitioning in summer, with higher evaporation rates linked to more vegetated surfaces. The available energy is a crucial factor in winter (Q_H is often negative as a consequence of energy being directed mainly into Q_E) and vegetation plays a smaller role. Higher evaporation/evapotranspiration rates (and lower β) from the BLS-MWS (1-3 mm day⁻¹ on average) compared with the EC measurements (0.5-2 mm day⁻¹) are partly attributed to the greater proportion of vegetation typically within the BLS-MWS source area. In winter, vegetation plays a smaller role (β is more similar between BLS-MWS and EC datasets) and the available energy is a crucial factor so Q_H is often negative as a consequence of energy being directed mainly into Q_E .~~ However, a number of methodological aspects also suggest estimates of Q_E and $Q_H + Q_E$ from the scintillometer system

may exceed those from EC. In addition to differences associated with source areas, the following issues require further exploration: selection and applicability of MOST scaling functions, especially for neutral and stable conditions; difference in energy balance closure between scintillometry and EC; and limitations of two-wavelength scintillometer systems (e.g. bias in the two-wavelength method when dewfall occurs) and better appreciation of their performance under a range of conditions (e.g. Bowen ratio). Deployment of an MWS in urban areas with a smaller proportion of vegetation, or during drier periods, may be less successful due to the reduced sensitivity at moderate β . Improvements to MOST (or an alternative solution) should be a main focus of future work, as the conversion of structure parameters to fluxes is accompanied by substantial uncertainties, especially for humidity.

With the technology applied it appears the bichromatic-correlation method does not provide a full solution to the limitations of the two-wavelength method. Nevertheless, information on path-averaged temperature-humidity correlation can be used to inform data processing and aid interpretation of results. The performance of both methods should be more closely examined and current understanding must be tested experimentally.

Since scintillometer data are already spatially integrated over a large area, changes in source area with meteorological conditions tend to make less of an impact on the average composition of the footprint. This offers significant advantages when using long-term datasets to parameterise or test models. Furthermore, direct integration of large-area observations into modelling studies may facilitate either assimilation of input data or evaluation of outputs, as most models will not account for the effects of footprint differences on collected data. Transforming local-scale measurements to representative values at the scale of model grids or satellite pixels is non-trivial over heterogeneous surfaces. For example, ~~evaporation~~evapotranspiration from urban greenspace can be significantly enhanced by warm surroundings (Spronken-Smith et al. 2000; Moriwaki and Kanda 2004). Hence flux measurements over large areas are required for development and evaluation of algorithms to

move between scales. ~~More long-term observational campaigns spanning a range of conditions are also needed.~~ The contrasting conditions between the two summer-to-winter periods studied here highlight the importance of making long-term observations in order to capture seasonal and inter-annual variability.

Field campaigns to compare different instruments and techniques, further supported by modelling studies, such as the LITFASS (Beyrich and Mengelkamp 2006) or BUBBLE (Rotach et al. 2005) experiments, are necessary both to learn more about the advantages and shortcomings of current techniques and also to develop a more thorough understanding of boundary layer dynamics and surface-atmosphere interactions.

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Appendix A. Choice of a suitable similarity function

Here, EC data are used to assess suitable similarity functions for Swindon. Dimensionless quantities formed from the structure parameters of temperature and humidity ($f_{MO,T}$, $f_{MO,q}$) were examined and compared to functions from the literature (Figure A 1). On the whole, the observed scaling with stability follows a similar form to the range of functions given in the literature. For temperature and humidity, f_{MO} increases with decreasing instability then starts to flatten out around $\zeta \approx -0.03$ as neutral conditions are approached. Humidity scaling becomes approximately constant and independent of stability in neutral and stable conditions. For unstable to near neutral conditions An88 and DB93 describe the behaviour fairly well. DB93 seems to best capture the observed behaviour with stability but the resulting fluxes are larger than reasonably expected, sometimes unfeasibly so compared to the energy available, and larger than the fluxes measured directly with the conventional EC method (fluxes directly obtained from EC can be compared to fluxes calculated via structure parameters and MOST scaling). Under stable conditions the scatter is much greater.

Instead of approaching a constant value as predicted by most of the functions in the literature, f_{MO-T} diverges at neutral conditions, becoming very large. Similar behaviour has been observed at a rooftop site in Basel (Roth et al. 2006), and for the normalised standard deviation of temperature (Fortuniak et al. 2013; Nordbo et al. 2013). It occurs as T_* becomes very small to compensate for large u_* to maintain a small heat flux (Equation 4) as neutrality is approached, and thus is a limitation of scaling in this way. Over smoother surfaces this effect may be observed less frequently as u_* is smaller so T_* can be larger for a given Q_H . Using functions of a conventional form (Equations 3a, b), such as those of An88 and DB93, can therefore considerably overestimate Q_H in neutral conditions (f_{MO-T} is too small so the T_* obtained is too large) and means Q_H values close to zero are underrepresented or simply not obtained. Using the function fitted directly to the Swindon EC data improves estimation of these smaller Q_H values. The observational fits have the conventional functional form in unstable and stable conditions, plus two extra terms to account for the divergence towards neutral conditions:

$$f_{MO}(\zeta) = \frac{C_T^2(z_m - z_d)^{2/3}}{T_*^2} = 4.84(1 - 11.6\zeta)^{-2/3} + 0.00024\zeta^{-1} - 0.001133\zeta^{-2} \quad (\zeta < 0) \quad (A1)$$

$$f_{MO}(\zeta) = \frac{C_T^2(z_m - z_d)^{2/3}}{T_*^2} = 3.54(1 + 2.23\zeta^{2/3}) + 0.00010\zeta^{-1} + 0.021083\zeta^{-2} \quad (\zeta > 0) \quad (A2)$$

However, the fit to temperature does not represent the humidity scaling well.

Since most of the widely used functions in the literature do not capture this trend (possibly due to a lack of neutral data in these studies), Q_H derived using similarity theory tends to be biased towards larger values under near neutral conditions. Although absolute errors are usually small (a few $W\ m^{-2}$) so too is the size of Q_H and the frequency of data between -10 and 10 $W\ m^{-2}$ is significantly underrepresented compared to Q_H obtained from EC directly. For example, where Q_H changes sign the similarity functions (An88, DB93 and TG92 (Thiermann and Grassl 1992)) result in

lower values during stable conditions and higher values during unstable conditions giving a steeper change of stability overall (Figure A 1e).

Appreciable differences in the fluxes can arise depending on the similarity function used: An88 and DB93 tend to yield higher fluxes than TG92 by about 10-15% on average, with better agreement under unstable conditions. Although the fitted function performs much better under near neutral conditions for Q_H , the overall agreement is not much better than for An88 or DB93 and the performance under near neutral conditions is worse for Q_E . Given that the observed divergence is thought to be a limitation of the conventional scaling technique, we therefore decided against using the experimental fit to derive the scintillometer fluxes. Instead, An88 scaling is used for both T and q , which closely matches the shape of the observed scaling and does not produce as significant an overestimation as DB93.

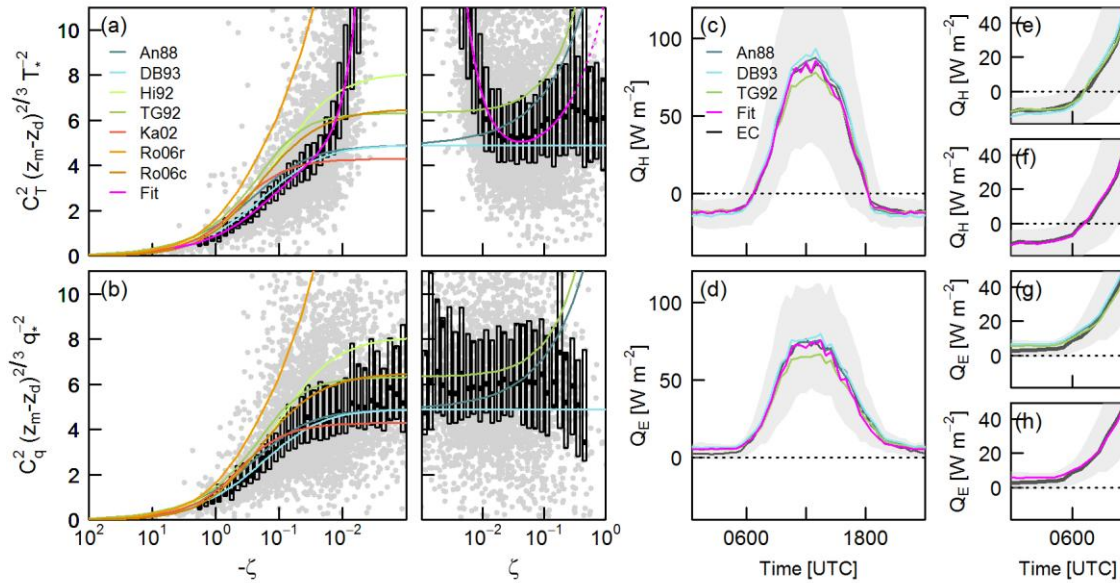


Figure A 1 Comparison between EC data and similarity functions from the literature: An88 (Andreas 1988), DB93 (De Bruin et al. 1993), Hi92 (Hill et al. 1992), TG92 (Thiermann and Grassl 1992), Ka02 (Kanda et al. 2002) and Ro06 (Roth et al. 2006) fits to rooftop (r) and canyon (c) datasets. Box plots (a, b) indicate median and inter-quartile range (IQR) binned by stability. A fit to the Swindon data ($|Q_H| > 5 \text{ W m}^{-2}$, $|Q_E| > 5 \text{ W m}^{-2}$) is also shown for temperature (a). Median diurnal cycle of (c) Q_H and (d) Q_E for all available data as measured directly by EC (IQR shaded) and as calculated via structure

parameters using the similarity functions indicated. The morning transition is magnified in (e-h); the fitted function is used in (f, h).

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