We thank both reviewers for their valuable comments and suggestions to improve the manuscript *Uncertainty of eddy covariance flux measurements over an urban area based on two towers*. Please find our point-by-point responses below.

Reviewer #1

General comments:

This paper presents a comparison analysis between two identical EC systems in central Helsinki to understand uncertainty of a single point EC measurement of the cumulative vertical fluxes of momentum, sensible and latent heat, and carbon dioxide in a highly dense urban area using several statistics and variables such as stationarity (FS), skewness (SK) and kurtosis (K), relative random uncertainty (RRE), TKE, turbulent transfer efficiencies (|ruw|, |rwt|) and power and co-spectra. As the authors stress this is the first study using a combination of two close EC systems conducted in a densely built urban area, this research is a step forward for understanding the impact of complex urban structure on fluxes and provides a useful guideline in general for other similar urban EC measurements.

However, there are some aspects that need to be illustrate more clearly to improve the manuscript. Please address the comments below and hopefully reflect them into the revised version.

Specific comments:

1. P5 L25. The RRE calculation equation (Eq. 3) is inconsistent with that in Lenschow et al. 1994, which they presented as

Thus, the relative error is

$$\frac{\sigma_F(T)}{|F|} = \left(\frac{2\mathcal{T}_f}{T}\right)^{1/2}\left(\frac{1+r_{ws}^2}{r_{ws}^2}\right)^{1/2}. \qquad (48)$$

In Eq. 3, the square root seems missing.

We noticed that this form of the relative random error is not directly used in our calculations but rather equation (46) from Lenschow et al. is used, where the flux variance follows the left-hand side of their equation (47). We have now fixed the manuscript accordingly (P5-6, L28-3).

And variables in Eq. 3 are not expressed clearly. i.e. What's the exact formula for calculating the integral time-scale (Γ*f*) or does it have a relation to the averaging period (30min) or have a specific value? How to calculate the correlation coefficient (*rws*)? Moreover, the expression (*rws*) is confusing with that of the turbulent transfer efficiencies in Eq. 5 and 6, are they indeed the same or different?

Integral time-scale is defined as the integral over the autocovariance function Rwx and in practice is estimated as the lag when R_{wx} drops to e^{-1}. We added this explanation to the manuscript. Its equation follows Lenschow et al. equation (26) and as this is simply an integration of Rwx, we left the equation out.

rws in the old equation (3) is the same as the turbulent transfer coefficient, but as that part of the manuscript was modified, no additional clarification for this connection was made.

We noticed that we use different abbreviation s and x for the variable to which the flux is calculated. To be concise we use x now throughout Section 2.2.

2. P6. For the calculation of spectra and co-spectra (Eq. 7-9), do they have any citations? What do the variables Sx(*f*) and Sxw(*f*) represent and what are their formulas? Why are spectra divided into 76 bins? How to determine the frequency *f* (HZ)?

Could you explain all these aspects more clearly, so that potential readers can better understand this work?

The book by Stull (1988) is probably the best citation on how to calculate spectra and co-spectra. We added this to P6, L13. Sx(*f*) is the power spectra of variable x and Sxw(*f*) the co-spectra between variable x and vertical wind speed. We added a bit more detailed explanation of these to the manuscript (P6, L15-18) but as these are calculated with Fast Fourier Transformation (FFT), which is a commonly known computational method, we decided not to add the detailed methodology on how these are calculated. The methodology can be found from e.g. Stull (1988).

The number of bins over which the raw spectral data are averaged is always a bit arbitrary but 76 bins have been used at the site also in the past (Nordbo et al. 2013). This will not affect the results but rather the visualization of the spectra. *f* is the frequency of the measurements (Hz) and this information was added to the manuscript (P6,L17).

3. P6 L24. It's confusing that the angles outside the flow distortion areas are so small: 5-18o for EC1 and 2-15o for EC1. Why aren't these angles ranges excluding the flow distortion area, i.e. 0-40 and 150-360 for EC1, 0-230 and 340-360 for EC2?

By angle here mean the vertical deflection angle and not wind direction. "Vertical deflection" was added to the sentence (P7,L11) to clarify this.

4. P8 L19. For daytime (Fig. 6a), the lowest RRE is sensible heat rather latent heat.

Yes. This is true for daytime. We changed the text to "…the lowest to daytime H (medians 12 and 13%)…" (P9, L18).

5. P8 L23. What's the possible reason for the contrary results between those previous studies (RRE lowest with momentum flux)?

The reason for the higher RRE in this study is likely the complex measurement location and to emphasize this, we added a sentence "…which is because of the complex measurement location and source-sink distribution at our site." to P9, L23-24.

6. P11 L8. Except the summer SKC and KC shown in Fig. 8, how about other months?

Same diurnal behavior is seen on other months but we only added summer here as we would need separate plots for different seasons due to day light saving. We added a sentence "Same behaviour is also seen on other months (not shown)." to the manuscript (P12, L8-9) to be clear.

7. P16 L5. What does inertial subrange mean? How to distinguish between negative and positive contributions? What do -4/3 slope and -2/3 slope represent in Fig. 10 and what's the basis to clarify between solid and open circles in Fig. 10a? How about other months except July 2014?

Inertial subrange is the range where turbulent energy is cascading from larger eddies to smaller ones. We added the approximative range of this (n = 0.1-0.4) to the manuscript (P17, L5). We are not sure we understand what the reviewer means with distinguish between negative and positive contributions. These negative values are only observed in the spectra of momentum flux and we clarified this in the manuscript (P17, L6). The value for each normalized frequency is the flux in that frequency bin. The two slopes are those predicted by Kolmogorov's theory. Explanations for these were added to Figure 10 caption: "The -4/3 and -2/3 slopes are those predicted by Kolmogorov". Frequencies with negative contributions are against the net flux and thus we wanted to show how at certain eddy sizes the eddies transport scalars in different directions.

Technical corrections:

P2 L21. Replace “paid on” with “paid to”. Also in P21 L17.
Corrected on both locations.

P3 L26. “the systems are located at 60.3 m”, isn’t it 60 m?
The measurement height is 60.0 m. There was a typo in the text and it has now been fixed.

P5 L1. “10 1 min-1”, what does the space between 0 and 1 mean?
The units of flow rates is litre per minute and l (not 1) is abbreviation for this. To avoid confusion, we now opened the units.

P5 Eq. 4. the prime over v is missing.
Prime added.

P7 L12. “correlation coefficient (R2)”, I think it’s determination coefficient.
Yes. Squared R is the coefficient of determination, which in our case is the square of Pearson correlation coefficient and that is why we used incorrectly only correlation coefficient. We have changed this to coefficient of determination throughout the text.

P12 L10. Typo: ldecreased.
Typo fixed.

P12 L23.Typo: hgreater.
Typo fixed.

P13 Fig. 7. To make it more clear, legend is recommended to add into the figure.
The figure legends were added to Figs. 7, 8 and 9 and A1.

Fig. 6 and Fig. 7. It would be better to use the same definition for daytime and nighttime. Either based on solar elevation angle (Fig. 6) or hour ranges (Fig. 7).
We agree that it is a bit unusual to have the different definitions for day and night-time in the two plots, but this was done on purpose due to the need of each figure. In Figure 6 the main point is to show how the RRE varies in different atmospheric conditions, which are to a large extent determined by solar radiation, whereas in Figure 7 we want to refer to human activity which is independent on the different hours of sunlight or darkness. Thus, we prefer leaving the different definitions to the manuscript.

P17 L17-18. The directions 250-330 and 50-130 are still not changed.
The limits have now been corrected also in the main text.

Reviewer #2
General comments
The Manuscript AMT-2018-89 by Leena Järvi et al. discusses a paired tower approach to assess the representativeness of measurements of vertical momentum, sensible heat, latent heat and carbon dioxide fluxes with the Eddy Covariance technique in a densely built urban environment. The two identical instrument systems were installed on the same building and only 10m apart, therefore they are virtually sampling the same source area outside of flow distortion angles that need to be excluded. The study is relevant to the scientific community since it will (1) help to better understand the relative and absolute magnitudes of measurement errors over an urban, heterogeneous surface area. Furthermore, the approach also allows to (2) assess the representativeness of measurements at sites equipped with a single Eddy Covariance system, specifically when measurements over flow distortion areas

need to be excluded which can result in systematic biases in temporally cumulated flux sums. The study was conducted with micrometeorological and statistical rigor; however, a list oftechnical corrections need to be addressed before publication in Atmospheric Measurement Techniques. Most of the corrections can easily be fixed by quite simple edits and efforts to make the text slightly more concise, predominantly in the Abstract and the Conclusion sections.

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Specific comments

(1) Given the extensive experimentation, subsequent processing and analysis of the data, the abstract has to be edited and refined quite substantially. In my view, this will ensure the accessibility of the technically dense study to a wider, perhaps even non-technical audience. Some of the sentences are worded in a way that is too vague, so they could be misinterpreted. I am providing more specific feedback on the abstract in the Technical Corrections section below.

We thank the reviewer for pointing out that the abstract is not necessarily meeting the right audience for the paper. Detailed responses can be found from below.

(2) The following result that is stated in the abstract appears to be not stated explicitly anywhere throughout the manuscript, or at least I was not able to find it: "the random uncertainties of the two systems are between 10 and 40 %." I suppose the values are simply "read off" of Fig. 6? If this is the case, it looks to me that really what was deducted here is that the interquartile range of the random uncertainties is between 10% and 40 %? I suggest to either provide the range of average (or median) uncertainties, or to add the statistical significance of the uncertainty assessments (e.g., at the 75% or 95% significance level). If the authors feel that would be too much detail for the abstract, then please incorporate this detail into the text of the manuscript. Otherwise the reader may be left guessing where this quite important result came from. Finally, the wording of this sentence as it stands also allows for some misinterpretation that the random uncertainties are calculated by looking at both towers together (which is ultimately one key objective of the study, cf. the key word "between"), when really the numbers 10%-40% simply represent the random uncertainties of one system at a time.

Thank you for pointing this out. We agree that it is more meaningful to have here the range of mean values rather than the interquartile range. We changed the range to 12-28% (also reported in the main text). With the suggested modification to the sentence it now reads "the median random uncertainties of the studied fluxes measured by one system are between 12 and 28 %" (P1, L17).

(3) One thought I kept pondering about while reading the article was the downstream implication of this study for future experimental EC studies in urban environments. Specifically, the results on the representativeness and sensitivities of the measurements as obtained by the paired tower approach. I.e., is the result conclusive of noconfirmation being needed at other locations? Are the results truly transferable to other urban locations with fairly homogeneous flux source areas as pointed out at the end of the abstract? Or, is further experimental validation needed? May the authors please discuss this in some more detail, perhaps at the end of section 3.4 in a short paragraph.

The referee raises here a good point. In addition to the abstract this is also shortly mentioned in the conclusions. As suggested we now added further discussion to the end of the Section 3.5 (P20, L25-30):

"The outcome of our study is that a single EC measurement point can produce reasonable estimations for surface fluxes above relatively homogeneous urban surface, but the next question naturally is that how applicable this result is for other urban EC sites. Each urban

measurement location is unique and in order to get a final answer, each site should be separately evaluated with more than one measurement setup. Nevertheless, the obtained uncertainties from this study can be used as a first approximation for urban EC measurements in a same way as the few two or multiple tower studies made in vegetated ecosystems are used to give general guidelines for the uncertainties."

(4) It is really encouraging to see that the random uncertainties decreased by applying the paired tower approach in an urban environment. Even better, the relative magnitude of the uncertainties appears to be in the same range as reported by previous studies with more homogeneous terrain. To me, this is one of the key results of the study, and could perhaps even be highlighted in the Abstract since it is highly relevant to future studies conducted in urban or other heterogenous terrain without "directional deviations" in the source area.

We cannot really say that the random uncertainties of the EC observations decrease by applying the two-tower approach as no joint value for the combined dataset is calculated. We only show that the systematic uncertainty decreases and this already mentioned in the abstract. However, we added a sentence "The obtained random and systematic uncertainties are in the same range as observed in vegetated ecosystems." (P1, L21-22) to emphasize the correspondence of the random and systematic uncertainties with those obtained in vegetated ecosystems.

Technical Corrections

Abstract, LL3-4: "Often one ecosystem is monitored using only a single EC measurement station bringing uncertainties to the ecosystem-level flux values." I would re-write this to: "Typically an ecosystem is monitored by only one single EC measurement station at a time, making the ecosystem-level flux values subject to random and systematic uncertainties"

Corrected as suggested.

Abstract, LL12-14: are "measurement location" and "measurement structures" used synonymously in this sentence? Might not be clear to a wider audience.

Yes. To clarify this, we removed measurement structures from the sentence and now it simply reads "The momentum flux is the most sensitive to the measurement location whereas scalar fluxes are less impacted" (P1, L13-14).

Abstract, L18: I suggest writing: "Combining the data from two EC systems also increases the percentage of usable half-hourly carbon fluxes from 45% to 69% at the annual level."

Modified to "Combining the data from two EC systems also increases the fraction of usable half-hourly carbon fluxes from 45 % to 69 % at the annual level." (P1, L19-21)

Abstract, LL17-19: I suggest to also give absolute values for the underestimation in grams of Carbon p.a., next to the 12% and 5-8%.

Added as suggested. We also added the values in units g C m-2 to the manuscript main text.

Abstract, L22: Which uncertainties are you referencing here? Random, systematic, or both? Please specify. (If I understood correctly, you are referencing both systematic uncertainties due to excluding flow-distorted wind sectors, and, random uncertainties due to turbulent sampling errors as assessed by the relative random uncertainty (RRE) metric.)

We refer to systematic uncertainty and this is now clarified also in the sentence (P2, L4).

Abstract, L22: I suggest changing "The same results can be assumed to apply in

similar dense city locations [...]" to "Comparable results can be expected in similarly dense city locations [...]"
Corrected as suggested (P2, L4).

Pg2, L26: please add a reference.
Reference added (P2, L31).

Pg2, L27: "to reject large amount of data": I suggest writing "to reject a relatively large fraction of the data".
Corrected as suggested (P2, L31).

Pg3, L2: I suggest writing "On top of that, any statistical gap-filling technique can be biased [...]" instead of "Either way, statistical gap-filling techniques can be biased [...]"
Corrected as suggested (P3, L7).

Pg3, L8: I would add the study of Hollinger & Richardson (2005) to this list of paired tower approaches, since it was the first of its kind.
Added as suggested (P3, L13).

Pg3, L19: Figure reference is missing. (???)
This was fixed.

Section 2.1: Can the authors please add one sentence in section 2.1 (Site description) on the representativeness of the flux source area as surveyed by the tower with respect to the "Helsinki city centre" that is referenced further down in the Conclusions
We added sentence "The two systems have a separation distance of 10 m and thus measure virtually the same source area" to P4, L2-3.

(Pg21, L4)? Perhaps simply by referencing information in the original citation for this site. Since the results of the study at hand are discussing the "representativeness" of measurements in a sampling sense, it may be helpful to the reader to be able to put things into perspective. It would also illustrate how essential it is to understand the fluxes extremely well at a fine spatial scale, to then use these measurements as the basis for accurate assessments of larger neighborhood or city level scales.
We modified the sentence to (P23, L5-8) "This result is naturally location-specific for this highly built-up site with vegetation fraction only 22% and relatively homogeneous roof level (Nordbo et al. 2013). The same result could be considered to apply also in other dense city centers with similar relatively homogeneous surface characteristics."

Pg5, L26: Spelling mistake in the word "square", please run a spell check before submitting the revision.
Done.

Pg8, L1: "the median R2 between the two measurement systems is 0.85"
Added as suggested (P8, L11).

Pg8, L25: this discussion may be more meaningful if an equation for R2 was provided. There are different equations for R2 in the statistical literature. Also, I suggest to re-write this same sentence and the following to: "Both statistical variables RRE and R2 should theoretically be a measure of random uncertainty. When RRE between the two systems are larger, R2 is expected to be smaller. Furthermore, we expected the two

resulting uncertainty rankings (according to RRE and R2) across the different fluxes to be consistent."

We added sentence "calculated as the square of the Pearson correlation coefficient" to P8, L6. We do not calculate joint RRE for the two setups but rather separate RRE's for the two systems. We modified the change to "Both statistical variables RRE and R2 should theoretically be a measure of random uncertainty. When RREs measured with the two systems are larger, R2 between the two systems is expected to be smaller. Furthermore, we expected the two resulting uncertainty rankings (according to RRE and R2) across the different fluxes to be consistent." (P9, L25-28).

Pg12, L10: typo "1decreased"

Typo fixed.

Uncertainty of eddy covariance flux measurements over an urban area based on two towers

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Abstract. The eddy-covariance (EC) technique is the most direct method to measure the exchange between the surface and the atmosphere in different ecosystems. Thus, it is commonly used to get information on air pollutant and greenhouse gas emissions, and on turbulent heat transfer. ~~Often one~~ Typically an ecosystem is monitored ~~using only a~~ by only one single EC measurement station ~~bringing uncertainties to~~ at a time, making the ecosystem-level flux values subject to random and systematic uncertainties. Furthermore, in urban ecosystems we are often compromised to conduct the single-point measurements in non-ideal locations such as close to buildings and/or in the roughness sublayer bringing further complications to data analysis and flux estimations. In order to tackle the question of how representative a single EC measurement point in an urban area can be, two identical EC systems – measuring momentum, sensible and latent heat, and carbon dioxide fluxes – were installed on each side of the same building structure in central Helsinki, Finland, for July 2013–September 2015. The main interests were to understand what is the sensitivity of the vertical fluxes on the single measurement point and to estimate the systematic uncertainty on annual cumulative values due to missing data if certain, relatively wide, flow-distorted wind sectors are disregarded.

The momentum and measured scalar fluxes respond very differently to the distortion caused by the building structure. The momentum flux is the most sensitive to the measurement location whereas scalar fluxes are less impacted~~by the measurement structures~~. The flow distortion areas of the two EC systems (40–150° and 230–340°) are best detected from the mean-wind-normalised turbulent kinetic energy and outside these areas, the median random uncertainties of ~~the two systems are between 10 and 40~~ the studied fluxes measured by one system are between 12 and 28 %. Different gap-filling methods to yield annual cumulative fluxes show how using data from a single EC measurement point can cause up to 12 % (480 g C m^{-2}) underestimation in the cumulative carbon fluxes when compared to combined data from the two systems. Combining the data from two EC systems ~~increases also data coverage~~ also increases the fraction of usable half-hourly carbon fluxes from 45 % to 69 % at the annual level. For sensible and latent heat, the respective underestimations are up to ~~5–8 %.~~ 5 and 8 % (0.094 and 0.069 TJ m^{-2}). The obtained random and systematic uncertainties are in the same range as observed in vegetated ecosystems. We also

show how the commonly used data flagging criteria in natural ecosystems, kurtosis and skewness, are not necessarily suitable to filter out data in a densely built urban environment. The results show how the single measurement system can be used to derive representative flux values for central Helsinki but the addition of second system to other side of the building structure decreases the ~~uncertainties. The same~~ systematic uncertainties. Comparable results can be ~~assumed to apply in similar~~ expected in similarly dense city locations where no large directional deviations in the source area are seen. In general, the obtained results will aid the scientific community by providing information about the sensitivity of EC measurements and their quality flagging in urban areas.

1 Introduction

It is recommended that surface fluxes measured using the eddy-covariance (EC) technique are done in the inertial sublayer and free from obstructions (Roth, 2000). These assumptions are often easy to meet over natural surfaces–but can be challenging for EC systems above cities. Often the EC measurements are made within or in the vicinity of the roughness sublayer, the adjacent layer to the surface with height of 2–5 times the mean building height (Raupach et al., 1991). In this layer, turbulence is not homogeneous but rather varies greatly in space, and the Monin-Obukhov similarity theory (MOST) is not anymore strictly valid. Despite the non-ideal conditions, EC measurements from urban areas are needed for the purposes of wind engineering, understanding the urban surface-atmosphere interactions, in the estimation of urban carbon budgets (Christen et al., 2011; Nordbo et al., 2012a) and on improving the description of urban areas in numerical weather and air quality predictions via the measured turbulent fluxes of heat (Grimmond et al., 2010; Karsisto et al., 2015; Demuzere et al., 2017). In order for the urban EC systems to meet the requirements of the technique, we are often forced to conduct the measurements on top of buildings or other platforms such as telecommunication towers (Wood et al., 2010; Liu et al., 2012; Brümmer et al., 2013; Nordbo et al., 2013; Keogh et al., 2012; Ao et al., 2016) instead of narrow lattice masts which would minimise the effect of the structure itself on the EC measurements. Thus strictly speaking, the measurements are not necessarily made completely free of the impact of roughness elements even if the measurement height would be at sufficient height above the surrounding roughness elements. The interaction between the EC measurements and the measurement platform itself causes challenges for obtaining high quality EC datasets and special attention should be paid ~~on~~ to the effect of the so-called flow distortion area on the measurements (Barlow et al., 2011). Urban EC measurements have furthermore raised the need for local scaling of mean turbulent properties with minor deviations from inertial-sublayer scaling (Rotach, 1993; Roth, 2000; Vesala et al., 2008; Wood et al., 2010) and corrections for local-scale anthropogenic sources (Kotthaus and Grimmond, 2012).

The basic quality screening of a single sensor in measuring vertical fluxes can be performed based on the vertical deflection angles and expected turbulence, and sometimes even by simply disregarding whole (flow-distorted) wind sectors (Barlow et al., 2011). It is not however ideal if we have to reject ~~large amount of~~ a relatively large fraction of the data. For

cumulative emission estimates, the flux data need to be gap-filled – but in urban areas this is more complex than in vegetated environments due to the large amount of explanatory variables and the high spatial variability of the sources and sinks (Menzer et al., 2015). The used gap-filling methods in urban EC flux datasets vary from simple look-up tables to artificial neural networks (Schmidt et al., 2008; Kordowski and Kuttler, 2010; Christen et al., 2011; Järvi et al., 2012), but the more complex and time-demanding solutions might not always be considerably better than the more simple ones. Järvi et al. (2012) found only 4% difference in cumulative carbon dioxide (CO_2) fluxes when utilising median diurnal cycles and neural networks in filling data gaps at a semi-urban site in Helsinki. ~~Either way,~~ On top of that, any statistical gap-filling techniques can be biased if certain wind directions are compromised above heterogeneous surfaces and therefore single-point EC measurements might not give realistic cumulative flux values. The same applies to the representativeness of a single measurement point for a studied ecosystem in general. Already at forested sites, which are generally considered to be easier for EC measurements than urban areas, the uncertainties in CO_2 flux originating from a single measurement point have been reported to be 6 % (Hollinger et al., 2012). In the past, simultaneous observations from more than one EC station have been used to estimate uncertainties in EC-measured fluxes above vegetated surfaces ~~(Kessomkiat et al., 2010; Peltola et al., 2015; Post et al., 2015)~~ (Hollinger and Richardson, 2005; Kessomkiat et a in urban areas no estimations have been derived from direct EC measurements with more than one measurement system at same level.

The aim of this work is twofold. Firstly, we want to examine the sensitivity of a single-point EC system in measuring the vertical fluxes of momentum, sensible and latent heat, and carbon dioxide in a highly dense urban area. Secondly, we want to understand what is the implication of the non-ideal measurement location and resulting data removal on the calculation of cumulative fluxes, which are important for emission-inventory comparison and planning of neighbourhoods. These two aims will be examined with the aid of two identical EC measurement systems located on the opposite sides of a bluff-body tower in the centre of Helsinki.

2 Methods

2.1 Measurement site and instrumentation

The measurements were conducted in central Helsinki (Figure 1) where two identical EC setups were installed on top of a hotel building (Figure 2) at height (z) of 60 m above the ground for July 2013 until September 2015. Within 1 km radius of the measurement location, 37 % of the surface is covered with buildings, 41 % with paved surfaces leaving only 22 % of the surface covered with vegetation (Nordbo et al., 2015). The surrounding buildings are fairly uniform with a mean height of 24 m, displacement height of 15 m and aerodynamic roughness length of 1.4 m (Nordbo et al., 2013). However one notable exception is the Hotel Torni building itself: its main building is up to 15 m above the ground level, the tower up to 58 m and upper masonry extending up to 66 m. The two EC systems (EC1 and EC2) were mounted on the opposite sides of an upper masonry on a 2.3 m high measurement masts (Figure 2). ~~Thus, the~~ The systems are located at ~~60.3~~60 m which is 2.5 times the mean building height and therefore they should be above the roughness sublayer and blending height where local-scale surface sources and sinks have aggregated together (Raupach et al., 1991). The centre of Helsinki is located on a peninsula, but

previous analyses on the source area of EC1 system have shown the flux footprint to lie above the city and not the sea (Kurppa et al., 2015; Auvinen et al., 2017). The two systems have a separation distance of 10 m and thus measure virtually the same source area. The downside of the measurement location is that the upper masonry disturbs the flow and we choose to neglect data for certain wind directions based on quality considerations. Based on the mean-wind-normalised turbulent kinetic energy (TKE), the areas are approximated to be 40–150° and 230–340° for EC1 and EC2, respectively (Figure 3).

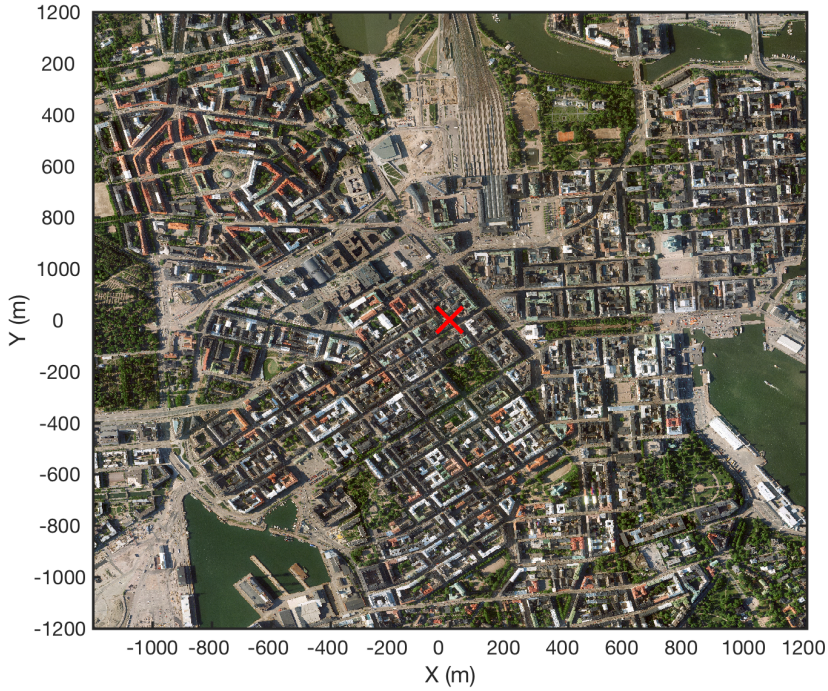

Figure 1. Aerial image of central Helsinki (Kaupunkimittausosasto, Helsinki, 2011). Hotel Torni is marked with red cross.

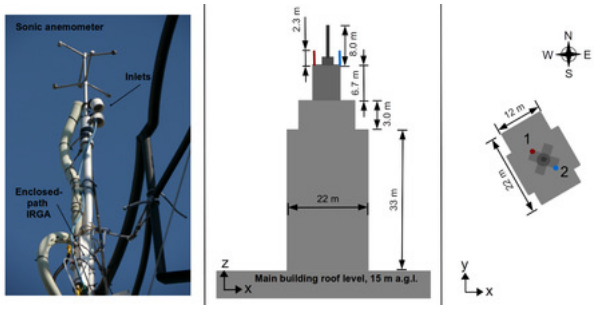

Figure 2. Left: a photo of one EC installation. Middle: a side view of the tower. Right: a plan view. See Nordbo et al. (2013) for more details.

Each system comprised of a 3D ultrasonic anemometer measuring the sonic temperature and 3D orthogonal wind speeds (USA-1, Metek GmbH, Germany), and an infrared gas analyzer (LI-7200, LI-COR Biosciences, Lincoln, NE, USA) giving concentrations of water vapour and CO_2. The air inlets were positioned 0.15 m below the anemometer centre and air was drawn through a 1 m long stainless steel tube (with inner diameter of 0.04 m) to the gas analyser. The flow rates were 10 ~~l~~litres min^{-1}. Tubes were heated with a power of 9 W m^{-1} to avoid condensation of water vapour on their walls. The raw EC data were sampled with a frequency of 10 Hz, from which the 30-min flux values were calculated using commonly accepted procedures (Nordbo et al., 2012b). The fluxes were determined using the maximum covariance technique where the window mean and width for the lag time were identical for the two systems (0–1.2 s for CO_2 and 0–7 s for H_2O). Before the calculation of the fluxes, data were despiked and linearly detrended. The high-response losses resulting from the tube attenuation were corrected with the aid of measured temperature cospectra yielding CO_2 response time of 0.11 s for EC1 and 0.14 s for EC2, respectively. Wind coming from the flow distortion areas removed 27 % of the EC1 data and 38 % of the EC2 data. The larger fraction with EC2 is due to the prevailing wind direction from South–West.

2.2 Data analysis

In order to understand possible differences between the two measurement setups, several variables and statistics describing turbulence characteristics will be evaluated. Stationarity (FS), skewness (SK) and kurtosis (K) are common variables used to examine the quality of EC data with the first providing information about the stationarity of the flux measurements and the latter two about the form of the probability function of the measured concentration, temperature or wind speed (Vickers and Mahrt, 1997). Stationarity is calculated by dividing each 30-min flux period into six sub-sets for which the flux values are separately calculated and their mean furthermore compared with the 30-min flux values. Typically, with differences below 30%, data are considered to be high quality and differences below 60% still suitable for general data analysis. In this study, the strict limit of 30% will be used. SK describes the asymmetry of the probability function of a variable and it is calculated from

$$SK = \frac{\overline{(x'^3)}}{\sigma_x^3}, \tag{1}$$

where x is a velocity or scalar variable, overbar indicates the 30-min time average, prime the deviation from the mean of the variable and σ_x is its standard deviation. SK between –2 and +2 is ~~commonly~~ considered to be good quality EC data. K is a measure of sharpness of the probability function i.e. its high values indicate peaks in the data. It is calculated from

$$K = \frac{\overline{(x'^4)}}{\sigma_x^4}. \tag{2}$$

K between 1 and 8 is considered as reasonable quality data.

The relative random uncertainty (RRE) of the vertical flux of scalar x ($F = \overline{w'x'}$, where w is the vertical wind speed) ~~measurements~~is calculated as the square root of the random ~~flux error~~ error variance (σ_F^2) ~~relative to the suqare of~~ normalised with the absolute value of the flux according to Lenschow et al. (1994)~~.~~:

$$\mathrm{RRE} = \frac{\sigma_F(\Gamma)}{|F|} = \frac{2\Gamma_f}{\Gamma}\frac{1+r_{ws}^2}{r_{ws}^2}(2\mu_\rho\frac{\Gamma_\rho}{\Gamma})^{1/2}, \tag{3}$$

where ρ refers to the instantaneous flux ($w's'$). μ_ρ is the flux variance

$$\mu_\rho = \mu_w \mu_x + F^2, \tag{4}$$

where μ_w and μ_x are the variances of w and x, Γ is the averaging period (30 min), ~~Γ_f~~ and Γ_ρ the integral time-scale ~~and r_{ws} the correlation coefficient between the time series.~~defined as the integral over the autocovariance function (R_ρ, (Rannik et al., 2016)) and in practise is estimated as the lag when R_ρ drops to e^{-1}.

The turbulent kinetic energy (TKE) is obtained from

$$\text{TKE} = 0.5(\overline{u'^2} + \overline{v^2} + \overline{w'^2}). \tag{5}$$

The turbulent transfer efficiencies for momentum and heat fluxes are calculated from

$$|r_{uw}| = \frac{\overline{u'w'}}{\sigma_u \sigma_w}, \tag{6}$$

and

$$|r_{wT}| = \frac{\overline{w'T'}}{\sigma_w \sigma_T}. \tag{7}$$

The power and co-spectra of momentum (τ), sensible heat (H) and carbon dioxide (F_c) fluxes are calculated using fast Fourier transforms for 60-min periods (2^{15} points) using widely used procedures (Stull, 1998). Spectra are divided into 76 logarithmically even-spaced bins ~~. The frequency dependent atmospheric spectra~~ for which the mean values are calculated. The normalised forms for power spectra of variable x ($S_x(f)$) and co-spectra between w and x ($S_{xw}(f)$) are used, where they are multiplied by the measurement frequency (f) and divided by variance ($\text{var}(x) = \mu_x$) and covariance ($\text{cov}(x, w)$) according to

$$\frac{f S_x(f)}{\text{var}(x)} \tag{8}$$

and ~~co-spectra~~

$$\frac{f S_{xw}(f)}{\text{cov}(x, w)}\cancel{,}. \tag{9}$$

~~of the vertical flux and variable x~~The normalised spectra and cospectra are are plotted against the normalised frequency n:

$$n = \frac{f(z-d)}{U}, \tag{10}$$

where ~~f is the frequency (Hz) and~~ U is the mean wind speed.

3 Results

3.1 Turbulent transport and vertical fluxes

The flow distortion areas of both EC systems (no filtering based on FS, SK and K) due to the upper masonry are clearly distinguishable from the vertical deflection angle (θ), normalised TKE and turbulent transfer coefficients (Figure 3). Even

though the two EC systems were to our best attempts designed to be identical and symmetrically located on the opposite side of the masonry, we observe quantitative asymmetry in the first and second moment statistics. The vertical deflection angle, which sets $w = 0$ in the two-dimensional coordinate rotation ($\tan^{-1}(\overline{w}/U)$) and describes the distortion of the measurement structure on the measurements, experiences fluctuating behaviour in these areas indicating modified flow structure due to the building masonry (Figure 3a). Some of the deviation can be explained by variation in the surrounding topographies in the direction of flow distortion areas.

Outside the flow distortion areas, the vertical deflection angles vary between 5–18° with EC1 and between 2–15° with EC2 which are at the same range as observed at BT Tower in London (Barlow et al., 2011). The normalised TKE at the flow distortion area measured with EC1 reaches 2.5 and with EC2 1.7 showing clearly the asymmetry in the areas. Both EC systems give a mean value of 0.34 for the normalised TKE outside the flow distortion areas indicating them measuring similar turbulence (Figure 3b). Furthermore, TKE is fairly uniform with wind direction despite the measurement location being considered to be complex from the point of view of micrometeorological measurements. Also the transfer efficiencies for heat are similar between the two systems with the values of 0.32 for EC1 and 0.29 for EC2 outside the flow distortion areas (Figure 3c). The transfer efficiencies of momentum are clearly different from that of heat and have largest deviations between the two systems (Figure 3d). The transfer coefficient for heat has a clear dip when the flow is disturbed whereas the momentum transfer coefficients follow a more complex pattern. This indicates the different effect of the measurement platform on the transport of momentum and heat with stronger effect on the first.

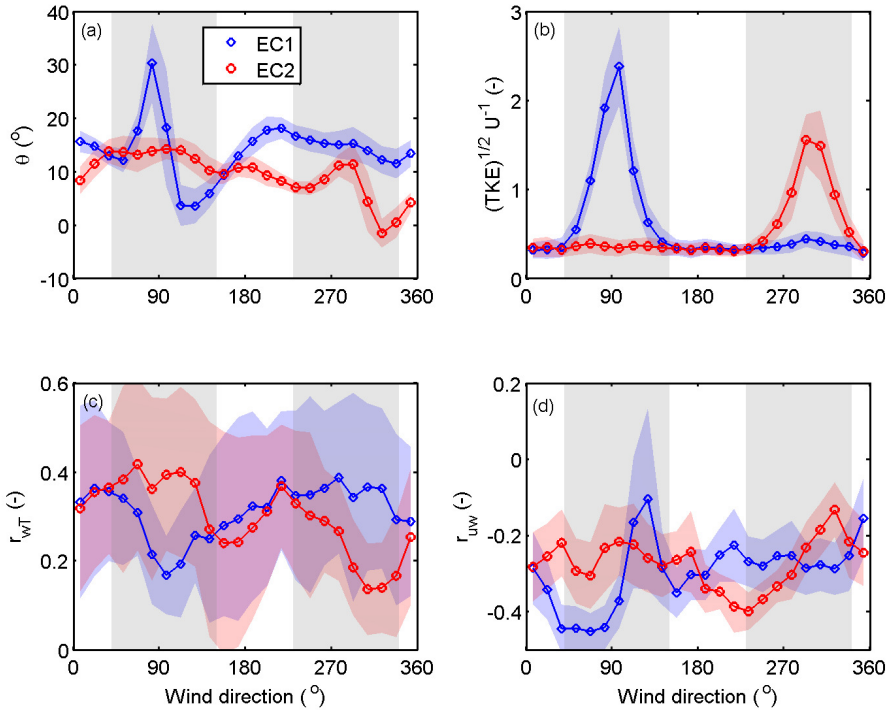

Figure 3. Wind direction dependence of (a) the vertical deflection angle (θ), (b) normalised turbulent kinetic energy (TKE$^{1/2}$ U^{-1}) and turbulent transfer efficiencies (c) of heat (r_{wT}) and (d) momentum (r_{uw}) from EC1 and EC2 for July 2013 until September 2015. Only winds speeds $U > 1$ m s^{-1} and for r$_{wT}$ $|H| > 10$ W m^{-2} are taken into account. Lines and symbols represent the 15° bin averages and the patches $\pm$ 1 std. The disturbed wind directions (40–150° for EC1 and 230–340° for EC2) are marked with grey areas.

The asymmetry of the flow distortion areas is furthermore reflected in the vertical fluxes of momentum (τ), sensible (H) and latent heat (LE), and CO_2 (F_C) (Figure 4). The strength of asymmetry varies with atmospheric stability and between variables indicating that purely prevailing meteorology cannot be responsible for the observed differences but rather the morphological effects play a role. Outside the flow distortion areas, differences between the two systems are small and depend on the studied flux. The best correlation between the two EC systems is seen in H with the median of ~~correlation coefficient~~ coefficient of determination (R^2 calculated as the square of the Pearson correlation coefficient) being 0.95, the slope of the linear least square regression (EC2 = Slope·EC1 + Intercept) being close to one and the intercept within $\pm$5 W m^{-2} (Figure 5). The maximum difference in the absolute values is 20 W m^{-2} (Figure 4b) in unstable conditions. In the correlation of τ, largest differences of all fluxes with a sinusoidal pattern as a function of wind direction are seen. The slope varies between 0.5–1.8 and the intercept is systematically below zero indicating lower momentum flux measured by the EC2 than EC1 (Figure 5a,b). Furthermore, the median R^2 between the two measurement systems is 0.85 (Figure 5c). The directional dependencies and correlations between

the two systems in measuring LE and F_C follow a similar pattern indicating similarity between the two variables (Figures 4c,d and 5). For LE, the correlation statistics are however somewhat lower than for F_C. LE has the ~~correlation coefficient~~ coefficient of determination in the range of 0.6–0.9, the slope in the range of 0.7–1.0 and the intercept in the order of 10 W m^{-2} with a greater flux measured with EC2 than EC1. For F_C the respective values are 0.8–0.9, 0.7–1.1 and 0–5 μmol m^{-2} s^{-1}. The absolute differences yield -1.9 W m^{-2} and -0.3 μmol m^{-2} s^{-1}, respectively. The correlation statistics in our case are slightly poorer that observed over a a grassland in UK (Mccalmont et al., 2017), where R^2 scatter suggested sampling uncertainty between 5–7% when compared to our 10–20%.

The separation distance between the two EC systems is less than 10 m and thus they are expected to measure the same source area outside the flow distortion areas. At the same time the observed differences cannot arise from the post-processing as fluxes were calculated and processed in a similar manner. Some of the difference can still originate from instrument drifting, but this would indicate non-directional dependence. As a result, the differences in the fluxes measured by the two systems very probably relate to the variation of the flux field caused by complex terrain. In past studies above vegetated ecosystems, the random uncertainty of flux measurements resulting from instrumental errors, heterogeneity of the surface and turbulence has been determined using so-called two-tower approach (Hollinger and Richardson, 2005; Kessomkiat et al., 2010). Its assumption is that the two time series should be independent from each other and thus cannot be used in our case when the two systems are measuring the same footprint. We can however still calculate the relative random error (RRE) in order to get an understanding about the random uncertainties of our EC measurements. Of all studied vertical fluxes, the largest random uncertainties relate to τ (medians between 23–28%) and the lowest to ~~LE (medians between 16–20~~daytime H (medians 12 and 13%) (Figure 6). For τ no systematic pattern between daytime/night-time is seen whereas for the other fluxes, nocturnal uncertainties tend to be larger when also the scalar fluxes are small. For these also RRE from EC2 are slightly larger than from EC1 whereas for τ these are vice versa. The RREs are of the same order of magnitude as observed at the semi-urban site in Kumpula and above vegetated ecosystems. In these, however, the RRE associated with τ tends to be the lowest contrary to our study (Finkelstein and Sims, 2001; Billesbach, 2011; Nordbo et al., 2012b), which is because of the complex measurement location and source-sink distribution at our site.

Both statistical variables RRE and R^2 should ~~in principle provide the same information about~~ theoretically be a measure of random uncertainty. When RRE~~from~~s measured with the two systems are larger, R^2 ~~should respectively~~ between the systems is expected to be smaller. Furthermore, we expected the two resulting uncertainty rankings (according to RRE and R2) across the different fluxes to be consistent. However, this is not observed and based on R^2 the fluxes can be ranked in increasing order LE, F_C, τ and H both in day- and night-time (0.79, 0.82, 0.86, 0.92 and 0.66, 0.85, 0.88, 0.94). A possible explanation for this is that R^2 is calculated between the two EC systems and is impacted by systematic disturbances and the building masonry. Thus, RRE is considered to be more representative for flux random uncertainties.

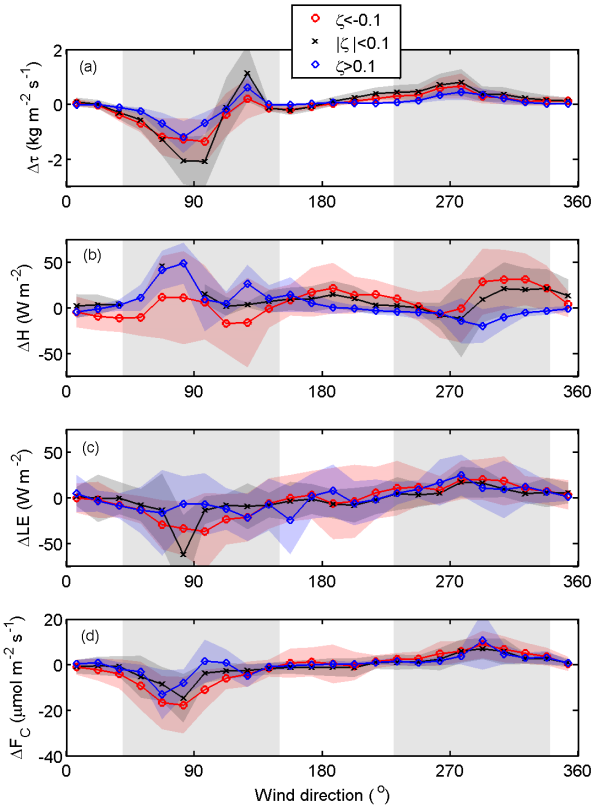

Figure 4. Wind direction dependence of the differences in the (a) momentum (τ), (b) sensible (H) and (c) latent heat (LE), and (d) CO_2 (F_C) fluxes between the two EC systems (EC1–EC2). Differences are calculated for the whole measurement period and data are separated into different stability classes (unstable ($\zeta < -0.1$), stable ($\zeta > 0.1$) and neutral ($|\zeta| < 0.1$) based on the stability parameter ζ. Lines and symbols represent the 15° bin averages and the shaded areas $\pm$ 1 std. The neglected wind directions (40–150° for EC1 and 230–340° for EC2) are marked with grey areas.

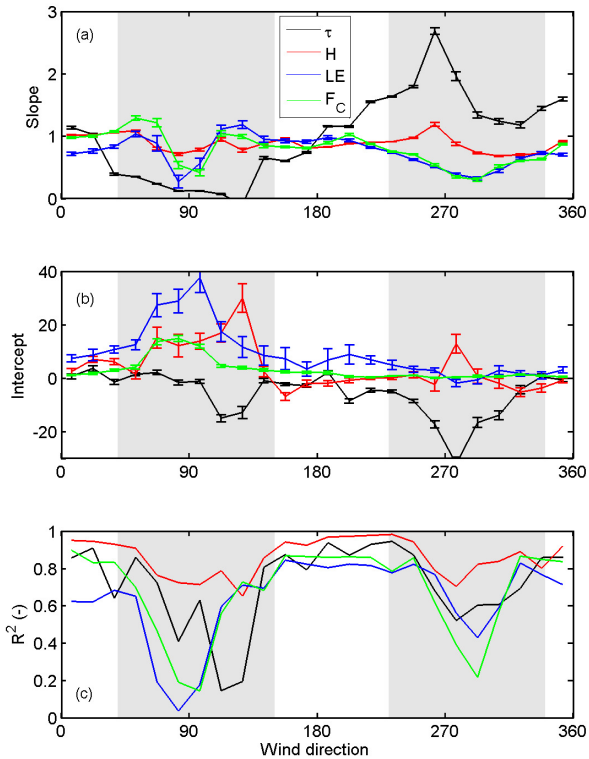

Figure 5. Wind direction dependence of the (a) slope, (b) intercept (kg m^{-2} m^{-1}, W m^{-2}, μmol m^{-2} s^{-1}) and (c) squared ~~correlations~~ coefficient of determination ~~(R^2)~~(R^2) of the linear least square fit of momentum (τ), sensible (H) and latent heat (LE), and CO_2 (F_C) fluxes between the two EC systems (EC2 = Slope·EC1 + Intercept) during July 2013 until September 2015. The neglected wind directions (40–150° for EC1 and 230–340° for EC2) are marked with grey areas.

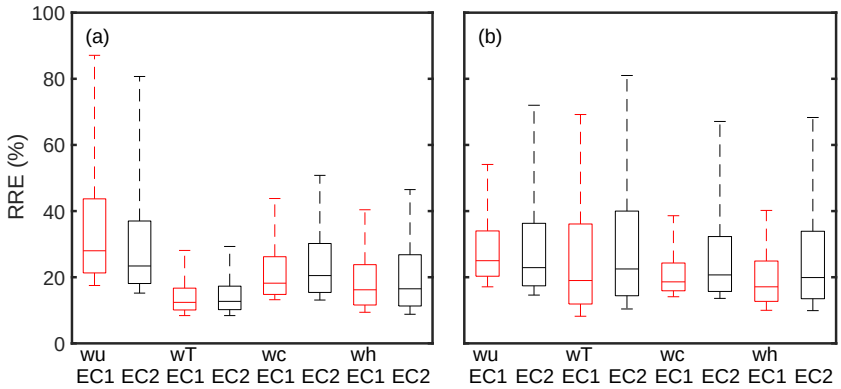

Figure 6. Relative random error (RRE) for (a) daytime (solar elevation angle $> 0°$) and (b) night-time (solar elevation angle $\leq 0°$) momentum (wu), heat (wT), CO_2 (wc) and water vapour (wh) covariances from the two systems EC1 and EC2 outside the flow distortion sectors. Whiskers and boxes represent the 10th, 25th, 50th, 75th and 90th percentiles.

3.2 Skewness and kurtosis

SK is within the good data quality limits (-2<SK<2) for all studied variables, excluding CO_2 (Figure 7, Table 1). Particularly elevated values in the skewness of CO_2 (SK_C) are seen during the daytime in direction 150–200° with the median SK_C reaching 4 whereas in other directions the medians are around 1. The 90th percentiles can reach as high as 5 in direction 150–200° as it is summarised in Table 1. A similar elevated pattern can also be seen in the kurtosis of CO_2 (K_C) with the median values reaching 25 indicating spiky behaviour in CO_2 (Figure A1). These elevated values are only seen during the daytime so these must relate to the daily activities emitting CO_2 and/or prevailing meteorological conditions. The same can clearly be seen from the diurnal variability of both SK_C and K_C shown in Figure 8 for summer months from June till August. Same behaviour is also seen on other months (not shown). While for directions 150–200° elevated values for both statistical variables are seen, in other directions the diurnal variability of SK_C and K_C is relatively flat with the 90th percentiles remaining mostly below 2 and 6, respectively.

In the direction of elevated SK_C and K_C, both variables start to increase in the morning at 6:00 matching with the increase both in road traffic and atmospheric instability observed in Helsinki (Kurppa et al., 2015). Two clear peaks in SK_C and K_C are seen around noon and afternoon between 15:00-19:00. The first peak matches with maxima mixing conditions and the latter with afternoon rush hour. Commonly, at the time of morning rush hour (7:00-9:00) the atmospheric mixing is still relatively weak and pollutants from the street level are not necessarily as easily transported to the measurement level (Contini et al., 2012; Kurppa et al., 2015). Previously, a skewed distribution of turbulent velocity components within and just above the street canyon has been related to street canyon vortexes causing sweeps and ejections (Oikawa and Meng, 1995). This could also

be a potential explanation for the high SK_C and K_C values in direction 150–200° since these directions matches with wind blowing perpendicular to the streets in the grid type street network in Helsinki. Also previous studies utilising large eddy simulation have shown how street canyon ventilation and sweeps increase in more unstable conditions (Gronemeier et al., 2017; Raupach et al., 2015) which is systematic with our results related to the timing of the maximum SK_C and K_C. But the effect of meteorological background conditions cannot be ruled out since the directions with elevated SK_C and K_C match with flow coming from the sea which can further modify the flow and skewed distribution of CO_2 concentration. High skewness values of CO_2 data have previously been connected to local-scale anthropogenic sources (Kotthaus and Grimmond, 2012). At the hotel building, small ventilation units are located 9 m below the measurement systems in the north-eastern, north-western and south western corners, but as these do not match the directions 150–200° and systematic signals are seen in both EC1 and EC2, these units cannot be responsible for the increased SK_C and K_C. Furthermore, these local-scale sources have been connected to increased fluxes F_C and H as well as ~~ldecreased~~ decreased LE whereas in our case slightly higher flux values are only seen in F_C in unstable conditions in directions 150–200° (Figure B1). Nonetheless the reason for the elevated SK_C and K_C, filtering F_C data based on these variables would remove realistic flux values and therefore they should be used with caution in post-processing of CO_2 fluxes.

At the same time with increased SK_C and K_C in the southern direction, the flux stationarity of F_C remains below 0.2 which is considered to be of high-quality flux data (Figure 9). Thus, applying only the stationarity criteria either with 30 or 60% limit but no skewness and kurtosis criteria would leave most of the data for further data analysis. The most non-stationary variable is the latent heat flux with 90th percentiles systematically over 1 in all directions and hours as measured by both setups. FS_h gets slightly greater values with EC1 than EC2 with the first having median values of 0.24 (90th percentile 1.24) in summer and 0.39 (1.56) in winter, and the latter 0.21 (1.08) and 0.39(1.53), respectively. Interestingly, relatively large flux stationary values of momentum flux are seen both by day and night. Usually, the momentum flux is least filtered based on the stationarity criteria but in our case, due to the complex measurements location, relative large data proportions would be filtered away. The median values are 0.27 (0.69) in summer and 0.17 (0.51) in winter for EC1 being fairly similar to EC2 with median values of 0.28 (0.67) and 0.19 (0.45). Despite the similar magnitude quartile values, EC1 gets ~~hgreater~~ greater values in directions 190–360° and EC2 symmetrically in directions 0–180°.

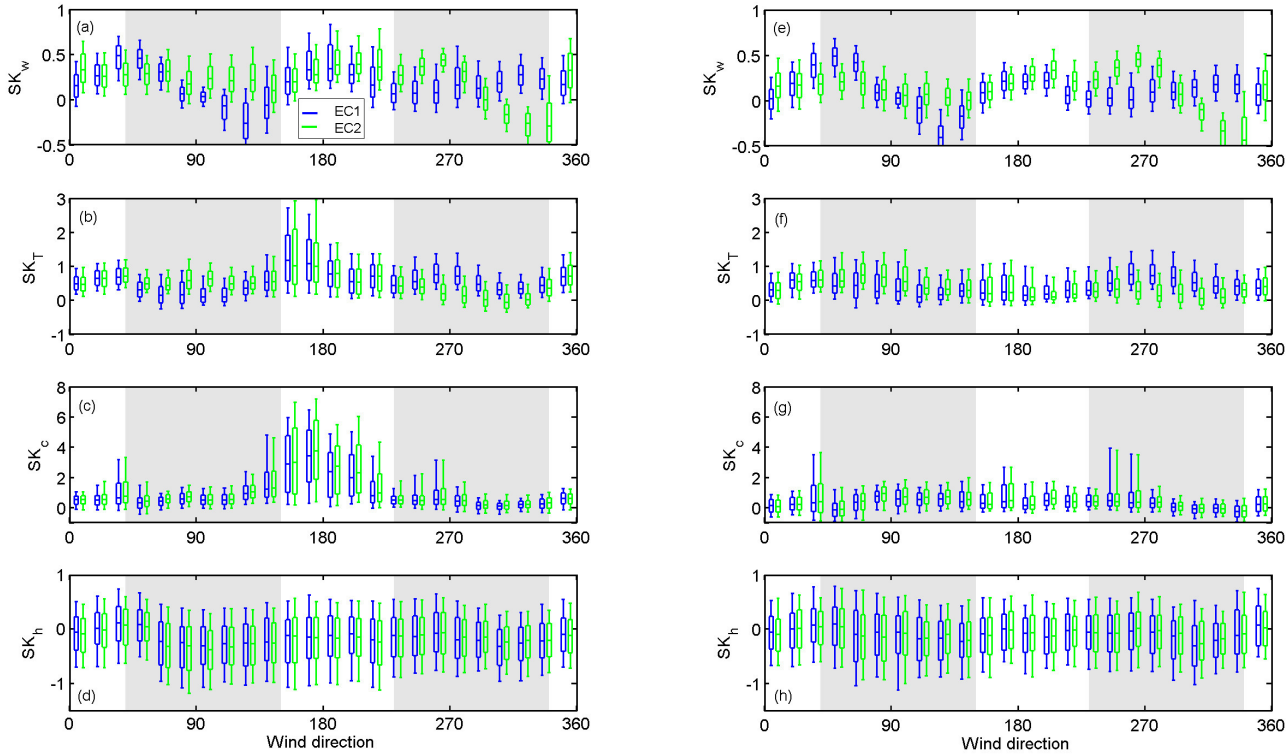

Figure 7. Skewness (SK) of (a,e) vertical wind speed (w), (b,f) air temperature (T), (c,g) CO_2 (c) and (d,h) water vapour (h) as a function of wind direction for hours 6:00–21:00 (a-d) and 21:00–6:00 (e-h) for EC1 (blue) and EC2 (green) during July 2013 until September 2015. Whiskers and boxes represent the 10th, 25th, 50th, 75th and 90th percentiles.

Table 1. Medians and percentile values (10th, 50th and 90th) of skewness (SK), kurtosis (K) and flux stationarity (SF) of vertical wind speed (w), air temperature (T), CO_2 (c) and water vapour (h) measured by the two EC setups (EC1 and EC2). Data are separated to summer (June–August) and winter (December–February) and CO_2 statistics are differentiated for wind sectors (WD1 150–200 and WD2 the remaining sector). N is the number of data points.

EC1	Season		N	SK			K			FS		
w	Summer		10335	-0.09	0.17	0.56	3.1	3.5	4.4	0.06	0.27	0.69
	Winter		8042	-0.13	0.12	0.42	3.1	3.5	4.2	0.03	0.17	0.51
T	Summer		10333	0.06	0.55	1.25	2.7	3.6	6.0	0.04	0.18	0.68
	Winter		8028	0.01	0.47	1.37	3.0	4.1	7.7	0.04	0.20	0.92
c	Summer	WD1	633	-0.02	2.07	5.15	3.4	11.7	45.0	0.02	0.12	0.45
		WD2	6695	-0.45	0.39	1.45	2.6	3.5	9.0	0.01	0.09	0.42
	Winter	WD1	967	-0.03	1.54	5.73	2.8	8.4	50.3	0.01	0.04	0.24
		WD2	4447	-0.20	0.49	2.93	2.5	3.5	22.4	0.01	0.07	0.35
h	Summer		8209	-1.08	-0.31	0.44	2.2	3.1	5.3	0.03	0.24	1.24
	Winter		5397	-0.51	0.06	0.62	2.0	2.6	3.7	0.05	0.39	1.56
EC2	Season		N	SK			K			FS		
w	Summer		10480	-0.17	0.26	0.61	3.2	3.9	5.1	0.05	0.28	0.67
	Winter		7702	0.00	0.26	0.49	3.2	3.8	4.6	0.03	0.19	0.45
T	Summer		10470	0.00	0.52	1.17	2.6	3.6	5.9	0.04	0.17	0.75
	Winter		7701	-0.03	0.35	1.26	3.0	4.3	8.9	0.03	0.21	1.00
c	Summer	WD1	767	-0.02	2.11	5.46	3.3	12.1	48.1	0.01	0.09	0.38
		WD2	7617	-0.44	0.43	1.67	2.6	3.6	11.0	0.01	0.07	0.36
	Winter	WD1	1346	-0.08	1.73	6.23	2.7	9.2	60.2	0.00	0.03	0.13
		WD2	6294	-0.14	0.53	3.31	2.6	3.6	25.0	0.00	0.06	0.31
h	Summer		8232	-1.10	-0.32	0.40	2.3	3.1	5.3	0.03	0.21	1.08
	Winter		7593	-0.50	0.06	0.61	1.9	2.6	3.6	0.05	0.39	1.53

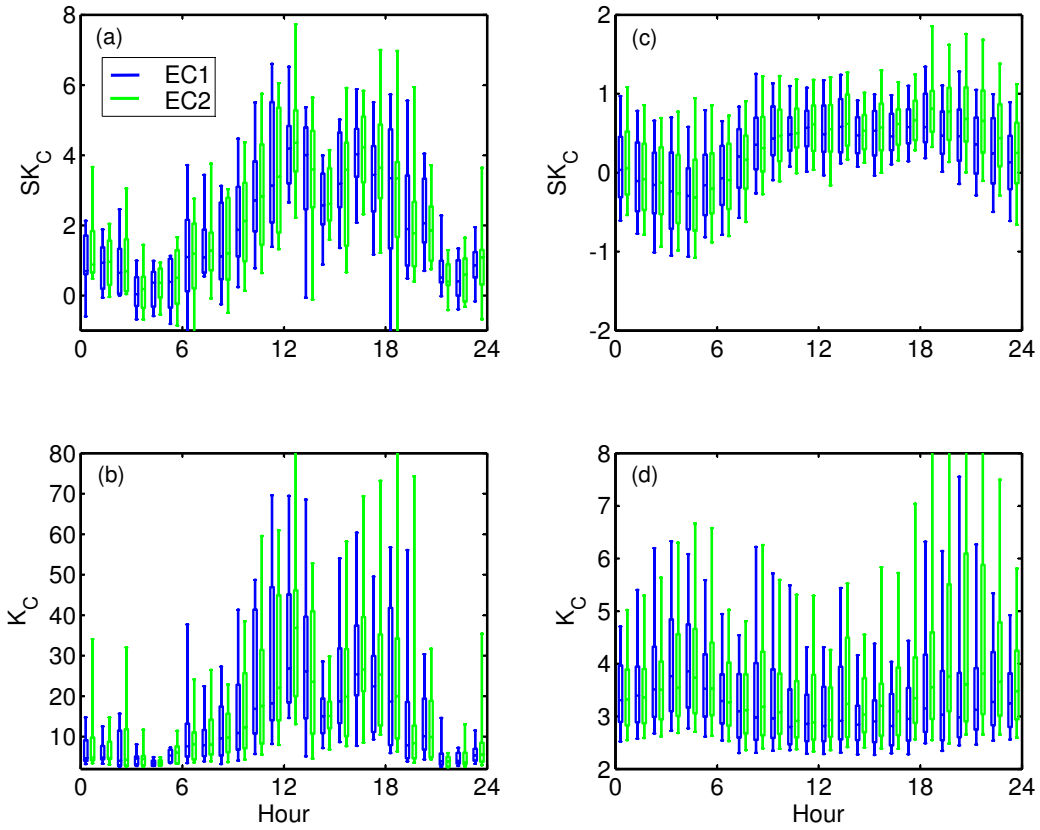

Figure 8. Diurnal variability of skewness (SK) and kurtosis (K) of CO_2 for the 150–200° sector (a-b) and for the other directions (c-d) in summer (June to August). Notice the different y-axes on each plot. Whiskers and boxes represent the 10th, 25th, 50th, 75th and 90th percentiles.

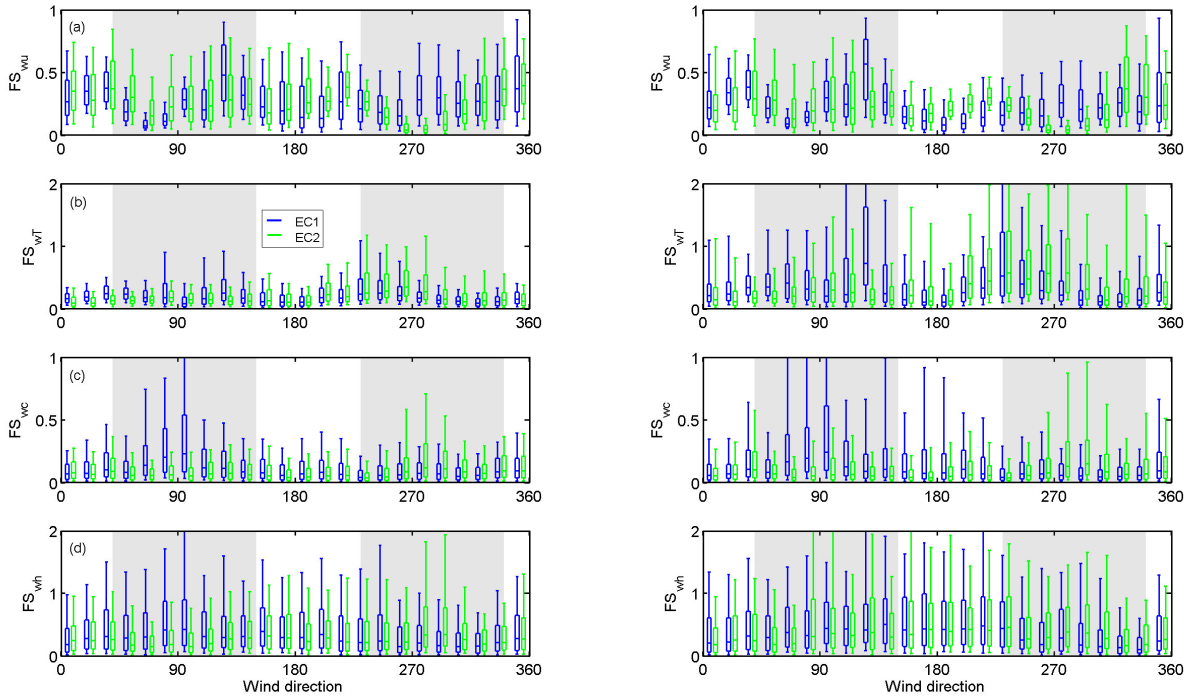

Figure 9. Stationarity (FS) of (a,e) vertical wind speed (w), (b,f) air temperature (T), (c,g) CO_2 (c) and (d,h) water vapour (h) as a function of wind direction for hours 6:00–21:00 (a-d) and 21:00–6:00 (e-h) for EC1 (blue) and EC2 (green) during July 2013 until September 2015. Whiskers and boxes represent the 10th, 25th, 50th, 75th and 90th percentiles.

3.3 Atmospheric spectra

More information about the similarity/dissimilarity of the two EC systems can be obtained via spectral analysis (Figure 10). The largest differences outside the flow distortion areas can be seen in the co-spectrum of momentum flux with similar contribution only at $n = 0.02 - 0.1$ between the two systems (Figure 10a). With EC1, more contribution is seen at larger eddies and at the inertial subrange (n = 0.1-0.4) the decay is faster than with EC2. A possible explanation for the higher-energy larger eddies is the building wake-effect. With both systems, negative contributions to the total momentum flux are seen at normalised frequencies > 0.5 which are likely to be related to the measurement location being on top of a tower. This is supporting the previous findings that velocity components are more impacted by the measurement location than the scalars. Similarly to τ, in the co-spectra of F_C the larger eddies (below normalised frequency 0.03) have slightly more contribution to the total flux measured by EC1 than EC2 and the energy decaying at the inertial subrange ($n > 2$) is faster than in the case of EC2 (Figure

10c). Thus, the flux differences seen in τ and F_C between the two systems are to a large extent caused by the larger eddies rather than small-scale variations. For the temperature flux co-variance (Figure 10e), such differences are not seen but rather the contribution of different-sized eddies is very similar between the two systems. Atmospheric spectra of all quantities measured by both systems are similar (Figure 10b,d,f). This indicates different transport mechanisms for temperature and CO_2 which has also been found when comparing the transfer efficiencies of the different scalars in this study and in Nordbo et al. (2013) at the same site.

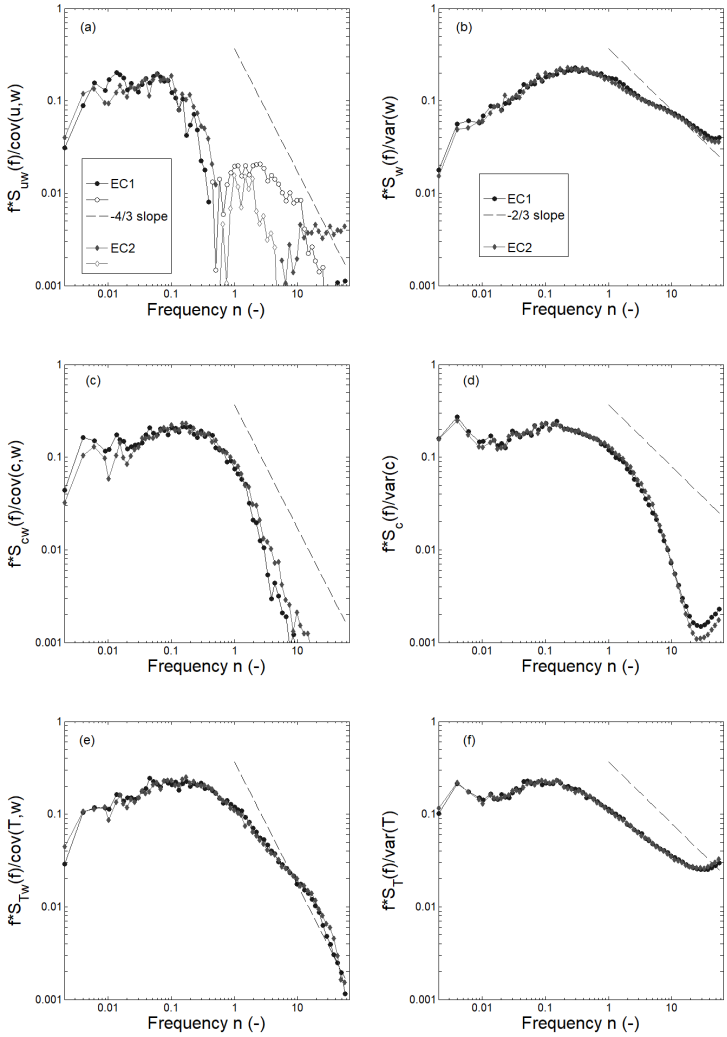

Figure 10. Co-spectra (a,c,e) and spectra (b,d,e) of wind (u and w-component, respectively), CO_2 concentration and air temperature (T) as measured with the two EC systems for the undisturbed wind directions for July 2014 ($2.5 < U < 4$ m s^{-1}, solar radiation > 10 W m $^{-2}$). Solid symbols indicate positive and open symbols negative contributions of the particular normalized frequency ~~$(n = f(z - d)/U)$ is the normalized frequency~~ n $(n = f(z-d)/U)$. The -4/3 and -2/3 slopes are those predicted by Kolmogorov.

3.4 Cumulative surface exchanges

One of the key questions of this study is on how representative a single EC measurement point, in measuring vertical fluxes, can be when the measurements are forced to be conducted close to urban structures causing potentially a large removal of data due to flow distortion areas. After flow distortion and stationarity filtering, the temporal annual coverages at the continuous measurement site EC1 vary from 24–50%, with H and F_C having mean data coverages of 44 % and 45 % when compared to LE 31% (Table 2). The inclusion of the second EC system increases the data coverage substantially with H having mean coverage 65 %, LE 45% and F_C 69 %. The next step is to examine the impact of the different data coverages on the cumulative flux values.

The annual cumulative flux values of CO_2, sensible and latent heat calculated for two annual periods (July 2013–June 2014 and July 2014–June 2015) using different gap-filling methods are shown in Figure 11. EC1 and EC2 are gap-filled with their own median cycles using a three-month period around the month being gap-filled with a separation into workdays and weekends. EC1 + EC2 is a combination of EC1 and EC2 systems with data from the first taken in directions ~~250–330~~230–340° and the latter in directions ~~50–130~~40–130° and in other directions the mean of the two systems is calculated. Missing data were furthermore gap-filled in similar fashion as EC1 and EC2. In the case of F_C, EC1+EC2 gives 3–12 % larger cumulative flux values than using only EC1 or EC2 with an annual mean value of 0.375 kmol m^{-2} corresponding to 4500 g C m^{-2}(Table 2). This indicates that the resulting error in cumulative carbon fluxes due to the single EC measurement point is up to 12 % when other error sources are ignored. For H and LE, the differences between the combination data set and EC1 and EC2 are up to 5.3 % and 8.1 %, respectively, with larger cumulative values obtained with EC1 + EC2 than the separate instruments. The difference in F_C is of the same order of magnitude as what has been observed above a forest site within a separation of 30 m between two EC systems (Rannik et al., 2006). If in addition to the flux stationarity, we would have used the common limits of K<1 and K>8 and |SK|>2 to filter out data, the data coverages of the single EC systems would decrease by 11 % for F_C and 3 and 1 % for H and LE (Table 2). This would give a mean cumulative F_C of 0.3445 kmol m^{-2} (4134 g C m^{-2}), which is 3.5 % lower than what obtained by using combination EC1 + EC2 (0.357 kmol m^{-2} = 4284 g C m^{-2})). Thus, using all FS, SK and K to filter our flux data will cause 4.5 % lower cumulative F_C than that of using only FS.

The outcome of our study is that a single EC measurement point can produce reasonable estimations for surface fluxes above relatively homogeneous urban surface, but the next question naturally is that how applicable this result is for other urban EC sites. Each urban measurement location is unique and in order to get a final answer, each site should be separately evaluated with more than one measurement setup. Nevertheless, the obtained uncertainties from this study can be used as a first approximation for urban EC measurements in a same way as the few two or multiple tower studies made in vegetated ecosystems are used to give general guidelines for the uncertainties.

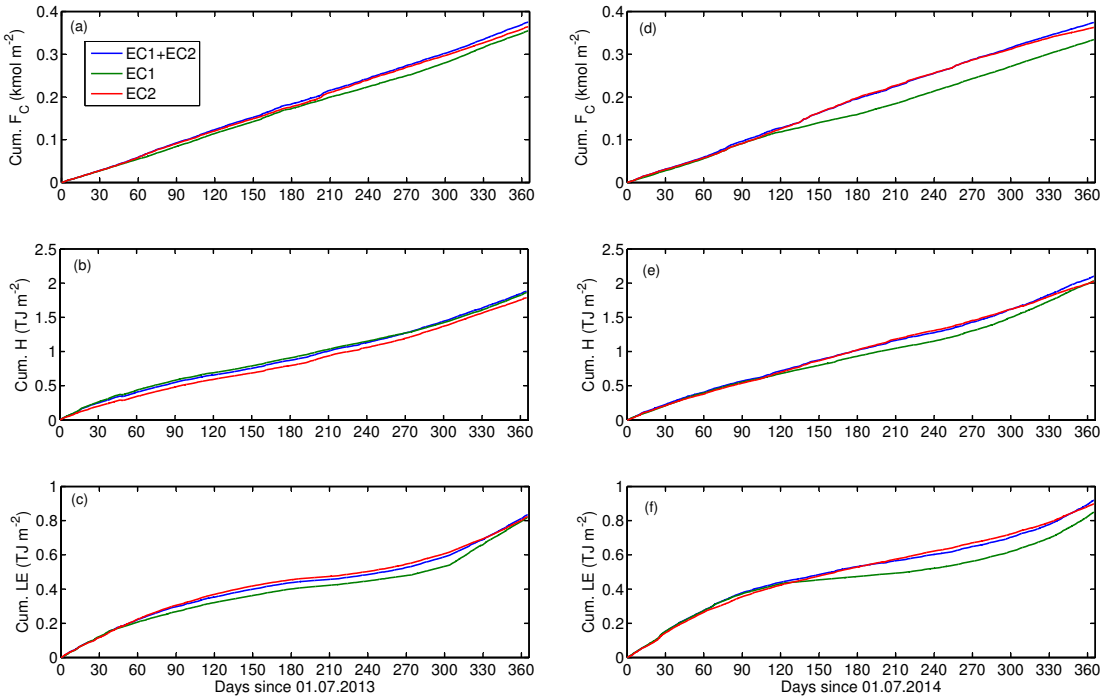

Figure 11. Annual cumulative fluxes of (a,b) CO_2 (F_C), (b,e) sensible (H) and (c,f) latent heat (LE) for different datasets for July 2013–June 2014 (a-c) and July 2014–June 2015 (d-f). 1st of July. EC1 + EC1 consists of EC1 measurements for sector 230–340°, EC2 measurements for sector 40–150° and the average of the two systems outside the flow distortion sectors (40–150° for EC1 and 230–340° for EC2). The gap-filling of each time series is done based on the diurnal variations over three months period around the month, working days being gapped separately from weekends and holidays.

Table 2. Gap-filled cumulative (cum) vertical flux values and percentage of data (%) being gap-filled for two separate years. Fluxes are either filtered using only stationarity (SF < 0.3) or stationarity, kurtosis (K<1 and K>8) and skewness (|SK|>0.2). F_C = CO_2 flux, H = sensible heat flux and LE = latent heat flux. See Figure 11 caption for details for EC1 + EC2, EC1 and EC2.

Period	Flux	Filtering	EC1 + EC2		EC1		EC2	
			cum	(%)	cum	(%)	cum	(%)
	F_C (kmol m^{-2})		0.375	33.0	0.355	60.1	0.364	50.2
$7/2013-6/2014$	H (TJ m^{-2})	SF	1.880	37.4	1.861	55.6	1.786	59.2
	LE (TJ m^{-2})		0.835	56.1	0.819	72.9	0.824	73.6
	F_C (kmol m^{-2})		0.374	29.8	0.334	59.1	0.363	51.4
$7/2014-6/2015$	H (TJ m^{-2})	SF	2.100	32.5	2.033	54.1	2.024	54.3
	LE (TJ m^{-2})		0.919	54.3	0.850	75.6	0.898	69.9
	F_C (kmol m^{-2})		0.357	47.1	0.343	68.8	0.346	62.8
$7/2013-6/2014$	H (TJ m^{-2})	SF, K, SK	1.918	41.6	1.897	59.7	1.862	62.9
	LE (TJ m^{-2})		0.827	57.2	0.814	73.5	0.816	74.3
	F_C (kmol m^{-2})		0.367	44.5	0.320	68.1	0.365	64.8
$7/2014-6/2015$	H (TJ m^{-2})	SF, K, SK	2.127	35.2	2.058	56.7	2.082	56.3
	LE (TJ m^{-2})		0.913	54.9	0.839	76.0	0.896	70.3

4 Conclusions

In this study, simultaneous measurements from two EC systems were compared over highly built-up Helsinki city centre. The identical systems were located symmetrically either side of atop a tower structure with building masonry located in between. Data were identically analysed. This allowed us to examine the sensitivity of a single-point EC system in measuring the vertical fluxes of momentum, sensible and latent heat, and carbon dioxide, and to understand what are the implications of the non-ideal measurement location and resulting data removal of the studied fluxes.

The flow distortion areas (40–150° and 230–340°) of the two EC systems caused by the building masonry are most clearly distinguishable from wind-normalised TKE. These areas together with a stationarity limit of 30 % resulted in data coverage ranging in 24–50 % with a single system. Outside the flow distortion areas, momentum flux is the most sensitive of all fluxes for the measurement location and flow modifications caused by the masonry with random uncertainties being around 25 %. With scalar fluxes these remained between 18 and 22 %. Most of the differences in momentum fluxes are due to larger-scale eddies as revealed by spectral analysis indicating larger-scale structures being responsible for the observed differences between these two fluxes.

The two systems had a separation distance of 10 m indicating both systems measuring virtually the same source area and therefore the differences are considered to be caused by variations in flux fields due to the complex surroundings and measure-

ment platform. Despite the measurement location of the EC systems being non-ideal from the point-of-view of flow distortion, the possible bias caused by a single measurement point is less than 12 % for CO_2 flux and less than 5 and 8 % for sensible and latent heat fluxes, respectively. In general, the results show how a single point EC measurement can be representative for flux estimates in Helsinki city centre despite the relatively large flow distortion area removing 27 % of the data. This result is naturally location-specific ~~, but the~~ for this highly built-up site with vegetation fraction only 22% and relatively homogeneous roof level (Nordbo et al., 2013). The same result could be considered to apply also in other dense city ~~centres with relative homogeneous road network and other activities around the measurement tower~~centers with similar relatively homogeneous surface characteristics.

We furthermore show that kurtosis and skewness of concentration measurements, common variables used to flag EC data over vegetated surroundings, are not reasonable measures to filter CO_2 flux data in dense urban environment due to the combined effect of temporally varying traffic network, meteorological conditions and characteristics of the upwind source area causing natural spikiness to the CO_2 data. Flux stationarity is not impacted in a similar fashion and is therefore considered to be more suitable for filtering CO_2 flux data in urban areas. The usage of all three variables to filter out CO_2 flux data will cause an underestimation of 4.5 % to annual cumulative carbon fluxes.

Our results are the first from urban areas to characterise the representativeness of single-point EC flux measurements in a densely built urban environment using a combination of two EC systems located close to each other. The related uncertainties are of the same order of magnitude as observed above vegetated ecosystems. The obtained values can be used as a rule-of-thumb when evaluating in general the representativeness of urban EC measurements used to estimate direct vehicular and building emissions of greenhouse gases and air pollutants. We point out how particular attention should be paid ~~on~~ to the data quality control procedures commonly used above vegetated surfaces.

Data availability. Data sets used in the data analysis will be saved to and can be freely downloaded from https://b2share.eudat.eu/

Appendix A

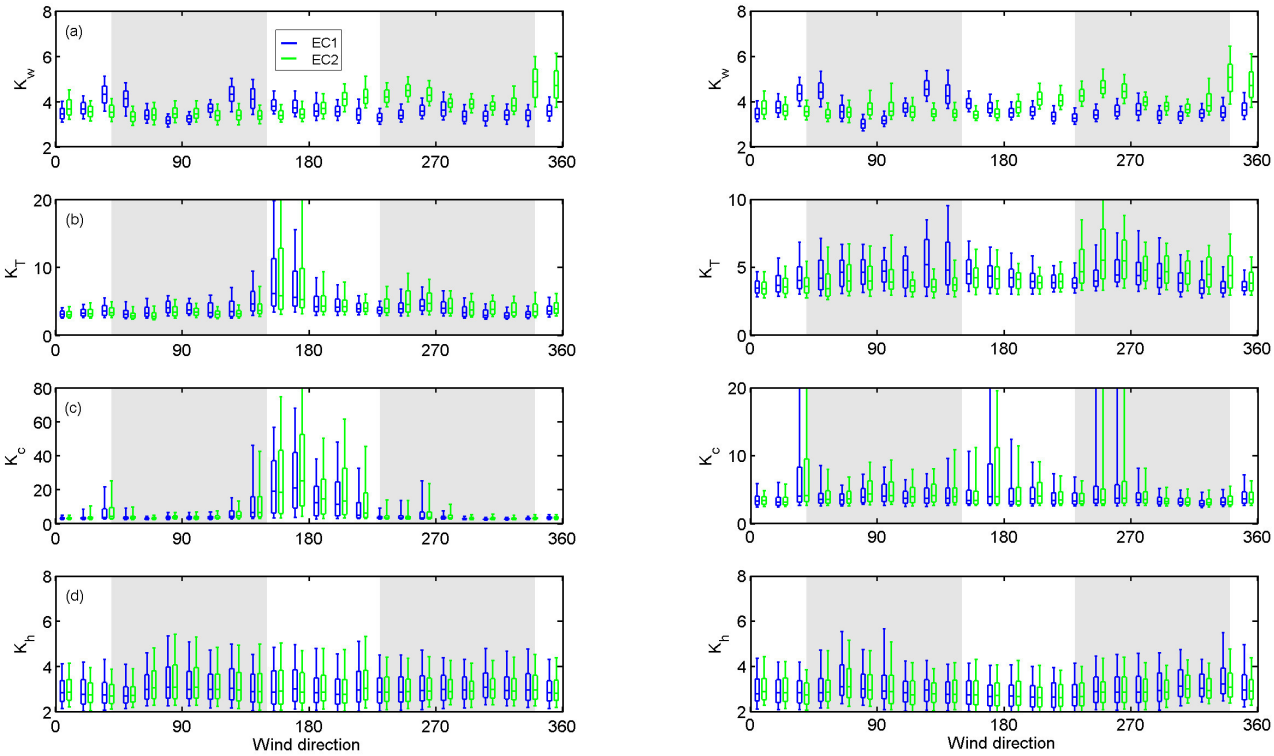

Figure A1. Kurtosis (K) of (a,e) vertical wind speed (w), (b,f) air temperature (T), (c,g) CO_2 (c) and (d,h) water vapour (w) as a function of wind direction for hours 6:00–21:00 (a-d) and 21:00–6:00 (e-h) for EC1 (blue) and EC2 (green) during July 2013 until September 2015. Whiskers and boxes represent the 10th, 25th, 50th, 75th and 90th percentiles.

Appendix B

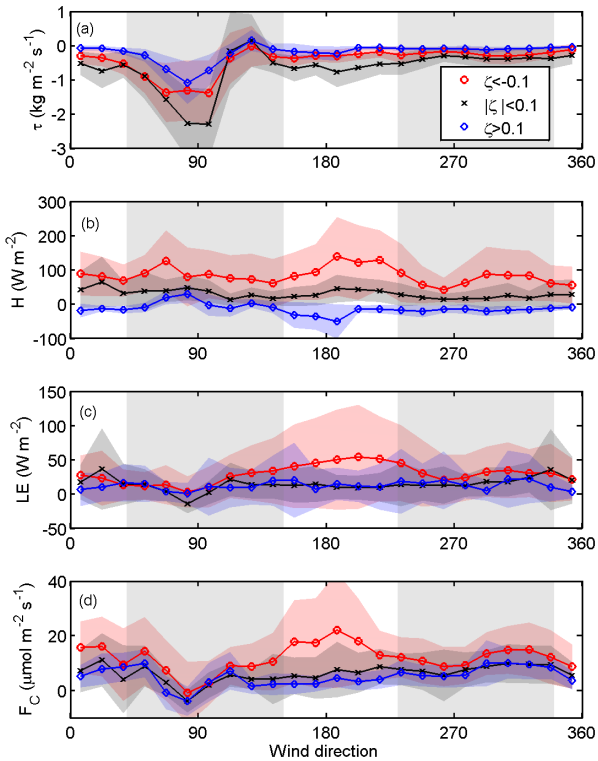

Figure B1. Wind-direction dependence of (a) momentum (τ), (b) sensible (H) and (c) latent heat (LE), and (d) CO_2 (F_C) fluxes for EC1. The statistics are calculated for the whole measurement period and data are separated into different stability classes (unstable ($\zeta < -0.1$), stable ($\zeta > 0.1$) and neutral ($|\zeta| < 0.1$). Lines and symbols represent the 15° bin averages and the shaded areas ± 1 std. The neglected wind directions (40–150° for EC1 and 230–340° for EC2) are marked with grey areas.

Author contributions. L.J., A.K., R.D.K., T.V. and C.R.W planned the measurements; T.V.K. and P.R. were responsible for the eddy covariance measurements; M.K. calculated the eddy covariance data; L.J. and Ü.R performed further data analysis. All authors participated to writing the manuscript.

Competing interests. The authors declare no competing financial interests.

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