On the Temperature Structure Parameter and Sensible Heat Flux over Helsinki from Sonic Anemometry and Scintillometry

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ABSTRACT

Two commercial large-aperture scintillometers, Scintec BLS900, were tested on pathlengths of 1840 and 4200 m at about 45–65 m above ground in Helsinki, Finland. From July 2011 through June 2012, large variability in diurnal and annual cycles of both the temperature structure parameter $C_{2T}^2$ and sensible heat flux $H$ were observed. Scintillometer data were compared with data from two eddy-covariance stations. A robust method was developed for the calculation of $C_{2T}^2$ from raw sonic-anemometer data. In contrast to many earlier studies that solely present the values of $H$, the main focus here is on comparisons of $C_{2T}^2$ itself. This has advantages, because optical-wavelength scintillometers measure $C_{2T}^2$ with few assumptions, while the determination of $H$ implies the applicability of the Monin–Obukhov similarity theory, which has several inherent limitations. The histograms of $C_{2T}^2$ compare well between sonic and scintillometer. In-depth analysis is focused on one of the scintillometer paths: both $C_{2T}^2$ and $H$ comparisons gave similar and surprisingly high correlation coefficients (0.85 for $C_{2T}^2$ and 0.84–0.95 for $H$ in unstable conditions), given the differences between the two measurement techniques, substantial sensor separation, and different source areas.

1. Introduction

The scintillometry method is based on atmospheric refraction. For optical waves, the refraction is dominated by atmospheric temperature fluctuations, so one can confidently obtain the structure parameter of temperature $C_{2T}^2$. The understanding of $C_{2T}^2$ itself is important for astronomical seeing and ground-to-satellite communications (Travouillon et al. 2003; Tunick 2005), as well as understanding turbulence itself (Coulter and Doran 2002). But the emphasis in scintillometer studies is to estimate sensible heat flux $H$. Scintillometry is desirable because it gives a path average (most typically over some hundreds of meters) that is comparable to the scales typically used in meteorological modeling. Because of the spatial averaging, it is possible to obtain estimates of turbulence quantities over shorter time periods than is possible with the eddy-covariance (EC) method (Aubinet et al. 2012). Yet, the most common way to examine the reliability of scintillometer data is to compare them with local single-point data from sonic anemometers (Andreas 2012; Beyrich et al. 2012; Evans et al. 2012).

The derivation of $H$ from $C_{2T}^2$ requires many additional assumptions of the nature of turbulence (Moene 2003). These assumptions include the validity of Monin–Obukhov (MO) similarity theory (MOST), which is valid for a horizontally uniform surface layer, and of questionable validity above it. The application limits of MOST for scintillometry flux measurements above the surface layer have not been thoroughly addressed to date (Beyrich et al. 2012). Moreover, despite the fact that scintillometry gives quite promising results for large heat fluxes in the convective atmospheric boundary layer (Moene et al. 2009), its performance for small sensible heat fluxes (especially under stable stratification even in the surface layer) is not very good (Andreas 2012). The stable cases are of special

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interest for air quality applications, because small changes in stratification can result in substantial changes in turbulent mixing. Because $C^2_f$ is a function of turbulent dissipation rates (Monin and Yaglom 2007, chapter 8, item 21), it provides information on turbulence and thus the direct use of $C^2_f$ is desirable in applications such as numerical modeling. To approach this problem, the understanding of the behavior of $C^2_f$ over various terrains is needed.

While scintillometry has been widely applied over grassland and cropland, and some of those studies have been over heterogeneous terrain (e.g., Schüttemeyer et al. 2006; Ezzahar et al. 2007; Ward et al. 2011), only few scintillometry studies have been performed over cities (Kanda et al. 2002; Lagouarde et al. 2006; Roth et al. 2006; Masson et al. 2008; Pauscher 2010; Salmond et al. 2012; Zielinski et al. 2012; Wood et al. 2013b). Cities cause difficulties in the interpretation of scintillometer data, given the possible heterogeneous surface below the path—in particular, the difficulty in determining effective height (including knowledge of the zero-plane displacement height). Furthermore, all studies over cities have been conducted in midlatitude cities. Therefore, our aim is to understand $C^2_f$ and scintillometer results over less-well-studied urban terrain at high latitudes, given the interest in stable flow over cities (Kukkonen et al. 2005).

In the future, if a model–measurement intercomparison is to be done, then one desires a purely measured quantity to compare with a purely modeled one. For the case of scintillometer-derived fluxes, one compares a flux derived with MOST using experimental values of a stability parameter with a flux derived with MOST using a modeled stability parameter. It would be desirable to compare measured $C^2_f$ (e.g., from sonic anemometers, scintillometers, or acoustic remote sensing) with $C^2_f$ somehow derived from a model. For such a comparison, one has to be sure that $C^2_f$ is a reproducible parameter, at least in measurements—that is, that measured $C^2_f$ is representative for some area around the measurements. Thus, the research question is, “How reproducible is $C^2_f$ at various scales in the urban environment?”

In this paper, we report (i) the first results from many months’ data from two scintillometers and compare them with data from two sonic anemometers over Helsinki, Finland, and (ii) the evaluation of an algorithm for obtaining $C^2_f$ from sonic anemometers.

2. Materials and methods

a. Instrumentation and site description

Two large-aperture scintillometers (BLS900, Scintec AG, Germany) and two sonic anemometers (USA-1, Metek GmbH, Germany) have been part of a suite of equipment installed across the city of Helsinki, Finland, on the coast of the Gulf of Finland (Fig. 1; Table 1). They are a part of the Helsinki Urban Boundary-Layer Atmosphere Network (URBAN; http://urban.fmi.fi; Wood et al. 2013a), with increasing activity in observing the urban boundary layer in particular since 2004. The site is characterized by the vicinity of the sea and the strong seasonality in climate, caused by the high latitude ($>60^\circ$N) and semicontinental climate. Downtown Helsinki is located in a peninsula protruding southward (Fig. 1a), including the sites of Torni, Sitra, and Elisa. Most of the land area on the map is 5–15 m above mean sea level (MSL), with some hills up to about 30 m.

It is desirable to have near-horizontal scintillometer paths, given that $C^2_f$ depends on height—for example, $C^2_f \propto z^{-4/3}$ for the free-convection (FC) limit (described later). The first scintillometer with a pathlength of 4.2 km (city-scale scintillometer) has been in operation since 5 July 2011. Its transmitter is located on Hotel Torni in downtown Helsinki, and a sonic is operating just above the transmitter (Nordbo et al. 2013). The receiver of the city-scale scintillometer is in Kumpula on the Finnish Meteorological Institute (FMI) roof. Nearby is the semirurban third Station for Measuring Ecosystem–Atmosphere Relations (SMEAR III)–Kumpula mast with a sonic at the top (Järvi et al. 2009). The mean height MSL of the ground under the scintillometer path is 12.0 m ($\pm$8.2 m standard deviation), and the mean building height AGL is 16.0 m (Fig. 1b). The second scintillometer, with a 1.8-km path (downtown scintillometer), has been in operation since 1 March 2012. Its transmitter is on the Elisa lattice mast; its receiver is on the Sitra building. This path is over the densely packed downtown (Fig. 1d), where the mean building height AGL is 18.2 m and the ground height MSL is 9.0 m ($\pm$3.8 m). The beam and land slopes are such that westerly winds will result in higher effective heights than easterly winds by about 10 m.

The 10-Hz sonic-anemometer time series, of the three components of wind and sonic temperature (i.e., virtual temperature), were used to calculate turbulent fluxes: friction velocity $u_*$ and $H$, in addition to the Obukhov length $L$. All flux data were corrected for a range of standard effects, including moisture (Nordbo et al. 2012). Sonic data were subset into two groups: one with basic quality assurance (only de-spiked) and one with stringent quality assurance according to flux nonstationarity (Foken and Wichura 1996) and possible flow distortion from the mounting mast/building (at Torni for wind directions of $50^\circ$–$185^\circ$ and for $0^\circ$–$50^\circ$ at SMEAR III–Kumpula).

b. Obtaining structure parameter from scintillometers

The mean square difference of a conservative scalar $X$ between two points, $r_1$ and $r_2$, is proportional to the two-thirds power of the distance between the points (Monin and Yaglom 2007, chapter 8, item 21).
and Yaglom 2007, chapter 8, item 21.6), within locally homogeneous isotropic turbulence:

$$\left( X_1 - X_2 \right)^2 = C_X^2 (r_1 - r_2)^{2/3}. \tag{1}$$

The proportionality coefficient $C_X^2$ is called a structure parameter of the scalar $X$.

The small fluctuations of the signal intensity in large-aperture scintillometers provide a means to measure the

<table>
<thead>
<tr>
<th>Site</th>
<th>Instrument</th>
<th>Coordinates</th>
<th>Ground height MSL (m)</th>
<th>Instrument height MSL (m)</th>
<th>Effective height AGL (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elisa, downtown</td>
<td>Scintillator</td>
<td>60.164 000°N, 24.946 667°E</td>
<td>12.0</td>
<td>68.0</td>
<td>48.3</td>
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<tr>
<td>Sitra, downtown</td>
<td>Scintillator</td>
<td>60.164 158°N, 24.914 011°E</td>
<td>4.0</td>
<td>72.0</td>
<td>48.3</td>
</tr>
<tr>
<td>Torni, downtown</td>
<td>Sonic anemometer</td>
<td>60.167 803°N, 24.938 600°E</td>
<td>15.0</td>
<td>75.2</td>
<td>45.0</td>
</tr>
<tr>
<td>Torni, downtown</td>
<td>Scintillator</td>
<td>60.167 803°N, 24.938 600°E</td>
<td>15.0</td>
<td>67.4</td>
<td>33.6</td>
</tr>
<tr>
<td>FMI, Kumpula</td>
<td>Scintillator</td>
<td>60.203 644°N, 24.960 525°E</td>
<td>29.0</td>
<td>52.9</td>
<td>33.6</td>
</tr>
<tr>
<td>SMEAR III, Kumpula</td>
<td>Sonic anemometer</td>
<td>60.202 817°N, 24.961 128°E</td>
<td>29.0</td>
<td>60.0</td>
<td>35.0</td>
</tr>
</tbody>
</table>
structure parameter of the optical refractive index (Tatarskii 1971; Clifford et al. 1974):

\[ C_n^2 = 1.21 \sigma^2_{\ln} D_1^{7/3} R^{-3}, \]

where \( \sigma_{\ln}^2 \) is the variance of the logarithm of received intensity, \( D \) is aperture size, and \( R \) is scintillometer pathlength.

From 500-Hz light intensity measurements, 1-min averages of the structure parameter of the refractive index of air \( C_n^2 \) are calculated by the BLS900 SRun software (version 1.09). To ensure high data quality, any problematic 1-min data were discarded in our subsequent analyses: error codes are mainly due to (i) insufficient signal caused by rain or fog (0.3% and 0.5% in data from city-scale and downtown scintillometers, respectively) and (ii) power failures and instrument maintenance (24% and 7.3%, respectively).

The estimation of \( C_T^2 \) from \( C_n^2 \) relies on the refractive index being mainly dependent upon temperature, but also humidity and pressure. For dry air, the relationship between \( C_n^2 \) and \( C_T^2 \) is (Tatarskii 1971)

\[ C_T^2 = \alpha_1^{-2}(T^4/p^2)C_n^2, \]

where \( T \) is air temperature, \( p \) is atmospheric pressure, and \( \alpha_1 \) is a wavelength-dependent proportionality factor. For the BLS900, \( \alpha_1 = 7.8355 \times 10^{-5} \text{KPa}^{-1} \) (Scinetec 2011). Atmospheric pressure measurements from SMEAR III–Kumpula (HMP243, Vaisala Oyj, Vantaa, Finland) were used for both scintillometers. Air temperature measurements were from the Elisa mast (HMP45D, Vaisala Oyj) for the downtown scintillometer, and an average temperature of Elisa and SMEAR III–Kumpula (homemade platinum resistance thermometer Pt-100) masts for the city-scale scintillometer.

The relative error caused by humidity in \( C_T^2 \) calculated with Eq. (3) would not exceed 10% for 95% of the current dataset. Nevertheless, in this study the effect of humidity was accounted for by using Wesely (1976):

\[ C_T^2 = \alpha_1^{-2}(T^4/p^2)C_n^2(1 - 0.03/Bo)^{-2}, \]

where \( Bo \) is the Bowen ratio. The Bowen ratio is calculated as the ratio of sensible to latent heat flux; the latter was derived from flux measurements at the SMEAR III–Kumpula and downtown (Torni) sites.

c. Obtaining structure parameter from sonic anemometers

We estimate the structure parameter of temperature from time series of virtual temperature (i.e., uncorrected 10-Hz temperature data directly from the sonic anemometer) by fitting the parameters of model high-frequency spectra proposed by Kouznetsov and Kallistratova (2010). Because that reference is not permanent, we provide further details here.

Within an inertial subrange, the power spectral density of turbulent fluctuations for a scalar follows the “\(-7/3\) law” (Monin and Yaglom 2007). Thus, by applying Taylor’s hypothesis to fluctuations of virtual temperature (\( T_v \)), one can write a power spectral density in the temporal domain as

\[ P_{T_v}(f) = \frac{U}{16\pi} C_{T_v}^2 f^{-5/3}, \]

where \( U \) is a mean wind speed (\( \text{m s}^{-1} \)) and \( f \) is frequency (Hz). High frequencies in observed spectra are usually affected by noise and flattening at high frequencies because of aliasing of frequencies, that is, the Nyquist effect. To estimate spectra from time series, the Welch periodogram method (Marple 1987) is used. A periodogram is a spectral estimate calculated by averaging the intensities of windowed Fourier spectra for many short segments of the original signal. This averaging, besides the mean values of the spectral density at each frequency, allows one to estimate their statistical uncertainties. Having the spectrum with error bars, one can fit a model spectrum to it and estimate the accuracy of resulting parameters (Press et al. 2007). For the estimate of a structure parameter, the following model spectrum is used:

\[ P_{T_v}(f) = \alpha(f^{-5/3} + (f - f_s)^{-5/3}) + \beta, \]

where \( f_s \) is data sampling frequency (Hz), and \( \alpha \) and \( \beta \) are fitting coefficients; \( \beta \) gives a spectral intensity of white noise caused by random uncertainties in the instantaneous values, and the term \((f - f_s)^{-5/3}\) accounts for the energy folded back from above the Nyquist frequency because of the aliasing effect (Fig. 2). The structure parameter can be estimated from \( \alpha \) using

\[ C_{T_v}^2 = \alpha(U/16\pi)^{-2/3}. \]

The uncertainty of the resulting value can be estimated from the fitting error of \( \alpha \), and the goodness-of-the-fit of the model spectrum can be estimated with the Pearson chi-square test (Press et al. 2007). These values also allow for the quality control of the resulting structure parameters.

For practical calculations of the spectra, we used a one-size-fits-all approach: a fixed segment length of about 10 s (128 data points at 10 Hz), which was generally well within the inertial subrange of turbulence for the heights of several tens of meters. The calculations with the data used for this study have shown small dependence (<20%–30%) of the resulting structure parameters on the segment length within a range from 32 to 1024 points. Too-small segments lead to the decrease of the structure parameter...
accuracy at low values, when the spectrum is strongly affected by measurement uncertainties. This effect was most pronounced for low values of the temperature structure parameters. If segments are too long, then the signal from beyond the inertial subrange appears in the estimated spectrum. This results in a degradation of fitting performance of the model spectrum [Eq. (6)] and a corresponding increase in chi square. The choice of a segment length could be performed with some approximation of turbulent spectra (Kaimal et al. 1972); however, a simpler way is to choose a fixed segment length and then discard the resulting structure parameters that do not meet the quality criteria for the accuracy and goodness of fit.

Unlike the earlier methods (Greenhut and Mastrantonio 1989; Beyrich et al. 2005), the model spectrum [Eq. (6)] does not require any procedure to select the high-frequency limit of the inertial subrange in measured spectra, but it can use the spectra up to the Nyquist frequency. Attenuation of spectra, due to insufficient sensor response at high frequencies, was not observed; however, it can be incorporated into the model spectrum. Were this attenuation to become substantial, it would be detected with the chi-square test.

In this study, the sonic-derived structure parameter data were rejected primarily based on the chi-square test. The main reason for the test failure is too-low wind speed that invalidates the Taylor hypothesis for temperature fluctuations. The rejected fractions are 7.6% and 14.2% of all 30-min-average values for the SMEAR III–Kumpula and downtown (Torni) sites, respectively.

In Eq. (8), $C_{2T}$ slightly differs from pure $C_{2T}$ because of the effect of humidity. Because $C_{2T}$ is proportional to the square of temperature fluctuations, the square of the corresponding factor (Schotanus et al. 1983) was applied to get $C_{2T}$ from $C_{2T}$:

\[
C_{2T}^2 = C_{2T}^2 (1 - 0.06/Bo)^{-2}.
\] (8)

d. Estimating sensible heat flux from structure parameter

Several methods have been proposed for deriving sensible heat flux from $C_{2T}$ (Hill 1992). Based on MOST, the dimensionless $C_{2T}$ can be expressed as

\[
\frac{z'^{2/3}}{T_s} C_{2T}^2 = \phi_{CT} \left( \frac{z'}{L} \right),
\] (9)

where $L = -u_s^2 T/\rho g g$, $g = 9.8 \text{ m s}^{-2}$ is acceleration due to gravity, $\kappa = 0.4$ is the von Kármán constant, $\phi_{CT}(z'/L)$ is a universal function of atmospheric stability, $z'$ is the effective height (introduced later), and the scaling parameter for temperature is

\[
T_s = H/(u_s \rho c_p),
\] (10)

where $\rho$ is air density (kg m$^{-3}$) and $c_p$ is the specific heat capacity of air at constant pressure (J K$^{-1}$ kg$^{-1}$). Different expressions for $\phi_{CT}(z'/L)$ have been developed (Thiermann and Grassl 1992; Moene et al. 2004), and the effect of the choice on the final flux value is the order of 10%–15% (Meijninger et al. 2005). For the present analysis, we use the form (de Bruin et al. 1993)

\[
\phi_{CT} = 4.9 \left( 1 - 9 \frac{z'}{L} \right)^{-2/3} \quad \text{for } z'/L < 0.
\] (11)

Combining Eqs. (9)–(11), an expression for sensible heat flux can be derived, and such estimates are given the MO label. Values of $u_s$ and $L$ are used from nearby sonic data and thus iteration is not needed in the
calculation of $H$, for example, as is used in situations where EC data are not available (e.g., Hartogensis et al. 2003).

Under strongly unstable conditions (i.e., $z'/L \ll -0.1$), Eqs. (9) and (11) can be reduced to the asymptotic form (de Bruin et al. 1993, 1995); combining this asymptotic form with Eq. (10), $H$ can be estimated without any supplementary turbulence measurements. This is known as the FC limit:

$$H_{FC} = 0.58pc_z^g/(g/T)^{1/2}(C_7^2)^{3/4}. \quad (12)$$

$$z' = -1 + \sqrt{1 - 4c_2/L} \left[\int_0^1 \left[\frac{1}{4} \left\{\frac{1}{4} \frac{z(u) - z_d(u)}{L} \right\}^{2/3} G(u) du \right]^{3/4} \frac{-2/3}{-2/3} \right]. \quad (13)$$

where $c_2 = 9$ is a coefficient from the universal function of atmospheric stability [Eq. (11)]. For the free-convection limit, $z'$ becomes independent of stability and reduces to the form (Hartogensis et al. 2003)

$$z' = \left\{\int_0^1 \left[\frac{1}{4} \left\{\frac{1}{4} \frac{z(u) - z_d(u)}{L} \right\}^{2/3} G(u) du \right]^{3/4} \right\}. \quad (14)$$

A formulation for stable stratification also exists (Kleissl et al. 2008), but it is not needed here because we will only calculate $H$ for unstable stratification. The scintillometer effective height takes into account the spatial averaging and the stability dependence. The effective height as defined in the eddy-covariance community is simply the difference between the sonic-anemometer height and the zero-plane displacement height in the flux footprint.

Estimates of sensible heat flux are subject to some uncertainty. For greater certainty a source-area-model technique (Kormann and Meixner 2001) could be performed to estimate the zero-plane displacement height from morphological techniques (Grimmond and Oke 1999) for different upwind sectors and stabilities (and thus different $z'$ values). Such an analysis was not conducted here, partly because of the questionable source area estimates above cities, but one can qualitatively estimate the impact of upwind terrain on the measurement sites. Consequently, estimates of sensible heat flux were limited to the downtown scintillometer, where there is more homogeneity in the terrain below that scintillometer beam compared to the city-scale beam (Fig. 1). Estimates for downtown Helsinki (Nordbo et al. 2013) gave an average zero-plane displacement height of $z_d = 14.9 \pm 3.0$ m (plus or minus one standard deviation) within the source area of the Torni EC station. The effective height AGL for the downtown scintillometer is 48.3 m, assuming a constant zero-plane displacement height. This estimate has an uncertainty, because of neighborhood variation in $z_d$, in $z'$ of ±6%. For example, this corresponds to a ±6% uncertainty in $H$ when applying the free-convection limit [Eq. (12)] and 3% for neutral conditions (Hartogensis et al. 2003). However, the errors would be larger for the city-scale scintillometer path with its more heterogeneous surface (affecting both beam height AGL and zero-plane displacement height).

For comparison, the random uncertainty of $H$ from eddy-covariance measurements in Helsinki has been estimated to be 13% (Nordbo et al. 2013), and the value is very close to the error estimates for a forest site based on a two-tower approach and a successive days approach (Hollinger and Richardson 2005).

3. Results

a. Structure parameter from the scintillometers

The variability of $C_7$ over Helsinki shows an annual cycle and distinct diurnal cycle from spring through fall (Fig. 3a). Most of the largest $C_7$ (from around $10^{-2}$ to $10^{-1}$ K^2 m^{-2/3}) occurred during daytime unstable conditions. But also, there were a few high values during November, January, and February nights, consistent with the large occurrence of negative sensible heat fluxes over Helsinki. Indeed, the sonic-derived sensible heat fluxes were negative for 45% of the time in those particular studied months, partly driven by the long nights and snow cover (Wood et al. 2013a). The lowest $C_7$ values occurred mostly in winter; this is consistent with small diurnal variations in sensible heat flux due to weak insolation, and synoptic conditions of near-continuous cloud cover resulting in a neutrally stratified atmosphere.
Comparing $C_T^2$ between scintillometers (Fig. 3b) showed an agreement within a factor of 2 for most of the data; some difference is not surprising given the higher beam downtown and different source areas of the two instruments. The downtown scintillometer generally showed lower values of $C_T^2$ (despite having a higher $z_0$), perhaps because of a higher occurrence of neutral cases downtown, when stable stratification occurs at larger scales. The saturation at high $C_T^2$ is clearly seen for the longer-path city-scale scintillometer and is an instrumental effect (see the appendix).

**b. Comparison of structure parameter from sonic and scintillometer**

The ratios $C_T^2$(sonic)/$C_T^2$(scint) downtown indicate that the sonic gives on average slightly higher values of $C_T^2$ than the scintillometer (Fig. 4a) for most wind sectors, although their median difference lies within about 50%, whereas the individual values show a substantial scatter up to a factor of 5–10. For flow-distortion directions, median $C_T^2$ from the sonic is nearly 3 times that from the scintillometer, indicating turbulent-wake effects from the position of the sonic atop Torni.

The ratio of $C_T^2$ obtained from the two devices differs also depending on the atmospheric stability. During unstable conditions, the sonic generally gives greater values than the scintillometer and vice versa during stable conditions (Fig. 4b). Though downtown Helsinki is quite homogeneous, the source areas of the sonic at Torni and the downtown scintillometer still differ, and the variation of stratification obviously affects them differently. Another source of discrepancy could be the layered structure of $C_T^2$ in the stably stratified atmosphere, which enhances the effect of height difference between the sensors (Table 1). It is not clear to us if there are any other reasons for such stratification dependency.

A comparison between sonic and scintillometer downtown (Figs. 5a, b) for many days of data shows a good agreement for $C_T^2$ ($r = 0.85$). This corroborates the usability of the spectral method to calculate $C_T^2$ from sonic data and gives confidence to scintillometer and sonic measurements in very complex urban environments with varying ground and canopy height, notwithstanding the uncertainty in effective heights caused by a lack of source-area estimates. Moreover, the statistical distribution of the observed values of $C_T^2$ coincides quite well for the downtown scintillometer and the sonic at Torni (Fig. A1).
Two case days demonstrate the time evolution of $C_T^2$ and $H$ (Fig. 6): (i) clear-sky summertime with high atmospheric pressure (>1020 hPa) and southerly flow and (ii) cloudy wintertime with low pressure (<994 hPa) and westerly flow. For the sunny day, there is broad agreement among $C_T^2$ from all methods. Sensible heat flux, estimated directly from the EC method and indirectly from $C_T^2$ for different instruments, shows remarkable agreement, especially given the difference between methods and the difference between point and path-average measurements. Interestingly, one can see higher $C_T^2$ at SMEAR III–Kumpula than downtown overnight—caused by stable stratification. For the winter day, there is much more variation among the $C_T^2$ datasets, especially in their temporal evolution: at the semiurban site (SMEAR III–Kumpula) $H$ is near zero, while downtown stratification is unstable.

c. Relationship with sensible heat flux

It is not possible to estimate $H$ from $C_T^2$ alone, as derived from sonics or scintillometers (Fig. 7). The relationship is clear: low $C_T^2$ occurs during neutral stratification, but $H$ cannot be unambiguously known given a greater $C_T^2$ alone. Nevertheless, the free-convection theoretical relationship between $H$ and $C_T^2$ in unstable conditions [Eq. (12)] is followed in the sonic measurements very well despite the complicated surface (Figs. 7b,d). This also applies for the scintillometers except for the saturation effect at high $H$, especially for the city-scale scintillometer (Figs. 7a,c). The quality of $C_T^2$ as a predictor of $H$ is assessed using EC-derived fluxes for unstable stratification when we expect the method to work the best. Four combinations of fluxes derived from $C_T^2$, sonic/scintillometer, and free-convection/MOST are examined (Figs. 5c–f). For the latter, the stability parameter from the Torni sonic was used. Generally, the scintillometer $C_T^2$ results give slightly less scatter against $H$ from the sonic than the $C_T^2$ from the sonic itself, and the MOST method gives better agreement than the free-convection method. The better performance of the scintillometer method is caused by a better statistical certainty of the corresponding $C_T^2$, given the path average compared with the sonic point measurement. While similarity relationships hold on average, individual values of $C_T^2$ and $H$ from sonic might be inconsistent, because sampling errors of these quantities.
are quite high in single-point measurements and not correlated with each other. In the sonic–scintillometer comparison, at least $C_T^2$ (from scintillometer) is quite well determined. Because scintillometer results give the best agreement, credence is given to the notion of homogeneous building layouts downtown, that is, even though the footprints do not always overlap, the scintillometer-derived $C_T^2$ still gives slightly better agreement on $H$ than sonic-derived $C_T^2$.

These sensible heat flux comparisons are only slightly worse than other scintillometer studies (Lagouarde et al. 2006; Roth et al. 2006; Zielinski et al. 2012)—that is, giving high correlation coefficients of 0.85–0.95, but also rms errors of 20–100 W m$^{-2}$. Note, however, that the absolute scatter in Figs. 5c–f is mostly caused by larger values of $C_T^2$ (and fluxes). The performance of $C_T^2$ methods for $H$ in near-neutral cases is poor in terms of relative error. Because of spatial averaging, one can expect the scintillometer-derived $C_T^2$ to have good statistics even for small temporal samples.

4. Summary

Measurements were performed in the city of Helsinki using two large-aperture scintillometers (Scintec BLS900) and two sonic anemometers (Metek USA-1). One scintillometer has been installed in relatively homogeneous terrain downtown with a 1.8-km path; the other one has a longer city-scale path and more heterogeneity underneath. Sonics were installed at the end points of the city-scale scintillometer path (ideal points near the center of scintillometer beams were not possible because of practical constraints in finding available measurement locations in cities). The values of $C_T^2$ obtained from scintillometer data have clear diurnal and annual cycles. The diurnal cycle is most pronounced in summer. Low values of $C_T^2$, corresponding to neutral stratification, occur downtown much more often than at the city scale, which is consistent with the heat fluxes above the urban surface (Nordbo et al. 2013). A consistency in $C_T^2$ data between the downtown and city-scale scintillometers was nevertheless observed, despite the difference in their effective heights.

A robust method to derive $C_T^2$ from fixed-point high-frequency temperature measurements was developed and tested here. The method provides reliable quality parameters for the resulting values. This robust method was for the first time used for quantitative long-term urban comparisons of scintillometer and eddy-covariance measurements, and good agreement was observed. The method was also used to identify the saturation problem.
that was observed in cases of strong scintillations (see the appendix).

The challenges in estimating sensible heat flux from $C_2^T$ (Moene 2003) were highlighted, given the nonunique solution. A commonly used method, which we employed, to estimate sensible heat flux from $C_2^T$ relies on both assumptions in MOST and nearby auxiliary data, and so an advantage is lost by contamination of the fuller utility of the path average by introducing a point measurement (although estimates of $u^*$ have been made from scintillometer data; e.g., Chehbouni 2000). Even when using MOST, considerable uncertainty results, including uncertainty in effective height, which will always be a challenge for urban areas. There is generally good agreement for sonic–scintillometer comparison, although there is horizontal and vertical separation between the sonic anemometer and the center of the scintillometer beam (giving rise to effective-height and source-area inconsistencies). Furthermore, the rms error found is large enough to result in large absolute uncertainty for near-neutral heat fluxes, a problem also seen in EC flux data given detection limits and uncertainties on the order of $10 \text{ W m}^{-2}$.

The climate conditions in Helsinki represent a challenge for scintillometry, given the urban surface and the high-latitude location giving rise to negative sensible heat fluxes even above an urban surface. The values of sensible heat flux are typically small, which poses a problem to MOST-based methods. Moreover, shallow boundary layers of a few tens of meters that often occur over Helsinki can invalidate the surface layer scaling, which is a prerequisite of MOST. In such cases, a surface layer might not exist.

A challenge now presents itself: how do we make best use of $C_2^T$ itself in applications such as numerical models of weather prediction and air quality?

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**APPENDIX**

Saturation of the Scintillometers

To quantify the effect of saturation (Kohsiek et al. 2006) for our scintillometers, the histograms of $C_2^T$ were plotted for each sonic and scintillometer (Fig. A1). One can see a largely comparable $C_2^T$ between the two sonic anemometers—with a slight bias toward larger values downtown. When using MOST, considerable uncertainty results, including uncertainty in effective height, which will always be a challenge for urban areas. There is generally good agreement for sonic–scintillometer comparison, although there is horizontal and vertical separation between the sonic anemometer and the center of the scintillometer beam (giving rise to effective-height and source-area inconsistencies). Furthermore, the rms error found is large enough to result in large absolute uncertainty for near-neutral heat fluxes, a problem also seen in EC flux data given detection limits and uncertainties on the order of $10 \text{ W m}^{-2}$.
Scintec SRun 1.09 software are used for the histograms. Such behavior is likely caused by the inability of the implemented correction (Clifford et al. 1974) to correct all the data affected by saturation. It is not clear if this is an implementation problem or a problem of the correction itself. Most values of $C_T^2$ in our scintillometer measurements are smaller than $10^{-2} \text{K}^2 \text{m}^{-2/3}$, and for them the downtown histograms coincide quite well. We thus consider those data reliable.

**REFERENCES**


HSY, 2008: SeutuCD. Helsinki Region Environmental Services Authority, CD-ROM.


