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MONITORING THE SENSIBLE HEAT FLUX OVER URBAN AREAS USING LARGE APERTURE SCINTILLOMETRY: CASE STUDY OF MARSEILLE CITY DURING THE ESCOMPTE EXPERIMENT

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Abstract. Sensible heat flux estimated by Large Aperture Scintillometry (LAS) has been tested against the more traditional eddy covariance technique over Marseille city centre, a reasonably homogeneous surface. Over the 3 week test period fluxes were found to be similar, yet less noisy for the LAS due to the spatial integration. No systematic bias between the estimates was found as a function of wind direction, indicating the homogeneity of the site. Sensitivity analysis of the required aerodynamic parameters shows that careful attention must be paid to the displacement height along the measurement path. Spatial variability of surface sensible heat flux is studied via a second LAS measurement path over the city.

Keywords: Large aperture scintillometry, Optical scintillations, Sensible heat flux, Urban climatology.

1. Introduction

The spatial variability of cities resulting from the presence of different 'neighbourhoods' (with differing size and height of buildings, street pattern, vegetation cover, anthropogenic activity) in juxtaposition often makes classical eddy covariance measurements difficult because of insufficient fetch over terrain with consistent characteristics. However, many practical applications, such as air quality studies, require the modelling of the urban boundary layer and the consequent availability of surface fluxes at a scale

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of a few kilometres. Scintillometer measurements are attractive in this context because they can provide integrated fluxes directly. Several experiments have been conducted in the last decade over crops and natural vegetation using different types of scintillometers (De Bruin, 2002), and a growing community is now involved in scintillometry. However, to date few observations have been reported for cities despite a lot of work being carried out on turbulence over urban areas (Roth, 2000). Kanda et al. (2002), for instance, investigated a 250-m pathlength, using a laser scintillometer, over the city of Tokyo; however this type of scintillometer is limited to short pathlengths not exceeding a few hundred metres. Large aperture scintillometers (LAS) (McAneney et al., 1995) on the other hand can provide sensible heat fluxes integrated over distances of a few kilometres, which is more consistent with modelling efforts. Such instruments have been tested, here, over the city of Marseille as part of the ESCOMPTE-CLU project (http://medias.obs-mip.fr/escompte, Cros et al., 2004; Mestayer et al., 2005). The present paper gives the results of an evaluation exercise of LAS against classical eddy covariance measurements. This is possible because the city centre of Marseille is reasonably homogeneous, suggesting that eddy covariance measurements are likely to be spatially representative. This study includes a sensitivity analysis of the crucial surface parameters. Recommendations are suggested for practical use of LAS over urban areas. Finally, an example of an application to assess the spatial variability of sensible heat flux over the city using two LAS installed on different paths is given.

2. Estimation of the Sensible Heat Flux

We briefly recall the principles of the estimation of sensible heat flux from optical scintillometer measurements. For the fundamentals of scintillometry, see Clifford et al. (1974), Frehlich and Ochs (1990), Tatarskii (1993) and Hill et al. (1992).

Scintillometers provide a measurement of the structure parameter for refractive index $\langle C_N^2 \rangle$ integrated along the optical path (Wang et al., 1978; Churnside, 1993):

$$\langle C_N^2 \rangle = \int_0^1 C_N^2(u) W(u) du, \tag{1}$$

where u is the normalized distance ($u = x/L$, where x is distance from transmitter, L is pathlength) and $C_N^2(u)$ is the structure parameter at distance u. The weighing function $W(u)$ follows a bell-shape curve displaying a maximum in the middle of the path. For the sake of simplicity $\langle C_N^2 \rangle$ will simply be noted C_N^2 in what follows.

The average structure parameter for temperature C_T^2 can be derived from C_N^2 by:

$$C_T^2 = C_N^2 \; [T_a^2/(\gamma p)]^2 \; (1 \; + \; 0.03/\beta)^{-2}, \tag{2}$$

where β is the Bowen ratio, p is atmospheric pressure (Pa), T_a is air temperature (K), γ = 7.9 10^{-7} K Pa^{-1}. C_N^2 and C_T^2 have units $\text{m}^{-2/3}$ and K^2 $\text{m}^{-2/3}$ respectively.

In what follows (Sections 2.1 and 2.2) two methods have been used to derive the sensible heat flux from C_T^2; they are described in detail in McAneney et al. (1995) and De Bruin et al. (1995) for level, low roughness surfaces.

2.1. Mixed convection method

In the classical method (hereafter referred to as MIX) developed for mixed convection the temperature scale T_* is first computed from C_T^2. They are related by:

$$C_T^2 \; = \; T_*^2 (Z)^{-2/3} f[(Z)/L_\text{o}] \tag{3}$$

where $Z = z - d$ is the height of the optical beam above ground (z) corrected by the displacement height (d); the surface is assumed to be flat. The Obukhov length L_o, when neglecting the latent heat flux correction, is a function of friction velocity (u_*) and temperature scale (T_*):

$$L_\text{o} = -\frac{T_a u_*^2}{k g T_*} \tag{4}$$

where $k = 0.4$ and $g = 9.81$ m s^{-2}. The expressions for f vary according to different authors (see Appendix C of Hill, 1997). We tested two of them having the general form:

$$f\left(\frac{Z}{L_\text{o}}\right) = c_{uT1}\left(1 + c_{uT2}\left|\frac{Z}{L_\text{o}}\right|^{-2/3}\right), \tag{5}$$

for unstable conditions ($Z/L_\text{o} \leq 0$),

$$f\left(\frac{Z}{L_\text{o}}\right) = c_{sT1}\left(1 + c_{sT2}\left|\frac{Z}{L_\text{o}}\right|^{2/3}\right), \tag{6}$$

for stable conditions ($Z/L_\text{o} > 0$). First we considered the functions proposed by De Bruin et al. (1993), with ($c_{uT1} =$ 4.9; $c_{uT2} =$ 9.0) and ($c_{sT1} =$

4.9; $c_{sT2} = 0$). We also considered the Wyngaard functions (Wyngaard, 1973) revised by Andreas (1988) to reflect a von Karman constant of 0.4, with ($c_{uT1} = 4.9$; $c_{uT2} = 6.1$) and ($c_{sT1} = 4.9$; $c_{sT2} = 2.2$). In fact, the choice of the formulation for stable conditions has no impact in the case of the present experiment, since unstable conditions prevailed even during night-time.

A wind speed measurement u at a given height z_{m} on a mast allows the determination of u_* from the wind profile equation, which requires the roughness length for momentum (z_0) to be known:

$$u_* = ku\left[\ln\left(\frac{Z_{\mathrm{m}}}{z_0}\right) - \Psi_{\mathrm{M}}\left(\frac{Z_{\mathrm{m}}}{L_{\mathrm{o}}}\right)\right]^{-1} \quad (7)$$

where Ψ_M is the classical stability function (e.g. Panofsky and Dutton, 1984); Z_m is corrected for the displacement height d_{m} at the mast site $Z_{\mathrm{m}} = z_{\mathrm{m}} - d_{\mathrm{m}}$.

The method finally combines T_* and u_* derived from (3) and (7) to compute the sensible heat flux (H in W m^{-2}):

$$H = \rho c_p u_* T_*, \quad (8)$$

where H will hereafter be referred to as either H_{DBR} or H_{AND} according to the choice of the f function; ρ (kg m^{-3}) and c_p (J kg^{-1}K^{-1}) are the air density and heat capacity respectively. Since u_* and T_* both depend on atmospheric stability, through L_{o}, an iterative process is necessary. An initial computation is made assuming neutrality ($Z/L_{\mathrm{o}} = 0$). The value of H obtained allows a better estimation of T_* and u_* through Equations (3)–(7), which provides a new approximation of H and of the Bowen ratio $\beta = H/(R_{\mathrm{n}} - G - H)$, R_{n} and G being the net radiation and ground storage heat flux respectively. The procedure is repeated until the convergence on L_{o} is obtained, the criterion being a relative error less than 10^{-4} between two timesteps.

2.2. Free convection method

This method (hereafter referred to as FRE) assumes free convective conditions. It can be shown that combining Equations (3)–(5) when $Z/L_{\mathrm{o}} \to \infty$ allows one to compute H (referred to as H_{FRE}) directly from C_T^2:

$$H = \rho c_p b Z \left(\frac{g}{T_a}\right)^{1/2} \left(C_T^2\right)^{3/4}, \quad (9)$$

with

$$b = (c_{uT1})^{-3/4} (k\, c_{uT2})^{1/2}. \quad (10)$$

The Bowen ratio correction is neglected and C_T^2 is derived from measured C_N^2 directly (Equation (2)); Kohsiek (1982) experimentally found $b=$ 0.55 over sparse grass and suggested (9) could apply down to $-Z/L_o >$ 0.02. Using the above mentioned constants of the stability function leads to $b=0.474$ for Andreas and $b=0.576$ for De Bruin. De Bruin et al. (1995) used the value $b=$ 0.57 over a dry vineyard. Equation (9) appears very attractive from a practical point of view because it allows one to compute H over an unstable range without the need for any extra meteorological measurements. Nevertheless there is an uncertainty in the b constant of about 20%; moreover this method is very sensitive to the estimate of the displacement height d.

2.3. Introduction of topography

When scintillometer measurements are made over an area that possesses topographic variability, an average equivalent height of the beam must be defined. For each point of the beam, the flux as well as the structure parameters result from the contribution of an upwind area the location and size of which depend on wind direction, topography and position of the point considered. A detailed analysis of the effect of topography on scintillometer measurements requires modelling the footprint and knowing the spatial variability of sources upwind (Irvine et al., 2002a; Meijninger et al., 2002). For simplicity we make the very coarse assumptions that the flux is uniform and that the structure parameter at any point along the beam is only determined by its height, which ignores any direct surface contribution.

Given this, it is easy to show that combining Equations (1) and (3), the equivalent height corrected by the average displacement height Z_{eq} to be introduced into the MIX method is directly given by (Hartogensis et al., 2003):

$$Z_{eq}^{-2/3} f(Z_{eq}/L_o) = \int_0^1 (z_u - d_u)^{-2/3} f[(z_u - d_u)/L_o] W(u) du, \quad (11)$$

where z_u and d_u are the height of the beam and displacement height at distance u respectively. As it depends on L_o, the computation of Z_{eq} must be introduced in the loops of the iterative process above-mentioned.

For the FRE method, combining Equations (1)–(3) and (9) leads to

$$Z_{eq} = \left[\int_0^1 (z_u - d_u)^{-4/3} W(u) du \right]^{-3/4}. \quad (12)$$

Figure 1. Aerial oblique-view of the city centre (in the vicinity of the central mast site, see Figure 2) taken from an overflight during the ESCOMPTE campaign (July 12).

3. Experimental

3.1. The experimental site

The instruments were deployed to estimate the turbulent sensible heat flux integrated over the centre of the city using two LAS, and were relocated during the experiment to document three triangular directions. The city centre is dense with old buildings mainly from the 18th and 19th centuries, most of them 6–8 storeys and around 20-m high (Figure 1). All street directions are well represented for azimuths between 60° and 180° (clockwise from north) whilst the number of streets oriented between 0° and 60° is significantly reduced. The fraction of the plan area that is built upon is estimated to be 58% from aerial photographs (Long, 2003). Figure 2 shows the city around the study site, which appears relatively homogeneous, with only a limited number of large squares or more unusually large buildings. The roofs are generally covered with clay tiles with slopes of about 20°, and there are a few terraces generally covered with gravel. The average ratio of building height/street width (referred to as the street aspect ratio) varies between about 1.1 and 2 depending on the location within the centre of the city. The average vegetation cover estimated from aerial photographs is low (about 10%), with most trees aligned along a few streets and in the small number of gardens in courtyards on the interior of the blocks.

The site is rather hilly, particularly in the south-west of the city, where the altitude reaches 142 m at Notre Dame de la Garde church. Elsewhere

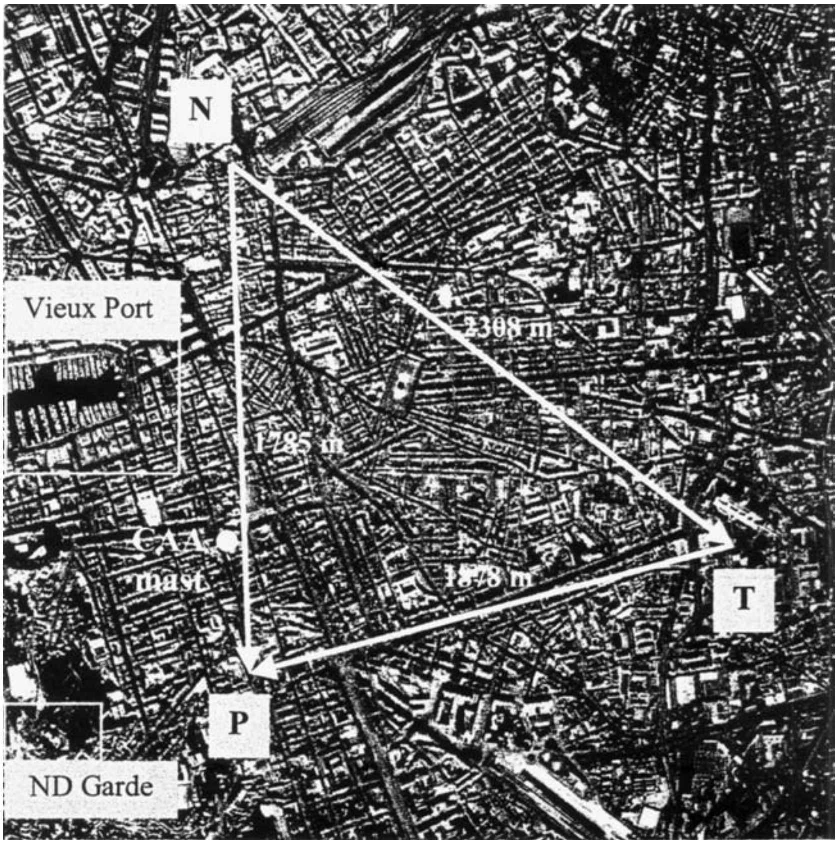

Figure 2. Aerial photograph of the city centre: 2800 × 2800 m sample of Institut Géographique National (IGN) panchromatic image on March 21, 1999 (with courtesy of IGN). N, P, and T refer to the position of the buildings where the scintillometers were installed.

in the study domain, heights range between sea level (Vieux-Port harbor) up to 70-m asl (Figure 3), with only gentle slopes. The 'BD Topo' database of the Institut Géographique National (IGN) provided the ground topographic relief and the altitude of the top of the buildings. The difference between the two allows the building height to be derived. Since the information about buildings is provided in vector form (heights and coordinates of the corners of the buildings), it is first rasterized and the average height of buildings h_b at a given resolution is computed as their height weighted by their surface area within every grid (Long et al., 2002, 2003). In our case, BD Topo was processed at a 50-m resolution.

3.2. Experimental setup

The two LAS, built by the Meteorology and Air Quality Group, Wageningen University, Netherlands were installed over the Marseille city centre between

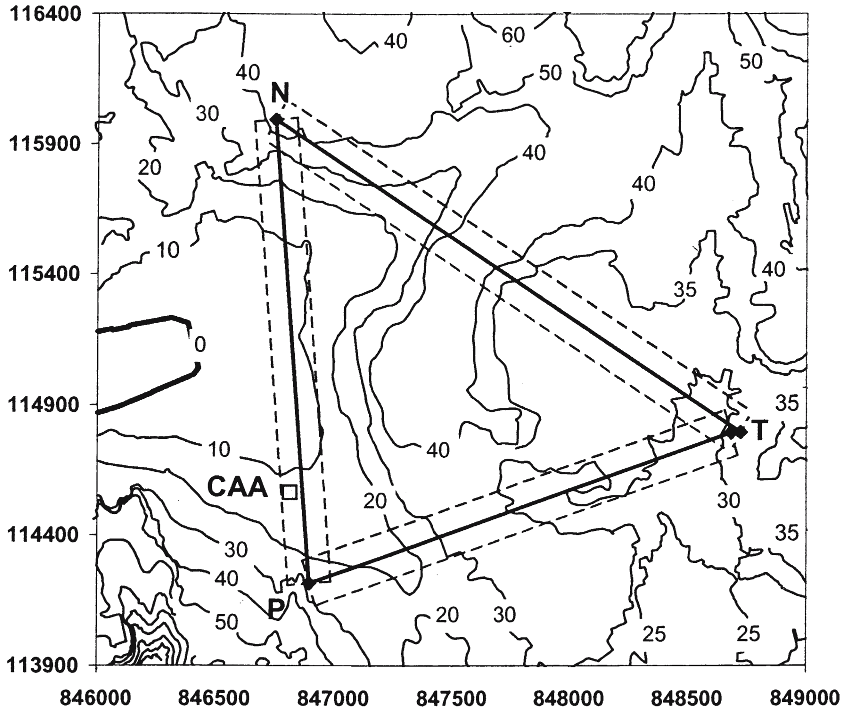

Figure 3. Topography of the centre of Marseille (the zero contour on the left border is the outline of the Vieux Port). The thick lines locate the optical paths of the scintillometers. The dotted lines indicate the 200-m wide strips along which the topographic profiles have been averaged for the LAS paths. The grey square (CAA) corresponds to the location of the central mast. Lambert III NTF latitude and longitude coordinates are given in metres (with an offset of 3×10^6 m on latitude).

June 17 and July 10 2001 (DoY 168–191), during the intensive field campaign of the ESCOMPTE project. These instruments were built according to the method described in Ochs and Cartwright (1980) and Ochs and Wilson (1993). They have a 0.152-m aperture and operate at a wavelength of $0.94\,\mu$m, with a square signal modulated at 7 kHz to discriminate between light emitted by the transmitter and that of ambient radiation. Output voltage V (volts) was sampled at 1 Hz and averaged over 15-min timesteps. The standard deviation of V (σ_V) was also recorded, and C_N^2 was computed taking into account the correction for non-linearity proposed by Lagouarde et al. (2002a) as

$$C_N^2 = 10^{(V\mathrm{cor}-12)}, \tag{13}$$

with $V_{\mathrm{cor}} = V + 1.0966\sigma_V^2 + 0.010\sigma_V$. Continuous high frequency recording (1 kHz) was also made for complementary purposes such as spectral analysis and the fundamental study of scintillations (Irvine et al., 2002b).

The transmitters and receivers were placed on tripods on the terraces of three buildings (Paradis, Nédélec, and the Timone Hospital referred to as P, N and T, hereafter) at 34.0, 26.1 and 53.1 m above the ground, respectively. The pathlengths were accurately measured using a laser meter and were found to be 1785, 1878 and 2308 m for PN, PT and NT, respectively (Figures 2 and 3). The elevation and topography of the ground (altitude z_g) and of the built canopy ($z_g + h_b$) along the paths were determined by averaging the profiles inside a 200-m wide strip centred on the path of each scintillometer (Figure 4) and smoothed at 10-m steps.

Reference measurements of the surface radiation budget and turbulent fluxes were also performed at a central site (Cour Administrative d'Appel de Marseille, 'CAAM' building located at 43°17′24″ N, 05°22′44″ E) virtually located on the PN scintillometer pathlength (Figures 2 and 3). In the immediate vicinity of the CAAM the street aspect ratio is estimated to be close to 2 and the vegetation cover about 16%. The set-up is described in detail by Grimmond et al. (2004). Sensible and latent heat fluxes were measured with the eddy covariance technique using an RM Young 81000 sonic anemometer and a Licor 7500 infrared gas analyzer mounted on a mast installed on the rooftop terrace of the building. The height of measurements was 43.9-m above street level when the mast was fully deployed, but was reduced to 37.9 m for safety reasons when strong winds were blowing. In both modes, the measurement height of turbulent fluxes remained fairly close to the optical path (see Figure 4A). A net radiometer was also mounted on the mast high enough to see the surrounding buildings and streets to provide representative values of net radiation.

The determination of the roughness length z_0 and displacement height d remains a difficult task for urban areas, since both depend on the combined effects on the flow of various characteristics of the urban canopy structure such as building height, built density, spacing of buildings and street width (Grimmond and Oke, 1999; Roth, 2000). Following Grimmond et al. (2002), we considered the values of the roughness length and displacement height to be $z_0 = 1.0$ and $d_m = 17.0$ m respectively. The value of d is deduced from the average height of individual building ($z_H \approx$ 24 m) estimated from a ground survey of the area around the CAAM site using the classical rule of thumb $d_m \approx 0.7 z_H$. These values are consistent with those suggested by Grimmond and Oke (1999) for 'tall and high density' urban areas. Recent computations by Grimmond et al. (2004) based on $z_H \approx 15.6$ m have led to a revised value of d_m closer to 11 m with a resulting value of $z_0 \approx 2.5$ m. This value seems an overestimate when compared against data found in the literature; the discrepancy here probably arises from differences in the definition of the mean building height. In any case sensitivity tests (see Section 4.3) will allow one to evaluate the impact of errors on z_0 and d_m on the scintillometer-derived sensible heat flux.

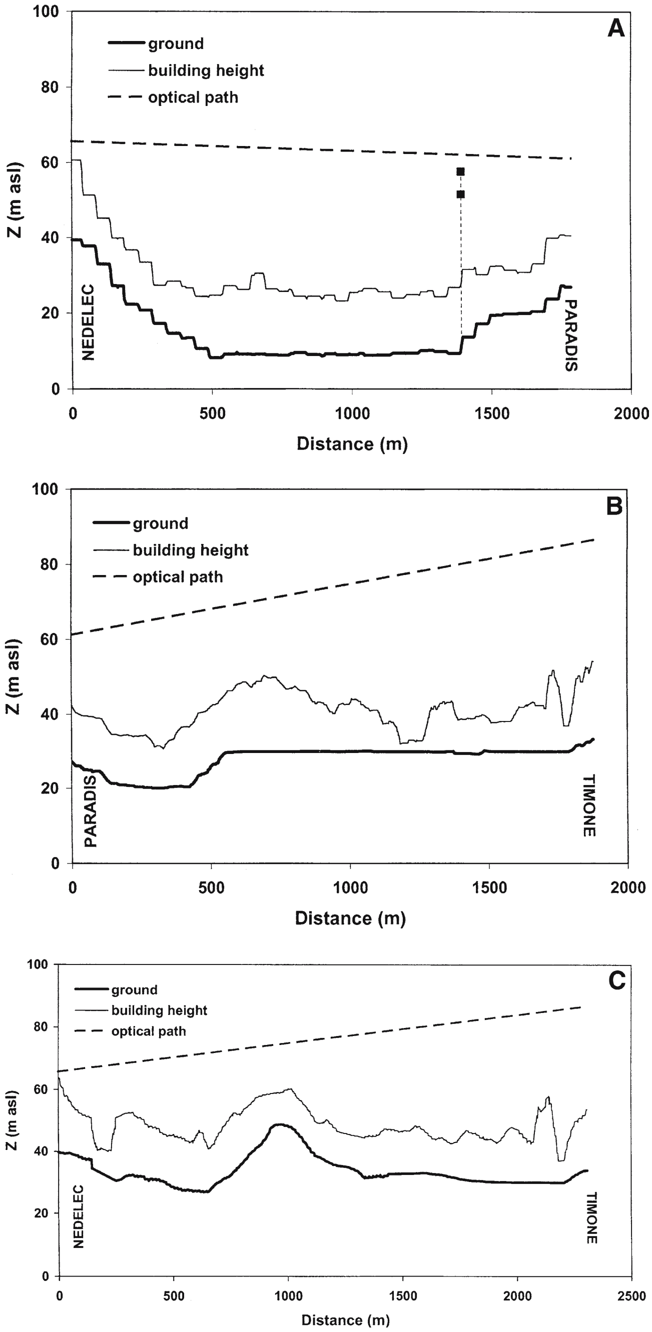

Figure 4. Topography of the ground (thick line) and of the built canopy (thin line) for the NP (A), PT (B) and NT (C) paths. The optical paths are also plotted (dotted lines). For the NP path, the two black squares indicate the positions of eddy covariance reference measurements for the mast when partly or fully deployed.

TABLE I
Location of scintillometers during the study.

Period	DoY	P–N	P–T	N–T
17 June–3 July	168–184	•	•	
04 July–10 July	185–191	•		•

The instruments were located as indicated in Table I. A scintillometer was left on the PN path for the whole study period to permit extensive validation against the flux measurements performed on the central mast situated close to this path. The other scintillometer was installed successively on the PT and NT transects for 17 and 7 days, respectively, so as to evaluate the possible spatial variability of sensible heat fluxes by comparison against the PN measurements.

3.3. Intercalibration of scintillometers

The two scintillometers were compared prior to deployment in Marseille. They were installed at the INRA research centre in Bordeaux close to the laboratory above a grass surface for 15 days. They were mounted at 2.5 m above the ground surface, with a pathlength of approximately 250 m. The scintillometers were sampled with parallel optical paths 5 m apart, and to avoid possible cross-interference between instruments, the two signals were emitted in opposite directions with one transmitter and one receiver placed at each extremity. The integration time was 10 min, and data points having a standard deviation greater than 0.1 V were eliminated. Unfortunately, the conditions were not dry enough to have a sufficient density of observations above $2\times10^{-14}\,\mathrm{m}^{-2/3}$, nevertheless the comparison between the two instruments revealed good correlation (Figure 5). The deviation was found to be 1.6% in the range $[10^{-16}, 6 \times 10^{-14}]$, which includes the magnitude of C_N^2 values encountered during the ESCOMPTE experiment. This corresponds to a discrepancy in H of about 1.2%. When estimated over the range $[10^{-16}, 2 \times 10^{-14}]$ (80% of ESCOMPTE data) to minimize the influence of the few scattered points above 3×10^{-14} on the statistics, the deviation between average scintillometer-derived C_N^2 vanishes. We therefore ignored any possible systematic deviation between the two scintillometers. Nevertheless for accurate comparison between instruments in the future, we recommend operation in conditions as dry as possible and close enough to the ground to observe large numbers of high C_N^2 values.

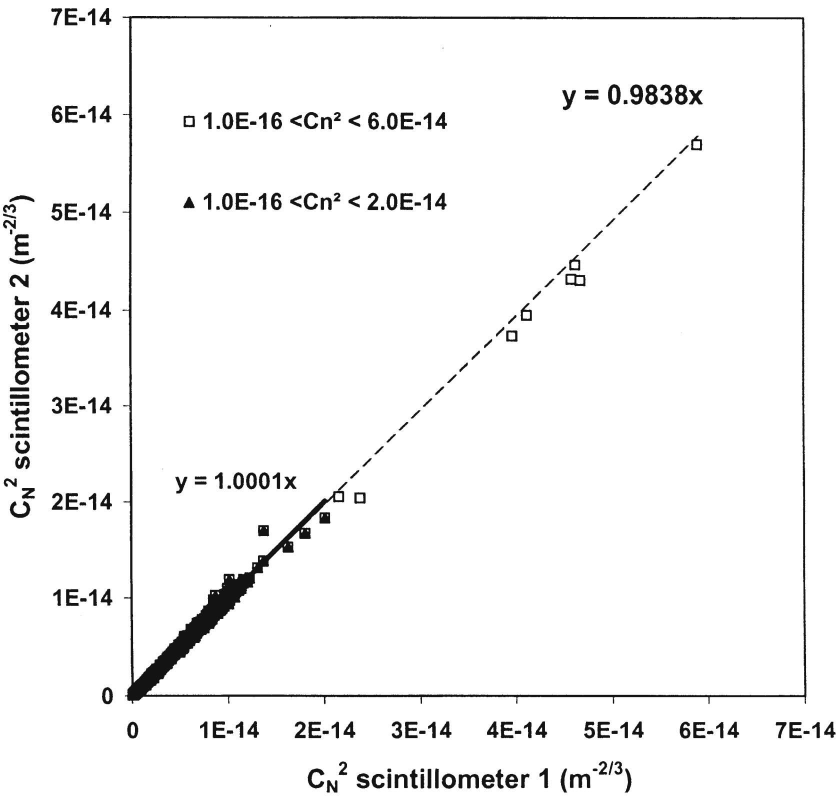

Figure 5. Intercalibration experiment: comparison between C_N^2 derived from scintillometers 1 and 2 along a 250-m path above grass (Bordeaux, May 2001). Thick and dotted lines respectively correspond to the regression lines computed over $[10^{-16}, 2 \times 10^{-14}]$ and $[10^{-16}, 6 \times 10^{-14}]$ C_N^2 intervals.

4. Results of Evaluations

4.1. MIX method evaluation

The displacement height over the city was estimated from the BD Topo derived building height h_b as $d = x_d h_b$, with x_d taken to be a constant. The coefficient x_d was calibrated from the only available point at the central mast location. Using the BD Topo method the average value of h_b around the central site was found to be 15 m. The value $d_m = 17$m estimated at the central mast results in $x_d = 1.15$. As it is defined, h_b not only depends on the mean height of the buildings, but also on their surface. It could be qualified as a 'volumetric' equivalent height inside a grid implicitly taking into account the building density. It is therefore lower than average building height, which explains x_d to be greater than 1.

In order to correctly calculate H from a LAS, an estimate of β is necessary (Equation (2)). This requires that the net radiation (R_n) and storage heat flux (G) are measured, or estimated, to readjust the value of β using H obtained in the iterative process. For R_n, we directly used measurements monitored on the central mast using a Kipp & Zonen CNR1 instrument. However no simple means exists for estimating G inside the urban canopy, and we therefore used a standard curve of the evolution of G throughout the day. This was obtained by averaging and smoothing the values derived as a residual from the energy balance measured at the central site: i.e. $G = R_{nm} - H_m - \lambda E_m$ where R_{nm} is the net all-wave radiation, and H_m and λE_m are the turbulent fluxes of sensible and latent heat (λ latent heat of vaporization, E_m is the vapour flux). In fact G also here includes the residual of the non-closure of the energy balance (Culf et al., 2004). This approach is justified by the fact, (i) that very similar climatic conditions were met during the experiment, and (ii) that high accuracy of G is not required because it is only used to estimate the Bowen ratio, which itself appears in a corrective term (see Equation (2)). This was confirmed by sensitivity tests (see later). The residual method has been used by Grimmond and Oke (1999) to determine the storage heat flux in several cities satisfactorily.

This estimate of G has also been used to quantify the available energy, $A = R_{nm} - G$, as a way to identify the sign of H, given that scintillation intensity measurements do not provide that information. Positive (negative) values of A were interpreted to indicate unstable (stable) conditions, which correspond to positive (negative) values of H. Of course there is a potential problem with using observed H to obtain G, then using $R_{nm} - G$ to determine the sign of H. We have allowed ourselves to do this in order to test the method; however in the future it will be necessary to estimate G independently.

A comparison between the sensible heat flux derived from scintillometry measurements using the De Bruin parameterization H_{DBR} for the Paradis–Nédelec transect and eddy covariance measurements H_{EC} is presented in Figure 6 for the period DoY 169–175. This week was selected because it is reasonably representative of the whole study period. The following comments can be made:

- The values of the sensible heat flux are large and account for the largest fraction of the daytime radiative heat surplus. The general agreement between H_{DBR} and H_{EC} is quite good. H_{EC} was computed over 30-min intervals and displays frequent fluctuations. Despite being integrated over shorter 15-min time intervals, H_{DBR} displays a much smoother evolution with time, one which is consistent with that of net radiation (Figure 6). This is a classical observation related to the fact that the spatial integration performed along the beam by the scintillometer is similar to an additional temporal integration.

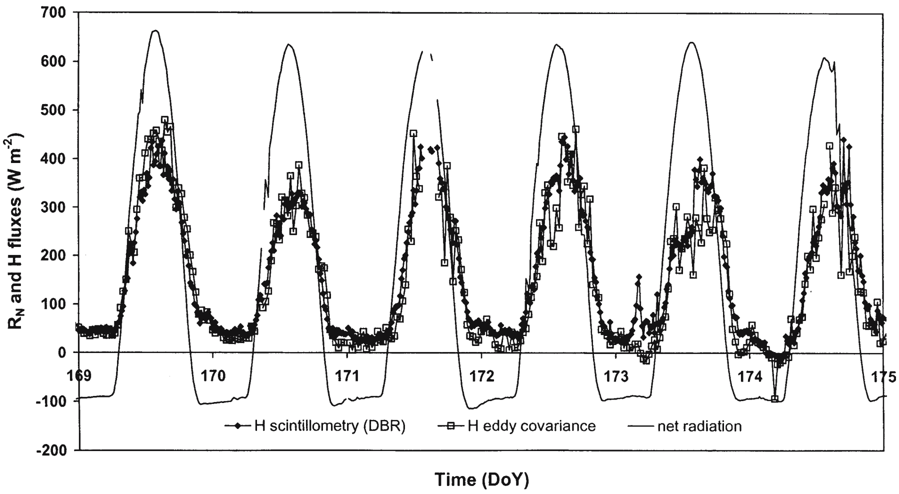

Figure 6. Sensible heat fluxes derived from LAS measurements using the MIX method over the PN path and measured by the eddy covariance method between DoY 169 and 175. Net radiation (R_n) is also indicated.

- In addition to the greater variability evident in the eddy covariance results, a few discrepancies between H_{DBR} and H_{EC} are observed on some days, with systematic differences either positive or negative. Particular attention was paid to these days to investigate possible effects of wind direction that can result from differences in size, shape, and location of the turbulent source footprint. Comparison of H_{DBR} against H_{EC} for the different classes of wind direction observed during the study period is given in Figure 7. The relatively uniform scatter of the points around the 1:1 line, independently of the direction class, suggests there is no strong bias related to the fetch direction and confirms the quality of the validation exercise.
- Nighttime values of the turbulent sensible heat flux remain positive most of the time. Fluxes directed upward away from the surface indicate atmospheric instability during the ESCOMPTE summer campaign.
- Large discrepancies between the two estimates of H can occur at night. For example, between days 172 and 173, when H_{DBR} displays positive values whilst H_{EC} is negative. Closer analysis reveals that these differences are related to poor characterization of atmospheric conditions, due to erroneous assumption of instability induced from positive values of A. However, when the signs of A and G are consistent, as is the case between 0300 and 0600 the following night (Figure 6), H_{DBR} is correct.

To globally assess the quality of the MIX method, two additional comparison exercises are presented. First, scintillometer derived sensible heat fluxes and eddy covariance measurements have been compared for the

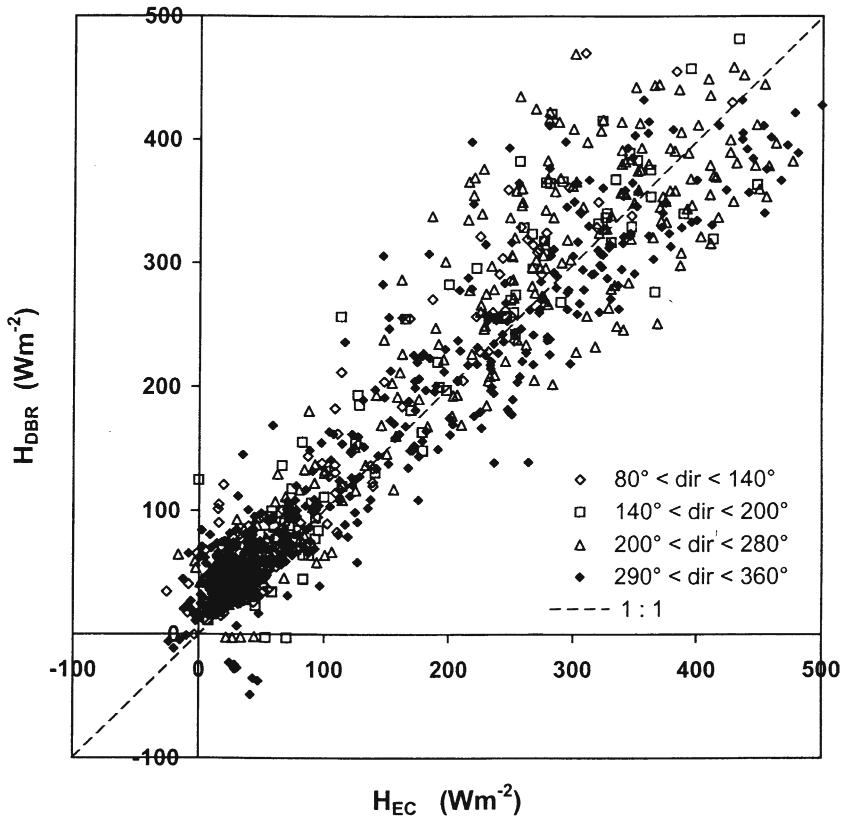

Figure 7. Comparison of H_{DBR} (MIX method) for the PN pathlength against H_{EC} fluxes for different classes of wind directions.

'ensemble average' day calculated for the whole campaign (DoY 168–190) (Figure 8). The general agreement is rather good. During the daytime, differences with H_{EC} of about 9% (overestimation) and 4% (underestimation) are noted for H_{DBR} and H_{AND} respectively. Both parameterizations lead to an overestimation of H_{EC} by about 15 W m^{-2} in comparison with H_{EC} during nighttime. The $\pm 1\sigma$ interval (σ is standard deviation) curves for H_{EC} only are indicated in Figure 8 for clarity: σ is very large and reaches 28% during daytime whilst it remains about 17% for H_{DBR} and H_{AND}. The difference can be explained by the smoothing naturally performed by the scintillometer through the spatial averaging on one side, and by instrumental reasons related to the sonic instrument used (RM Young 81000) on the other side. Secondly, the lack of bias with wind direction for H_{DBR} along the PN path against the H_{EC} fluxes (Figure 7) confirms (i) the homogeneity of the site and the representativity of the mast measurements, and finally (ii) the quality of the LAS-eddy covariance validation.

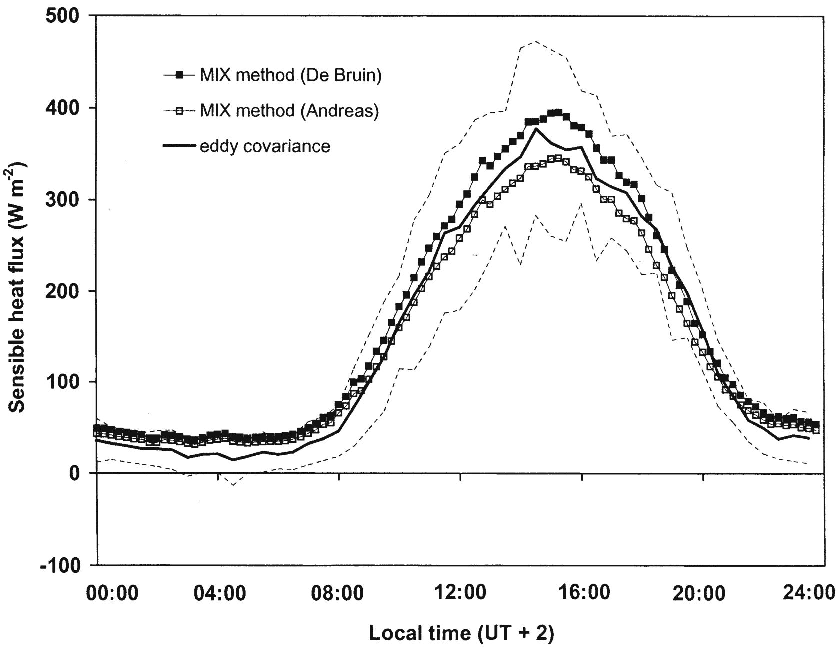

Figure 8. Comparison of LAS-derived flux using the MIX method H_{DBR} and H_{AND} for the PN pathlength against eddy covariance-measured flux H_{EC} for a synthetic 'average day' during the ESCOMPTE field campaign (DoY 168–190). Dotted lines indicate $\pm 1\sigma$ (standard deviation) for H_{EC}.

4.2. Comparison between the MIX and FRE methods

The sensible heat flux has been calculated on the NP path using both the MIX and FRE methods. The De Bruin parameterization of the f function has been considered first. Equation (9) has been used directly with $b = 0.576$ and Z/L_o has been estimated simultaneously from the mast measurements at a height of 37.9 m above ground. The comparison (Figure 9) shows the scatter is large and reveals a systematic underestimation of H_{FRE}. Nevertheless a threshold on Z/L_o at about -0.15 provides discrimination, both methods tending to converge for unstable conditions ($Z/L_o < -0.15$). Closer to neutrality ($0 > Z/L_o > -0.15$) important discrepancies are observed and the FRE method fails. Using the Andreas parameterization for the stability function f lead to the same results (not presented here), with a slight increase of the bias from the 1:1 line: this is consistent with the fact that using $b = 0.474$ (instead of 0.576) results in a decrease of $\approx 20\%$ of H_{FRE}, and that H_{AND} is $\approx 13\%$ greater than H_{DBR}. Similar comparisons performed along the two other paths (NT and PT) additionally confirmed these results.

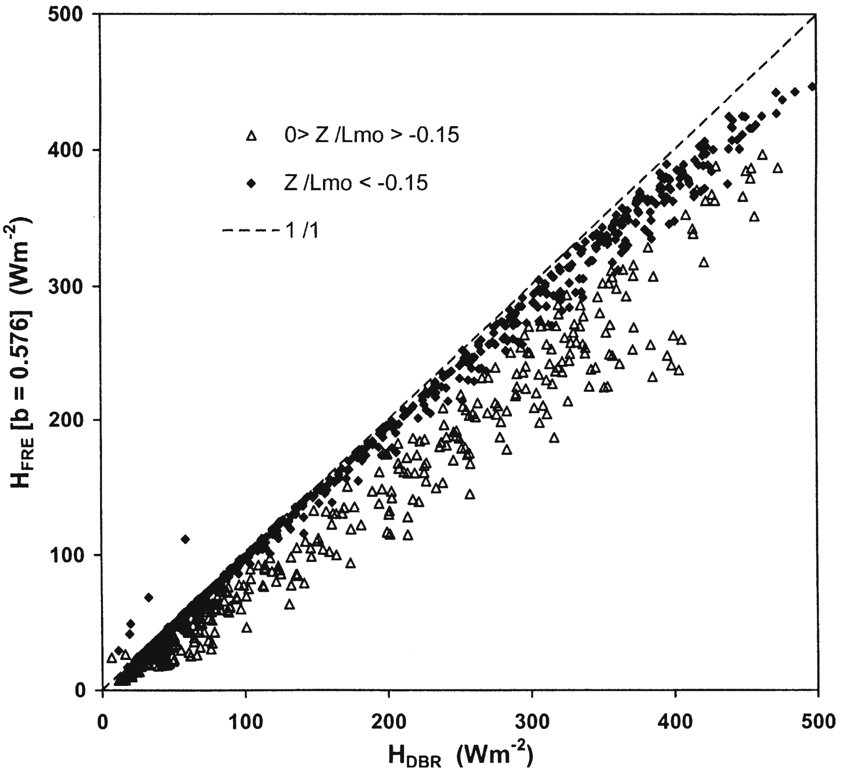

Figure 9. Comparison between the sensible heat flux calculated by the MIX method (H_{DBR}) and by the FRE method (with $b = 0.576$) over the PN path, with Z/L_o estimated at 37.9 m above ground on the central site mast.

A possible uncertainty in the estimation of the equivalent height Z_{eq} could be invoked to explain the bias for unstable conditions. The values computed by Equations (11) and (12) are provided in Table II, and appear quite consistent for every path whatever the method, which suggests the topography is correctly taken into account. The only source of error therefore could lie in an error (overestimation) on the displacement height along the path. Improvements can here be only expected from the development of robust methods for deriving this parameter from urban morphology data.

For long-term automatic monitoring of sensible heat flux, we therefore recommend use of the MIX method provided the surface parameters (roughness length and displacement height) are known with enough confidence. The impact of possible errors in these parameters is analysed below.

4.3. Sensitivity of the MIX method to surface parameters

The roughness length for momentum (z_0) and the displacement height (d_m) must be known locally around the reference mast where the wind speed is

TABLE II

Equivalent height Z_{eq} (m) of the three optical paths computed for the MIX and FRE methods.

	NP	PT	NT
MIX method (De Bruin)	34.16 (0.05)	27.62 (0.21)	22.62 (0.26)
MIX method (Andreas)	34.18 (0.05)	27.68 (0.22)	22.71 (0.26)
FRE method	34.14	27.42	22.16

For MIX methods, the standard deviation of the estimates of Z_{eq} at every timestep along the whole experiment is indicated in italics.

measured in order to compute the friction velocity (Equation 7). Moreover the displacement height also has to be estimated all along the pathlength to compute the equivalent height (see Equation (11)) and to derive the temperature scale T_* from scintillometer measurements. We assumed this to be proportional to the average building height through a coefficient x_d. Sensitivity tests allowed us to analyse the potential impact of errors in these aerodynamic parameters on retrieved fluxes, and the tests have been performed for the three paths simultaneously to evaluate the possible effects of topography. The results are presented in terms of the relative error in the computed H flux around its value for the nominal set ($d_m = 17$ m, $z_0 = 1.0$ m and $x_d = 1.15$) used in the previous validation exercise. Each parameter has been varied independently keeping the two others at their nominal values. The range of variation for each parameter has been made large enough to include realistic uncertainties on the parameters.

When wind speed measurements are performed high above the surface, the sensitivity to d_m remains low: with $z_m = 43.9$ m variations of d_m between 11 and 26 m caused relative errors in fluxes to be less than 5% (Table III). The errors range between about −3 to 11% when z_m height is decreased to 37.9 m. Moreover, quite logically since d_m appears through the term Log $(z_m - d_m)$ in the wind profile equation (Equation (7)), underestimation of d_m has less influence on scintillometer-derived fluxes.

The sensitivity to roughness length z_0 is more pronounced and is also related to the measurement height z_m. Table IV shows that over the realistic z_0 range of 0.7–1.5 m, which is quite typical according to Grimmond and Oke (1999) for tall and high density urban areas, the error lies between −6.0 and 9.2% for $z_m = 37.9$ m, and between −4.2 and 6.3% for $z_m = 43.9$ m.

The ranges of d_m and z_0 values tested are intentionally much larger than the realistic range of their actual values. The sensitivity tests show that if the reference measurement of wind speed is performed high enough (43.9 m in this case), the accuracy of H is likely to be better than 5%.

TABLE III

Sensitivity (relative error in %) of the scintillometer-derived sensible heat flux H_{DBR} to the displacement height at the wind measurement site (d_m) and to the height of the wind sensor (z_m), for the three scintillometer paths used.

d_m (m)		11	13	15	17	19	21	23	26
$z_m = 37.9$ m	NP	−2.8	−2.1	−1.1	0	1.3	3.1	5.1	9.8
	PT	−3.5	−2.4	−1.3	0	1.6	3.6	6.0	11.6
	NT	−3.2	−2.3	−1.2	0	1.5	3.3	5.7	10.7
$z_m = 43.9$ m	NP	−0.9	−0.7	−0.3	0	0.4	0.9	1.3	2.3
	PT	−1.0	−0.7	−0.3	0	0.4	1.0	1.5	2.6
	NT	−1.7	−1.2	−0.7	0	0.8	1.6	2.7	4.7

TABLE IV

Sensitivity (relative error in %) of the scintillometer-derived sensible heat flux H_{DBR} to the roughness length (z_0) at the wind measurement site and to the height of the wind sensor (z_m) for the three scintillometer paths studied.

z_0 (m)		0.5	0.7	1	1.5	2.0
$z_m = 37.9$ m	NP	−8.6	−5.0	0	7.9	15.4
	PT	−10.3	−6.0	0	9.2	18.0
	NT	−10.1	−5.8	0	9.0	17.5
$z_m = 43.9$ m	NP	−3.8	−2.2	0	3.5	7.0
	PT	−4.5	−2.6	0	4.0	8.1
	NT	−7.3	−4.2	0	6.3	12.4

Estimation of the displacement height along the pathlength, d_u, is more crucial. It must also be remembered that d_u is calibrated against d_m at the mast site through the x_b constant, which adds another uncertainty in the estimation of the sensible heat flux. Sensitivity tests were performed with x_d varied between 0.6 and 1.5 (Table V). The measurement height z_m did not have a significant impact in this case, and the relative error in the flux was estimated by merging all available data. The error varies linearly with the coefficient x_d, a 10% error in the displacement height (or on x_d) inducing an error of about 4.4% in H_{DBR}. The estimation of d_u made herein is based on the built volume only and does not take into account morphological features such as the spatial separation of the buildings, their shape, or the orientation of streets, all of which can have a significant impact on the displacement height (Rotach, 1994). The homogeneity of the city centre makes the case of Marseille rather easy and the representativeness of the determination of x_d at the mast site good. But for future applications over other

TABLE V

Sensitivity (relative error in %) of the scintillometer-derived sensible heat flux H_{DBR} with the displacement height along the beam, for the three scintillometer paths studied.

x_d	0.6	0.9	1.05	1.15	1.3	1.5
NP	23.3	10.6	4.3	0	−6.8	−15.2
PT	25.9	12.1	4.9	0	−7.7	−18.6
NT	27.9	12.8	5.1	0	−8.0	−19.2

cities, better estimates of d_u, based on the three-dimensional (3D) structure of the urban canopy will have to be introduced (Grimmond and Oke, 1999; Burian et al., 2002), as well as its variability along the paths, possibly including different types of urban structures.

5. Analysis of the Spatial Variability of Sensible Heat Fluxes

The spatial variability in surface fluxes is directly related to the urban terrain in several ways. The structure of the urban canopy (built area ratio, height of buildings, width and orientation of streets) conditions the values of the aerodynamic surface parameters. The scale of the heterogeneity here typically ranges between a few hundreds of metres to a few kilometres. The spatial characteristics of sources (vegetated areas, parks, anthropogenic heat sources) also induces additional variability with possible strong discontinuities at smaller scales (Schmid et al., 1991).

Schematically, the individual landscape patches, where the typical size corresponds to the length scale of the heterogeneity, develop their own surface boundary layers. These mix at a given height defined as the ‘blending’ height and often denoted z_b (Mason, 1988; Mahrt, 1996), above which measurements are thought to provide spatially-integrated values directly. The height z_b depends on a combination of different factors: it increases with the scale of heterogeneity, and decreases with increasing wind speed and atmospheric stability (Meijninger et al., 2002). When performed below z_b, scintillometer measurements are still able to provide integrated fluxes (Lagouarde et al., 2002b) whilst local point measurements remain more sensitive to spatial variability. Scintillometers therefore offer the opportunity to assess the variability of surface fluxes at a scale (about 1 km) quite compatible with urban boundary-layer models, and with a confidence that even dense networks of point measurements would be unable to provide over heterogeneous surfaces (Smith et al., 1992). Wind direction must nevertheless be taken into account because measurements at a given location are influenced by an area upstream referred to as the footprint. Several footprint models have been developed for point measurements (Schuepp et al., 1990; Schmid, 1994, 1997; Kljun et al., 2002), and Meijninger et al. (2002) recently proposed an adaptation to scintillometry.

Comparison between simultaneous scintillometer measurements along different paths provided a means to assess the spatial variability of sensible heat flux over the city centre given that each path had an independent footprint (Irvine et al., 2002a). The NP transect, monitored throughout the study period, and which was evaluated against the mast measurements, is here considered to be a reference in comparisons against the PT and NT paths. The wind regimes were different for the two parts of the study. During the NP–PT comparison four types of conditions were observed (Figure 10A): weak winds from the east-south-east at night, strong north-west wind (Mistral typical of the region), and mean south and west-south-west winds. During the DoY 185–190 period, two regimes prevailed: strong south-east winds and west and north-west winds of similar intensity (Figure 10b).

Figures 11 and 12 are plots of scintillometer-derived fluxes along the PT path (DoY 168–184) and along the NT pathlength (DoY 185–190), respectively, against those derived along NP. The MIX method (with De Bruin parameterization) was used for the computations. The friction velocity u_* was assumed to be uniform over the study area and was estimated at the central site mast using $d_m = 17$ m and $z_0 = 1.0$ m. Similarly the structure of the city centre was assumed to be homogeneous enough that we could retain the same value of 1.15 for the x_d coefficient for the three paths. PT and NP fluxes appear comparable only in Mistral cases ($290^\circ - 350^\circ$ directions, Figure 11): the regression line forced through the origin yields $H_{DBR}(PT) \approx 1.01 H_{DBR}(NP)$ ($R^2 = 0.955$). Points corresponding to low east-south-east winds are observed at night only, when turbulent fluxes are small. For other wind directions, $H_{DBR}(PT)$ is systematically smaller than $H_{DBR}(NP)$ (Figure 11) by about 13%. We also observed smaller fluxes along the NT transect (Figure 12) for the conditions met in the period that path was operated, with the same order of magnitude (about 11%).

The first results presented here illustrate the potential of combining different scintillometers over an urban area to assess the spatial variability of turbulent fluxes. Further characterization of the spatial variability of the sensible heat flux would require much longer periods of observation in order to sample a wide range of climatic conditions and wind directions. In addition a footprint model would help to map the areas contributing to the fluxes. Such a model derived from Meijninger et al. (2002) is currently being adapted (Irvine et al., 2002a). The spatial variability of sources over the city could be assessed from the thermal infrared imagery acquired during the campaign.

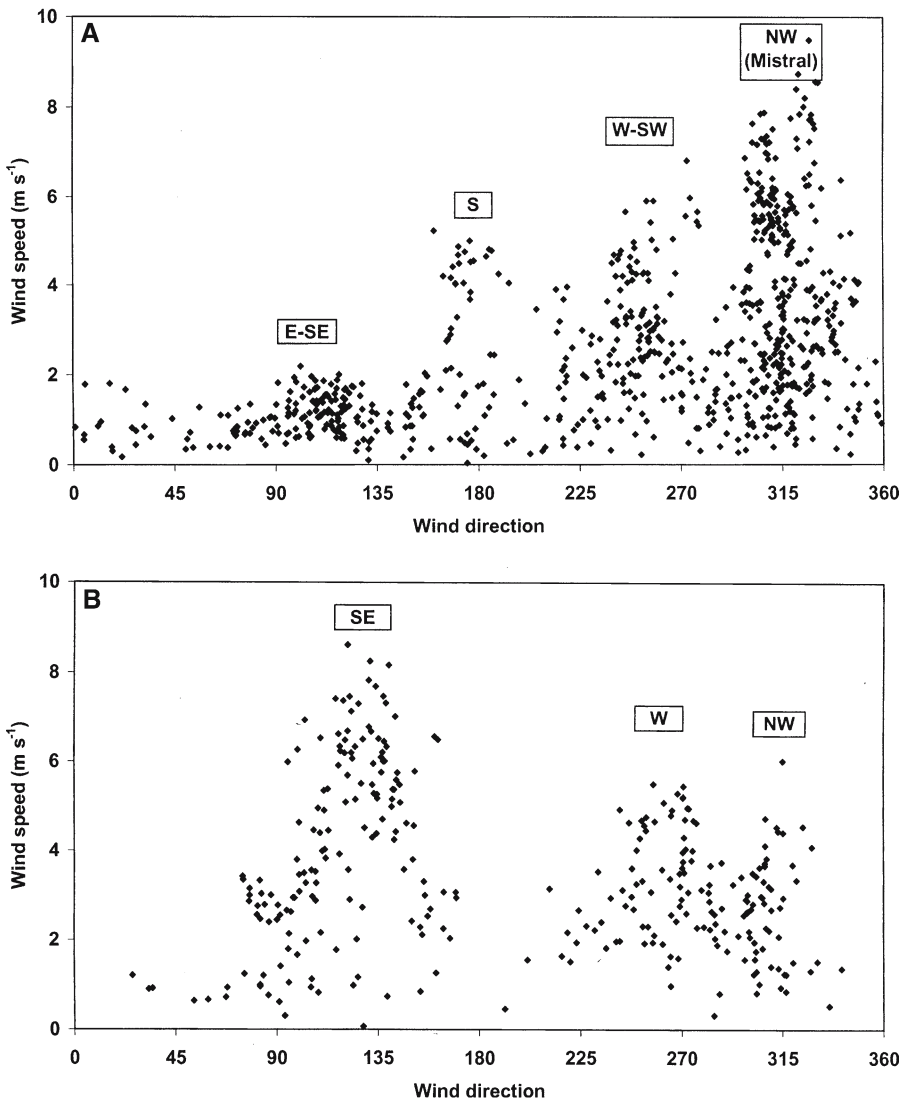

Figure 10. Wind regimes during the (A) NP–PT (DoY 168–184) and (B) NP–NT (DoY 185–190) comparisons.

6. Conclusion

Following on from studies performed over vegetation, the quality of the results obtained during the ESCOMPTE experiment over the city of Marseille confirms the potential of LAS in the direct measurement of integrated sensible heat fluxes over urban canopies, even in the presence of topography. The method was evaluated by comparing LAS-derived fluxes along a 1800-m pathlength against classical eddy covariance measurements

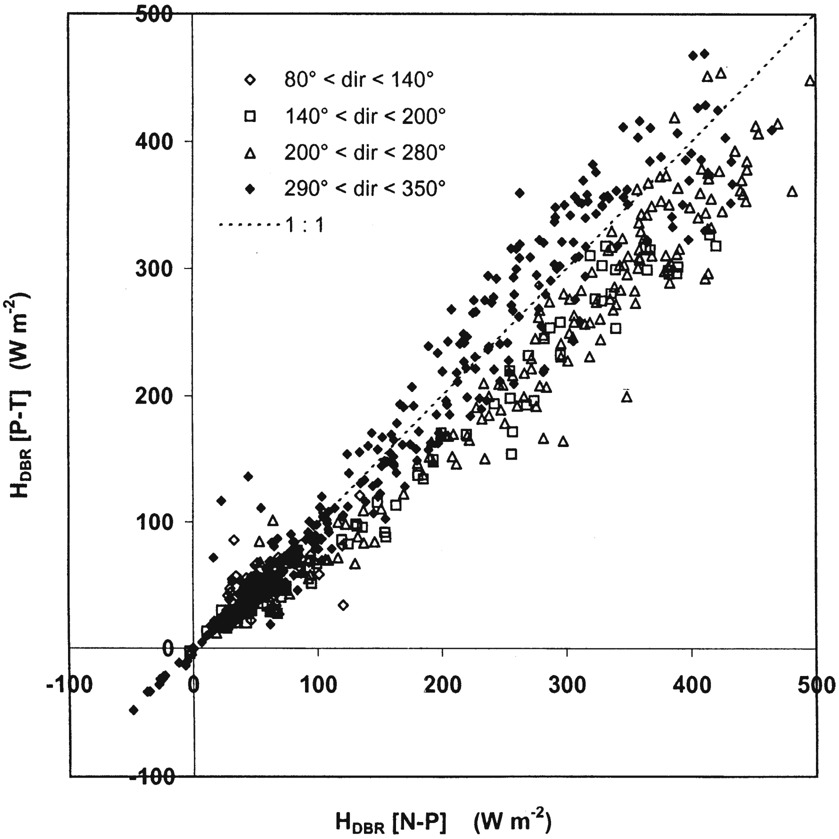

Figure 11. Comparison between LAS-derived sensible heat flux H_{DBR} along NP and PT paths (DoY 168–184) according to wind directions.

during a 3-week period. The general agreement found was good and an advantage of scintillometry is that it directly provides fluxes that display a smoother evolution through time than the eddy covariance technique. This is more realistic and consistent with the time evolution of the net radiation forcing: the spatial integration performed by scintillometers along the path naturally substitutes a time integration. This allows shorter timesteps: 15 min are adequate for LAS measurements, whilst even with a 30-min integration time, eddy covariance local measurements display large fluctuations. Several recommendations, based on the Marseille experiment, can be made for future operational routine monitoring of surface fluxes:

- The method based on the mixed convection formulation (MIX) is preferred to that of the free convection formulation (FRE), at least for measurements heights of a few tens of metres. The FRE method may be applicable at greater heights, where convective turbulence prevails, however, this remains to be tested.

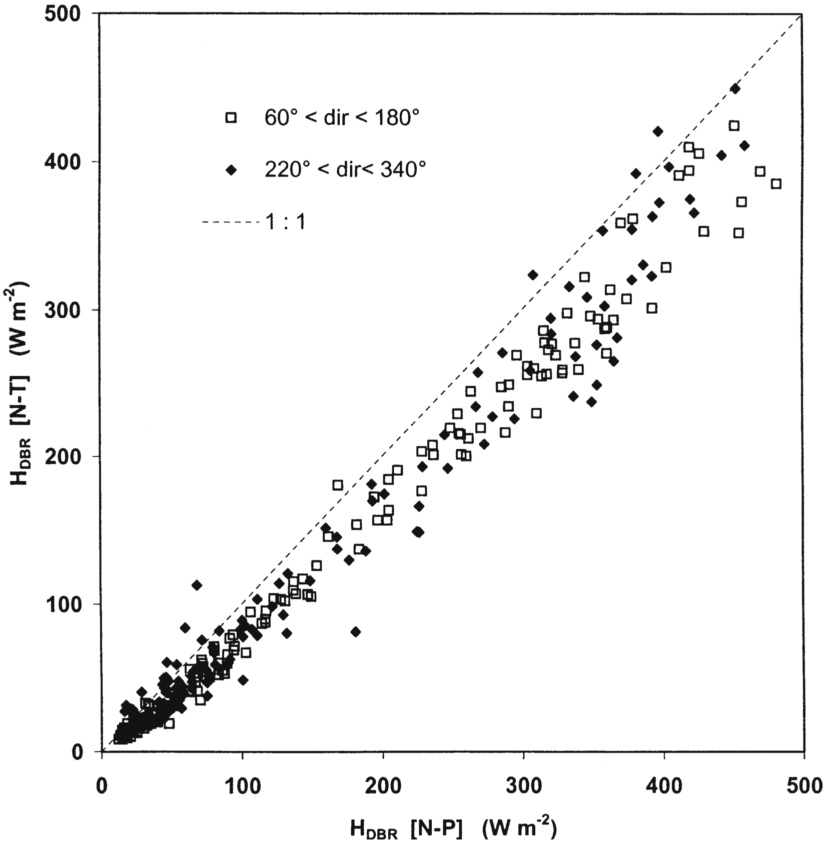

Figure 12. Same as Figure 11 for NP and NT paths (DoY 185–190).

- Two parameterizations from De Bruin and Andreas were tested. They provide similar sensible heat fluxes at night, slightly larger than eddy covariance retrieved ones (by about 15 $W\,m^{-2}$). During daytime, they differ by 13%, with 9% overestimation and 4% underestimation respectively. As sensitivity tests have shown that such differences could also be induced by uncertainties in surface aerodynamic parameters, no particular parameterization can be recommended at the present time. The long-term measurements conducted over the city of Toulouse in the framework of the CAPITOUL project in 2004–2005 (Masson et al., 2004) are expected to bring more insight into this problem.
- The height of the reference mast at which wind speed measurements are gathered to derive the friction velocity must be great enough, (i) to be situated above the blending height to minimize the influence of local non-homogeneities, and (ii) to minimize the sensitivity to errors in the surface roughness length and displacement height.
- It has been shown that the determination of the displacement height, and its variability right along the optical path, is crucial. This empha-

sizes the value of work to derive surface parameters from urban morphology and 3D databases.

- The storage heat flux appears through the Bowen ratio as a corrective term in the expression of the structure parameter for temperature. In the case of urban canopies, G has large values and a phase lag due to the large thermal inertia of the urban fabric, which complicates its determination. Moreover it is often difficult to discriminate from the residual of the non-closure of the energy balance. Sensitivity tests performed on the dataset revealed that a $\pm 50\%$ error in G had no effect on the scintillometer-derived sensible heat flux. This is explained by the dry summer conditions of Marseille, which give large Bowen ratios (see Equation (2)). In more humid conditions this relative insensitivity might not be true.

An important limitation of the 2001 Marseille study is its short duration (three summer weeks), which did not allow investigation of an especially wide range of atmospheric conditions. In particular stable atmospheric conditions were rarely encountered. For these conditions, two difficulties arise: first there is no agreement on the functions $f(Z/L_o)$ relating the structure parameter for temperature C_T^2 and the temperature scale T_* (De Bruin et al., 1995), and scintillometers cannot 'see' the sign of the flux. This means that in order to discriminate the sign of the flux atmospheric stability or instability must be known. In order to retain simplicity for operational use we suggest defining criteria such as the sign of the difference between the air temperature close to the ground (for instance, provided by a ground network) and at a greater height (for instance, measured at a reference mast). The consistency of such a criterion should be tested in a retrospective analysis using available measurements performed in previous experiments over various cities.

Simultaneous scintillometer measurements are a good means to characterize the spatial variability of turbulent fluxes over urban areas provided sources of error, such as differences in surface parameters, are controlled. Comparisons of fluxes along different paths show differences in relation to wind direction. In addition to long-term campaigns to collect data for a representative set of wind directions, a footprint model is necessary to map the areas contributing to the fluxes (e.g. Meijninger et al., 2002; Irvine et al., 2002a) and to assess their spatial variability completely.

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