Atmos. Meas. Tech. Discuss., 2, 1383–1417, 2009
www.atmos-meas-tech-discuss.net/2/1383/2009/

Atmospheric Measurement Techniques Discussions

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Uncertainty analysis of computational methods for deriving sensible heat flux values from scintillometer measurements

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Received: 8 April 2009 – Accepted: 27 May 2009 – Published: 5 June 2009

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The use of scintillometers to determine sensible heat fluxes is now common in studies of land-atmosphere interactions. The main interest in these instruments is due to their ability to quantify energy distributions at the landscape scale, as they can calculate sensible heat flux values over long distances, in contrast to Eddy Correlation systems. However, scintillometer data do not provide a direct measure of sensible heat flux, but require additional data, such as the Bowen ratio (β), to provide flux values. The Bowen ratio can either be measured using Eddy Correlation systems or derived from the energy balance closure. In this work, specific requirements for estimating energy fluxes using a scintillometer were analyzed, as well as the accuracy of two flux calculation methods. We first focused on the classical method (used in standard software). We analysed the impact of the Bowen ratio according to both time averaging and ratio values; for instance, an averaged Bowen ratio (β) of less than 1 proved to be a significant source of measurement uncertainty. An alternative method, called the "β–closure method", for which the Bowen ratio measurement is not necessary, was also tested. In this case, it was observed that even for low β values, flux uncertainties were reduced and scintillometer data were well correlated with the Eddy Correlation results.

1 Introduction

In order to better understand biosphere-atmosphere interactions, scientists require improved tools to accurately estimate exchanges of mass and energy at the land-atmosphere interface. Indeed, these fluxes represent the boundary conditions for studies dedicated to both continental surfaces and atmospheric processes. Currently, various techniques for surface flux measurements are used, including both local methods (Dugas et al., 1991; Dabberdt et al., 1993) and path-averaged ones (Meijninger, 2003). Furthermore, the emergence of remote sensing techniques (Bastiaanssen et al., 1998) leads to a need for in-situ flux estimation integrated over the average pixel size of satellite images for complementary information. Scintillometry is a ground-based technique that represents one of the few methods capable of providing information integrated over large areas; it allows for measurement of sensible heat fluxes on length scales ranging from a few hundred meters a few kilometres.

Scintillometers measure the structure parameter of refractive index (C_{n^2}), which characterises turbulence intensity within the atmosphere (Ochs and Wilson, 1993). By using the Monin-Obukhov Similarity Theory (MOST) and complementary parameters (meteorological conditions and site features such as vegetation height), C_{n^2} can be directly related to sensible heat flux. However, these additional parameters increase the sources of flux uncertainty. In a study over a complex sloping terrain, Hartogensis et al. (2003) estimated the respective contributions of each complementary measurement to the final error in the sensible flux. They concluded that the effective height of the scintillometer was most important (64%), followed by the transect length (14%) and the Bowen ratio (8%). The choice of the Monin Obukhov function f_T (see Eq. 5) can also be a large source of error; for instance, the relative difference between the parameterisation of de Bruin et al. (1993) and Andreas (1988) can reach 16% (Meijninger et al., 2004).

The first step in the classical calculation of the sensible heat flux by scintillometry is to convert C_{n^2} to C_{T^2} (the structure parameter of temperature) by introducing a temperature/humidity correlation factor, hereafter referred to as the Bowen ratio, β. The Bowen ratio is defined as the ratio of sensible heat flux (hereafter H) to latent heat flux ($L_v E$), both measured using an Eddy Covariance system (EC). The factor β can be neglected in the case of large β values (Moene, 2003), but has a large impact on the accuracy of C_{T^2}, and therefore on the sensible heat flux estimation in the case of strong humidity conditions (i.e., when $\beta<1$). During a measurement campaign in Turkey, Meijninger and de Bruin (2000) calculated H without any EC parameters and showed that taking $\beta=1$ instead of $\beta=0.3$ leads to a 15% error in H. The sensitivity of H to β values is even more important when $\beta<0.3$, and as H is weak, it is even more difficult to get a better accuracy on H due to measurement uncertainties in β, which can be quite large.

By comparing different EC systems, Twine et al. (2000) found a β standard deviation of 0.18 for a range of β-values varying from 0.1 to 2. Konzelmann et al. (1997) reported β values of 0.4±0.1 during a campaign in Switzerland dedicated to the study of evaporation in the mountains. Eventually, Hartogensis et al. (2003) assumed a 50% error in the Bowen ratio when calculating the respective contributions of each parameter to the flux error.

Green and Ayashi (1998) proposed an alternative method that does not require β as an input parameter. They calculated sensible heat flux (H) assuming a closed energy budget and using an iterative process. This method is called the "β-closure method" (BCM), according to Twine et al. (2000). Hoedjes et al. (2002) used it in Northwestern Mexico and obtained good results over irrigated cropland. With this method, Marx et al. (2008) calculated the sensible heat flux over two different surfaces, as well as the associated uncertainties caused by the inclusion of additional parameters in the computation algorithm. They found flux uncertainties of roughly 7% and 8%, respectively.

The main objective of this work is to compare two different algorithms for computing sensible heat flux and to comment on their robustness. We chose to evaluate the impact of the β value on the accuracy of sensible heat flux computations, and analysed the advantages and drawbacks of each algorithm for the H-flux computation. The results are presented with the related measurement uncertainty so as to show the reliability of each computational method. With these objectives, we used 2007 flux data measured with a scintillometer and an EC system at one of the CESBIO experimental sites. This approach was also used to survey Bowen ratio evolution and to focus on three different periods of the year corresponding to various ranges of β values.

After presenting the flux calculation theory with scintillometry, we describe the two algorithms for flux computation. First, the features of the classical method are discussed; we also pointed out the influence of time-scale computation of the Bowen ratio on flux estimation. Then, the "β-closure method" is presented, along with a detailed analysis of its robustness. Finally, values of sensible heat flux calculated by both methods and by EC stations are compared. Optimum conditions for the use of each method are determined, as are the relative errors associated with the scintillometry measurements.

2 Theory

2.1 Theory of wave propagation for scintillometers

Time variation of the refractive index (n) of air characterises turbulent air motions within the atmosphere, and is known to be closely related to temperature and humidity fluctuations. To describe the turbulent fluctuations of the atmosphere, we can use the structure parameter of refractive index, C_{n^2} which is defined as

$$C_{n^2} = \frac{\overline{[n(x+r)-n(x)]}^2}{r^{\frac{2}{3}}}, \tag{1}$$

where x is the measurement position of the air refractive index n and r is the distance between two measurement points.

A scintillometer is composed of a transmitter that emits a light beam and a receiver. The receiver measures fluctuations (or scintillations) in the beam intensity along its path through the atmosphere. The relationship between C_{n^2} and the propagation statistics of the electromagnetic radiation ($\sigma^2_{\ln I}$) is given by Eq. (2) (Wang et al., 1978).

$$C_{n^2} = 1.12\sigma^2_{\ln I} D^{\frac{7}{3}} L^{-3} \tag{2}$$

In the above equation, L is the optical path length (or transect); D is the diameter of the beam and $\sigma^2_{\ln I}$ is the variance of the natural-log of intensity fluctuations. C_{n^2} is the output variable of the scintillometer, as Eq. (2) is processed by the instrument electronics. Over the entire electromagnetic spectrum, from visible to microwave wavelengths, values of C_{n^2} depend only upon absolute temperature (T), absolute humidity (Q) and atmospheric pressure (P). Usually, the influence of pressure is neglected and C_{n^2} is expressed as a function of the structure parameter of temperature and humidity, (C_{T^2}) and (C_{Q^2}), respectively (Hill et al., 1980),

$$C_{n^2} = \frac{A_T^2}{\overline{T}^2} C_{T^2} \frac{A_Q^2}{\overline{Q}^2} C_{Q^2} + 2 \frac{A_T A_Q}{\overline{TQ}} C_{TQ} \quad (3)$$

The variables A_T and A_Q depend on the wavelength of the light beam, the absolute temperature and the humidity, according to Andreas (1989).

2.2 Sensible heat flux derived from an optical scintillometer

An optical scintillometer is more sensitive to variations of temperature than humidity, since the light emitted by the transmitter is in the near infrared. Assuming a temperature/humidity cross-correlation equal to unity ($|R_{Tq}| \approx 1$), Eq. (3) can be simplified to expres the structure parameter of refractive index as a function of C_{T^2} and β (Wesely, 1976):

$$C_{n^2} \approx \left(\frac{-0.78 \times 10^{-6} \times P}{T^2} \right)^2 C_{T^2} \left(1 + \frac{0.03}{\beta} \right)^2 \quad (4)$$

with T, the absolute temperature (K), and P, the atmospheric pressure (Pa). In this case, the sensible heat flux (H) can be derived from the structure parameter of temperature (C_{T^2}) according to the Monin-Obukhov Similarity Theory (Hill, 1989), with a universal function (f_T) that depends on the atmospheric stability (z/L_{MO}).

$$C_{T^2} = T_*^2 z^{-2/3} f_T(z/L_{MO}) \quad (5)$$

where, L_{MO} is the Obukhov length and T_*, the temperature scale. As the function f_T is parameterised from experimental data, many additional empirical expressions have been proposed (Wyngaard et al., 1971; Hill et al., 1992). For this study, we opted for the parameterisation proposed by Andreas (1988).

For unstable conditions (i.e., $L_{MO}<0$)

$$\frac{C_{T^2}(z_{\text{LAS}}-d)^{\frac{2}{3}}}{T_*^2} = 4.9\left(1-6.1\frac{z_{\text{LAS}}-d}{L_{MO}}\right)^{-\frac{2}{3}} \tag{6}$$

and for stable conditions (i.e., $L_{MO}>0$)

$$\frac{C_{T^2}(z_{\text{LAS}}-d)^{\frac{2}{3}}}{T_*^2} = 4.9\left(1+2.2\left(\frac{z_{\text{LAS}}-d}{L_{MO}}\right)^{\frac{2}{3}}\right) \tag{7}$$

where z_{LAS} the height of the scintillometer and d is the displacement height. Both the displacement height and the roughness length (z_0) are directly obtained by a measurement of the vegetation height, h_{veg}. These terms are roughly equal to 0.6 h_{veg} and 0.1 h_{veg}, respectively. The Obukhov length L_{MO} is expressed by

$$L_{MO} = \frac{u_*^2 T}{g k_v T_*} \tag{8}$$

where u_* is the friction velocity, which is estimated using the stability function $\psi_m(z/L_{MO})$ given by Panofsky and Dutton (1984) :

$$u_* = \frac{k_v u}{\ln\left(\frac{z_u-d}{z_0}\right) - \psi_m\left(\frac{z_u-d}{L_{MO}}\right) + \psi_m\left(\frac{z_0}{L_{MO}}\right)} \tag{9}$$

k_v is the Von Karman constant, z_0 is the roughness length and u is the wind speed at the measurement height.

Asanuma et al. (2007) investigated the calculation of sensible heat flux from homogeneous to heterogeneous surfaces using values of u_* provided by the EC system, and concluded that the sensitivity of H to u_* depends primarily on the stability index (z/L_{MO}) and on the differences between the scintillometer and EC system footprints.

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As the error can be large, iterations on L_{MO} and u_*, using the Eqs. (8) and (9), are advised for calculating H. Eventually, H can be derived from the parameters

$$H = -\rho c_p T_* u_* \tag{10}$$

where c_p is the specific heat of air at constant pressure, and ρ is the density of air.

In this paper, we used two different computation methods, but steps Eq. (4) through Eq. (10) were performed identically in both methods. The primary difference between methods was in the determination of the Bowen ratio (β). The first algorithm, referred to here as the "classical method", was derived from the WINLAS v.1 software package, provided by Kipp&Zonen, and was an iterative procedure combining Eqs. (5), (7) and (8). C_{T^2} was then calculated prior to iteration based on a β value obtained either by simulation or direct measurements. Thus, C_{T^2} value and its accuracy were dependent only on β. The second algorithm, here referred to as the "β-closure" method (BCM) was first used by Green and Ayashi (1998), and a brief description can be found in Meijninger et al. (2002a). In this method, H is calculated by closing the energy budget (Eq. 11):

$$R_N - G - S - \varepsilon = L_v E + H \tag{11}$$

where R_N is net radiation, G is the soil heat storage, $L_v E$ is the latent heat flux and S is the gathering of heat flux storages in the canopy, and under the mast. ε is the energy used for photosynthesis, and is usually small enough that it can be neglected (Lamaud et al., 2001). In this method, we assume that the Bowen ratio has been correctly measured, and that the energy budget can be balanced by redistributing the closure error across both fluxes. Using this assumption, β can be expressed as

$$\beta = \frac{H}{R_N - G - S - H} \quad . \tag{12}$$

The iterative procedure described in the "classical method" is also applied, but C_{T^2} is computed using the latter expression for β. However, because β depends on H as shown in Eq. (11), an extra iterative step is required. The principle advantage of the β-closure method is that no turbulent flux measurements are necessary. Only the net radiation (R_N) and the soil heat flux (G) are required. In most cases, the impact of S is also negligible and can thus be neglected.

A detailed description of each computational process, with the associated uncertainty analysis, is provided below.

3 Experimental

This study was conducted in Lamasquère, France (43°29′36″ N; 1°14′14″ E; altitude 180 m), 40 km west of the city of Toulouse. The work was part of the "Sud-Ouest" project, coordinated by CESBIO (http://www.cesbio.ups-tlse.fr/fr/sud_ouest.html), which is dedicated to understanding the effects of climate on regional ecosystems. The project's objectives are to diagnose the ecosystem's behaviour through the use of monitoring instruments and accurate modelling, and to simulate possible ecosystem evolution scenarios according to various land use patterns.

The site observed in this study was a flat, homogeneous field upon which wheat was grown during the year 2007 (cf. Fig. 1). A Large Aperture Scintillometer (LAS) that was designed and built at CESBIO by the GRITE team (Groupement de Recherche en Instrumentation et Techniques Environnementales) was installed in this field. Its aperture size (D) is 0.203 m and the wavelength of the light beam emitted by the transmitter is 940 nm. An optical band pass filter at approximately 940 nm is added to cut off all visible wavelengths. This scintillometer was positioned on a stable 3 m-high concrete tower built to avoid instrument oscillations due to strong wind. The path length between the transmitter and the receiver was approximately 567 m. The output signal, expressed as a voltage, was recorded by a low-power consumption computer at 1 kHz, and was filtered for absorption phenomena at 0.1 Hz (Meijninger et al., 2002b). C_{n^2} was calculated according to Eq. (2). A brief, preliminary comparison of the CESBIO-built instrument to another LAS (METAIR group from Wageningen University and Research

Center) was performed and provided a good correlation between the results of the two instruments.

During the intercomparison, the heights of both scintillometers were different, z_{LAS}=6 m for the METAIR LAS and z_{LAS}=3 m for the CESBIO LAS, but this height difference was accounted for in calculation of the sensible heat flux (H). Data from both scintillometers were found to be linearly related: $H_{GRITE}=1.28\times H_{LAS}$ (R^2=0.981). The coefficient (1.28) was found to be consistent across a number of measurements, and was attributed to the greater sensitivity of the GRITE scintillometer to the focus of the detector and the effective diameter of the light beam (a misalignment of the instruments can reduce the effective diameter of the beam observed at the receiver). This phenomenon has been previously reported in other comparisons of multiple scintillometers, with relative differences ranged from 5% (Meijninger et al., 2002a) to 21% (Kleissl et al., 2008). Since our scintillometer was in the development stage when this work was conducted, a calibration campaign was conducted prior to each measurement period, to avoid flux overestimation due to misalignment. In addition, a threshold was imposed on the signal amplitude so as to avoid dew effects on scintillometer measurements.

An eddy correlation system was installed at mid-transect of the scintillometer light beam at a 3.65 m height. The EC system was equipped with a CSAT3 sonic anemometer (Campbell Scientific Ltd.) to measure wind speed fluctuations in three dimensions, as well as sonic temperature, and an IR gas analyzer Licor 7500 (Campbell Scientific Ltd.) was used to measure H_2O and CO_2 concentrations. Typical meteorological sensors were also added to the EC mast to provide mean values for atmospheric pressure, air temperature and relative humidity. The net radiation (R_N) was measured using a CNR1 (Campbell Scientific). Soil heat flux (G) was measured at a depth of 5 cm using three heat flux plates (hpf01, Hukseflux), and was corrected to consider the storage between the surface and the heat flux plate. All fluxes were averaged over 30-min periods, which provided a good trade-off between eddy sampling and the stationary assumption. Some corrections were applied to the EC system flux estimates, accord-

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ing to the recommendations of the CarboEurope experimental program (Beziat et al., 2009). Thus, wind speed measurements were corrected for double rotation, as advised for crop and grasslands sites. Corrections also accounted for the time lag between the sonic anemometer and the analyser data logger, and high frequency spectral losses, as well as humidity effects, addressed via the Webb correction (1980).

In order to ascertain whether C_{T^2} behaviour followed the MOST, observed values of $C_{T^2}(z_{\mathrm{LAS}}-d)^{2/3}/T_*^2$ were plotted against observed values of $(z_{\mathrm{LAS}}-d)/L_{MO}$ on Fig. 2 for the entire dataset. The Monin Obukhov similarity function proposed by Hill (1992) and de Bruin (1993) were also plotted on the figure, and fit well with previous results, although a slight underestimation was observed. Values of T_* and L_{MO} were taken from the EC station (Hoedjes et al., 2007), while values of $C_{T^2}(z_{\mathrm{LAS}}-d)^{2/3}/T_*^2$ that diverged from Monin-Obukhov theoretical behaviour were rejected. Rejection criteria had a significant influence on results as they resulted in the exclusion of approximately 20% of the data.

3.1 Seasonal evolution of the Bowen ratio

Using Eq. (4), the Bowen ratio (β) is required to compute sensible heat flux from scintillometer measurements. In this case, β is provided through the EC measurements. In order to improve the significance of the scintillometer measurements, which rely on β and to limit artefacts due to EC measurements, severe criteria were used to eliminate non-relevant β values. Specifically, large uncertainties in the Bowen ratio are known to arise from variations in the turbulent fluxes measured by EC systems (mainly due to variations in latent heat flux L_vE). According to Billesbach et al. (2001), the accuracy thresholds for standard EC stations are typically 7 W/m^2 for the sensible heat flux and 15 W/m^2 for the latent heat flux. Therefore, turbulent flux values below these thresholds were systematically rejected. Data were also rejected from night time or thermally stable measurement periods, when LAS data might be affected by the accumulation of dew or water vapour.

Figure 3 shows mean daily β values derived from EC data for the period from 1 January 2007 to 1 October 2007. Since the Bowen ratio is closely related to vegetation transpiration capacity, and therefore to vegetation phenology, Leaf Area Index (LAI: leaf surface area per unit of soil surface area), representing the relative surface area of transpiring leaves, was also plotted. Three specific sub-periods were identified over the study period that appeared to correspond to different vegetation life stages (see Fig. 3).

The first period studied was at the end of April (DoY 109 to 114), corresponding to the maximum measured LAI, which was approximately 3.5, and varied rapidly. The Bowen ratio was low for this period ($\beta \approx 0.1$), due to high transpiration rates from the vegetation (h_{veg}=>0.6 m). The second period occurred in mid-June (DoY 163 to 169), when vegetation became senescent; green LAI was close to 0 (as was the transpiration rate), but vegetation height reached its maximum ($h_{veg}=0.9$ m) and the Bowen ratio reached the value $\beta=1$. The third period occurred at the beginning of September (DoY 248 to 254). Crops were harvested at this time, and the field was nearly completely covered by crop residue (resulting in low vegetation height: $h_{veg} \approx 0.15$ m). Sensible heat flux predominated during this period, resulting in a high Bowen ratio ($\beta \approx 2.8$).

3.2 Comparison of the "classical" and "β-closure" methods

In this section, the two methods for computing the sensible heat flux are described. The various input and output parameters of both methods are summarised in Table 1.

3.2.1 Classical method

Flux computation using the classical iterative method (WINLAS v.1 software) is described in Fig. 4. A first guess of the Obukhov length is required to initialise the calculation algorithm. The structure parameter of temperature (C_{T^2}) is first calculated using the meteorological data and the Bowen ratio. This coefficient allows the calculation of the temperature scale of the Monin-Obukhov similarity theory (MOST) T_* and the friction velocity u_* with this first value of L_{MO}. This latter term is then recalculated using the new values of T_* and u_*. When the algorithm for L_{MO} has converged, T_* and u_* are calculated again, and H can then be deduced using Eq. (9).

In the classical method, β is an input parameter estimated by independent measurements of H and L_vE (using EC or gradient flux systems). Thus, uncertainties in β are due to errors in the flux values measured by EC. Random errors in H and L_vE flux (due to the method of eddy correlation) have been estimated using a 5-year dataset of EC measurements. The method used was reported by Hollinger and Richardson (2005), who developed a methodology using daily differenced measurements with equivalent environmental conditions. Random errors in the flux calculated using our EC station data were σ_{L_vE}=0.134L_VE+5.8, R^2=86.5% and σ_H=0.117H+6.8, R^2=76.4%. Finally, the random error law for the Bowen ratio can be estimated for the same dataset, according to Gaussian error propagation: σ_β=0.301β+0.02.

3.2.2 β-closure method

Figure 5 describes the iterative procedure of the BCM. In this case, initial assumptions are needed for the Bowen ratio β and the Obukhov length L_{MO}. First, C_{T^2} is calculated using a first guess for β, and T_* and u_* are derived from a first guess for L_{MO}. Subsequently, L_{MO} is re-estimated and H is computed using T_* and u_*, whereas β is deduced from the energy balance closure (Eq. 12). When calculated L_{MO} values converge, T_* and u_* are computed to estimate the final value of the sensible heat flux.

The iterative procedure is similar to the one used in the classical method, except that β is derived from the energy balance closure, instead of being derived from the turbulent heat flux measurements (H and L_vE). As the Bowen ratio is determined iteratively, and not by measurement, its associated error (standard deviation) is nil. When attempting to determine H uncertainty, uncertainties on R_N, G and S will be added to Eq. (14), as they intervene in the energy balance closure.

In order to evaluate the energy balance closure and its impact on the method, a parameter was introduced to characterise the percentage of closure. This parameter was calculated according to EC data, and was designated the energy balance fraction (or Energy Balance Ratio when averaged over a long period of time, Gu et al., 1999):

$$\gamma = \frac{H + L_v E}{R_N - G - S} \tag{13}$$

This ratio can be represented by the available energy, which is the ratio of the difference between net radiation and the sum of soil heat flux and heat storage ($R_N - G - S$), all divided by the turbulent fluxes ($H + L_v E$). For the three periods considered, the energy balance fraction was equal to 81%, which is quite typical for this type of surface (Fig. 6).

3.2.3 Uncertainty calculation

As measurement uncertainties (random and systematic errors) may affect the final estimation of the flux, it is worth comparing both methods in terms of H uncertainty. Here, to determine the uncertainty of H, a standard deviation (σ_H) was calculated for both methods, according to formula for Gaussian Error Propagation (Marx et al., 2008):

$$\sigma_H^2 = \sum \left(\frac{\partial H}{\partial \text{Input}_i} \right)^2 \sigma^2_{\text{Input}_i} + \left(\frac{H_{hi} - H_{db}}{2} \right)^2 \tag{14}$$

where σ is the standard deviation and Input_i corresponds to the input variables of Table 1 (for the case of WinLas). The second term corresponds to the uncertainty in the MOST function, with H_{hi} and H_{db} corresponding to the different MOST functions reported by Hill et al. (1992) and de Bruin et al. (1993), respectively. Marx et al. (2008) provides measurement uncertainties for the parameters in Table 1: C_{n^2} (0.5%), T (0.1 K), u (0.5%), P (100 Pa), z_0 (10%), z_{LAS} (0.5 m), z_{EC} (0.1 m). The net radiation uncertainty was close to 6%, whereas the error in soil heat conduction measurements (G) was between 15% and 20% (Twine et al., 2000, Halldin and Lindroth, 1992).

Prior to investigating the influence of the Bowen ratio on H estimation, a preliminary uncertainty analysis was performed, e.g. if sensible heat flux values are calculated via the classical method, the uncertainties ε in the flux estimates for each period (which correspond to the average value of σ_H/H over that period) are ε=11.3% in April (LAI maximum), ε=11.4% in June (senescence) and ε=12.1% in September (bare soil). The difference between these results and the relative uncertainties of 7 to 8% found by Marx et al. (2008) can be explained by the height of the scintillometer, which was relatively close to the surface. Uncertainties could be reduced by an estimated 3% if the instrument height were doubled. In September, uncertainties associated with z_{EC} and z_0 tend to increase the uncertainty in H, as these latter parameters become quite small. Specifically, they depend on vegetation height (d), which is itself rather low during that period (h_{veg}=0.15 m): d=0.09 m and z_0=0.015 m.

4 Results and discussion

For the three considered periods of 2007, the Bowen ratio β varied between values of 0.02 to 4.86 (Fig. 3). As β can have very low values, it is important to quantify its influence on the flux estimates, both in terms of its effects on the uncertainty of H estimates, and to optimise the timescale over which β values are averaged (ranging from 30 min to seasonal periods). When a high degree of precision is required for H flux values and little information is available regarding the Bowen ratio, the "β-closure method" (BCM) is quite attractive, as no direct measurements of β are required. Indeed, it can be very useful for longterm experiments in which measurements of β are not accurate, due to a minimum instrumental setup at the field site. To quantify the impact of β on flux calculations, the robustness of the classical and BCM methods was investigated during the year 2007.

4.1 Sensible heat flux calculated via the classical method, influence of timescale averaging on the Bowen ratio

The effects of the timescale of the Bowen ratio computation on calculated sensible heat flux were studied. Comparisons were made using weekly or 30 min β-average values.

4.1.1 Use of a weekly averaged Bowen ratio

For the three selected periods, averaged β values were calculated over 5 to 7 days. β values of 0.12 were obtained for April (6 days), β=1.01 for June (7 days) and β=2.8 for September (7 days). H was then calculated via the classical method using these β values. Results are displayed for each period (April, June, September 2007) in Fig. 7, comparing scintillometer data versus EC fluxes. It appears that both datasets are well correlated in June (H_{LAS}=0.98H_{EC}, R^2=95%) and in September (H_{LAS}=1.02H_{EC}, R^2=91%), but they show some discrepancies in April (forcing to zero origin is not possible: H_{LAS}=0.49H_{EC}+23.6 R^2=68%). Time variability of the Bowen ratio in April is responsible for this scatter. Indeed, β values are extremely small in April, so that a slight variation in β causes a strong variation in H.

Uncertainties related to the flux computation were also quantified. For the classical method that uses β weekly averages, the flux errors were calculated using the Gaussian error propagation method (see Eq. 13). The uncertainty in β was given by σ_β=0.301β+0.02, and the uncertainties proposed by Marx et al. (2008) were used for the other parameters. The following uncertainties were obtained for the different periods: 14.8% error in H for April, 11.6% in June, and 12.1% in September.

4.1.2 Improvements due to the use of 30-min averaged Bowen ratios

Results from the April period were further investigated to determine what timescale is optimal for the calculation of H under low Bowen ratio conditions. Despite the fact that β variations are smaller in April than for the two other periods, small values of β during this period have a much larger impact on H.

In order to evaluate the impact of β on the fluxes, the sensible heat fluxes measured with the EC system were compared with those estimated via the classical method. First, fluxes were calculated with a constant β value of 0.12, then using a 30-min average value of β. The results presented in Fig. 7a show that using a 30-min β to compute the sensible heat flux improves the correlation significantly (H_{LAS}=1.02H_{EC}

R^2=74% vs. H_{LAS}=0.49H_{EC}+23.6 R^2=68%). Improvements can also be observed for the lowest and highest values of H, resulting in a better magnitude variability. The relative difference in these improvements can reach 36%, resulting in an absolute flux difference that does not exceed ΔH=15 W/m^2. The improvement of the correlation between the sensible heat fluxes was attributed to a stronger dependence of H_{LAS} on H_{EC} when β is estimated every 30 min using EC measurements. However, the correlation was not improved in June or September, when the same procedure was applied to the flux computation (see Fig. 7b and c). The results for these periods are not very sensitive to the choice of the β-averaging period because β is large enough, except for a few β values at the beginning of the day (mainly in June).

As was done previously, uncertainties in the sensible heat flux measurement (H) were calculated according to the Gaussian error propagation method. For this calculation, 30-min measurements of the Bowen ratio were used, which would tend to increase its impact on the flux uncertainty. For the different periods, a 17.3% error in H was obtained in April, 11.7% in June, and 12.1% in September. The uncertainties in H increased as the value of the Bowen ratio decreased. It must be noted that uncertainty in β only considers random errors. If the value σ_β=0.18 given by Twine et al. (2000) is used, which combines systematic and random errors, the predicted uncertainty in H is much higher (48% in April, 12.6% in June and 12.2% in September).

To sum up the results obtained with the classical method, it can be concluded that, for low Bowen ratio conditions, the sensible heat flux derived from scintillometer H_{LAS} is very dependent on the time scale of β averaging. When using an averaging period for β equal to the flux measurement time-step, an increase in the correlation between H_{LAS} and H_{EC} was observed. However, this was not a spurious effect due to a stronger dependency of H_{LAS} on H_{EC} via the Bowen ratio. Besides, sensible heat fluxes derived from scintillometer measurements suffer from high measurements uncertainties that range from 17% to 48% of the flux values. For high Bowen ratio conditions, it may be preferable to use a β value averaged over a 1-week period, as this period leads to smaller errors with the same degree of correlation between H_{LAS} and H_{EC}.

4.2 Sensible heat flux values calculated via the "β-closure method" (BCM), balance fraction and Bowen ratio influence

The requirement of β values calculated every 30 min to minimise measurement uncertainties could limit the use of scintillometry in wet conditions when the Bowen ratio is small. For instance, such conditions were encountered over the Amazonian forest by Da Rocha et al. (2003), who estimated a mean annual Bowen ratio β of 0.17, or by Sadhuram et al. (2001), who found that β can be even smaller than 0.1 during monsoon periods or over open ocean waters. In our experimental site, 38% of the days in 2007 corresponded to a Bowen ratio smaller than 0.4. Using an alternative computation method that does not include a measurement of β could thus extend the field of application of scintillometry. To this end, the accuracy and robustness of the "β−closure method" (BCM) were examined.

Hoedjes et al. (2002) applied this method to derive fluxes using scintillometry over an irrigated area in Mexico. Their measurements showed good correlations with EC results, and displayed a tendency to overestimate the sensible heat flux in dry conditions. In the current study, the sensible heat flux was calculated similarly for the three selected periods. The influence of the two main parameters, the energy balance fraction (γ), and the Bowen ratio, was also analysed. The results for the three periods are presented in Table 2. In April, β is very small (0.12) and the energy budget is poorly closed (γ=78.5%). In June, the energy balance fraction is still small (γ=79.7%) but the Bowen ratio increases ($\beta \approx 1$). In September, the energy balance is almost closed (γ=98.7%), and β is high. It was not possible to quantify the influence of β and γ separately, as both are dependent. Moreover, the smaller β, the less the degree of energy budget closure obtained. This trend can be explained by the lack of accuracy of $L_v E$ values obtained by EC measurements, which generally underestimate this variable (Nie et al., 1992; Brotzge, 2001).

In a preliminary analysis, it can be observed that the "β−closure method" tended to give the same results as the classical method, especially during the June and September periods (Fig. 8). However, γ and β seemed to affect the results of the "β-closure" method, as H was under-estimated when β decreased. Figure 8 shows the correlation between the classical method with a 30-min averaged β, and the BCM for the three periods: a) April, b) June and c) September. It is evident that the decrease in β was followed by an underestimation of H by 6% in April, 3% in June and 1% in September. It can be noted that including the storage term (S) in the energy budget modified the final H estimates by less than 1%. Thus, this term can be neglected while using the "β-closure" method without significant error.

In April, although the determination of the sensible heat flux with a scintillometer was more sensitive than during the other selected periods, good results were obtained with reasonable uncertainties (Fig. 8). For instance, if the sensible heat flux from the scintillometer is compared to the sensible heat flux from EC system (which can be considered to be the reference measurement), the correlation between H_{LAS} and H_{EC} was smaller using the BCM than the classical method with 30-min. β values, but still better than the classical method with weekly mean β values. Furthermore, the BCM method was less sensitive to measurement uncertainties under low β conditions, a finding that is very promising for the use of BCM in very wet regions.

According to Gaussian Error Propagation calculations, and with assumed uncertainties of 6% for R_N and 20% for $(G+S)$, averaged uncertainties for the different periods were reduced to 18.4% in April, 12.8% in June, and 13.1% in September. The contribution of the error in R_N and $(G+S)$ values on the final H uncertainty was approximately 1%.

5 Conclusions

Measurements of the mass and energy exchanges between the surface and the atmosphere at the ecosystem scale are a major topic of many projects involved in land-surface monitoring (e.g., Sud Ouest project). Whereas EC stations provide local measurements, scintillometers are able to estimate the sensible heat flux from measurements of the refractive index structure coefficient, C_{n^2}, integrated over distances up to several kilometres. However, their accuracy relies on the accuracy of the meteorological parameters required for calculating the sensible heat flux. Among these parameters, we focused on the Bowen ratio, β, which is the most sensitive to uncertainty in meteorological measurements, since it relies on the measurement of the turbulent fluxes H and $L_v E$ by standard EC systems. With the objective of installing scintillometers as autonomous devices, there is a strong incentive to further investigate the dependence of the heat fluxes measured by these devices upon input values for β. Therefore, two different computation methods of the sensible heat flux were tested to evaluate the requirements for installing scintillometers in tandem with additional measurement devices in order to achieve a desired degree of accuracy.

The influence of a measured Bowen ratio on flux calculations was first studied via a classical method (WINLAS software) for three different periods of vegetation growth (April, June and September 2007). The influence of Bowen ratio time-averaging was quantified during unstable conditions; the sensible heat flux H was calculated first with a weekly-averaged β, then with a 30 min-averaged value measured using an EC system. In June and September, when $\beta>1$, it was found that estimates of β obtained with longer averaging periods provided better results, as the influence of the time-averaging on the flux was small, while uncertainty was greatly reduced. In April 2007, when the Bowen ratio was smallest (β=0.12), using direct measurements of β at the time-step of flux acquisition improved the correlation between H_{LAS} and H_{EC}. However, this improvement was limited, as it produced an increase in the measurement uncertainty (between 17 and 48%).

The "β−closure method" is a useful alternative when information about the Bowen ratio is unavailable. In this case, the computational algorithm only requires net radiation and soil conductivity measurements to determine the Bowen ratio, assuming that the energy balance is closed. With this method, the results are rather satisfying even in April, considering the small under-estimation of H (<6%) even when the Bowen ratio was small. Furthermore, the uncertainty in H was limited to 18.5% in April, and

13% in June and September. These findings suggest that at low Bowen ratios, fluxes can be estimated with accuracy and with less uncertainty using the BCM than with classical methods. In addition, the BCM requires less instrumentation for turbulent measurements.

When using a scintillometer as an autonomous device, it is advisable to employ the Classical method with an approximated β (e.g. calculated from vegetation height or from numerical models) in high β conditions, as the correlation with EC measurements is high, with minor uncertainties. In low β conditions, the "$\beta-$closure method" is preferable, as one can reduce the uncertainties in flux estimates caused by the lack of accuracy in the estimation of β, and by the systematic and random errors in measurements. An interesting perspective might be to test this calculation method under very wet conditions (such as measurement campaigns over lakes or open ocean), in which EC station installation is difficult.

Acknowledgements. The SudOuest experiment was supported by the Conseil Régional Midi-Pyrénées, the CNES (Centre National d'Etudes Spatiales), and the Ministère de l'Environnement (GICC). It was also partly funded by the CarboEurope-IP program and CNRS/INSU. The authors would like to thank l'Ecole Supérieure d'Agriculture de Purpan and the congregation of Notre Dame de la Motte for welcoming us at the Lamasquère site. We would like to express our gratitude to all of the technical teams (Hervé Gibrin, Bernard Marciel). Finally, we are also very grateful to W. Koshiek for his helpful suggestions on the development of our scintillometer and to A. Moene for his help and comments regarding uncertainty calculations.

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The publication of this article is financed by CNRS-INSU.

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Table 1. Input and output parameters that are required for the classical and "β-closure" methods.

	Input parameters	Output parameters
WinLas (classical method)	$C_{n^2}, T, u, P, z_0, d, z_{\text{LAS},}, z_{\text{EC}}, \beta$	$H, L_{MO,} T_{*,} u_*$
β-closure method (BCM)	$C_{n^2}, T, u, P, z_0, d, z_{\text{LAS}}, z_{\text{EC}}, G, R_N$	$H, L_{MO,} T_{*,} u_{*,}\ \beta$

Table 2. Correlation (R^2) and linear fit between H estimated with the scintillometer according to both methods (the classical one (the 2 first columns) and the BCM) and H measured with EC station.

	β every 30 min	β over the week	BCM	γ	β
April	1.02× (R^2=74%)	0.49×+23.6 (R^2=68%)	0.95× (R^2=57%)	78.5%	0.12
June	0.99× (R^2=95%)	0.98× (R^2=95%)	0.96× (R^2=94%)	79.7%	1.01
September	1.02× (R^2=91%)	1.02× (R^2=91%)	1.01× (R^2=91%)	98.7%	2.8

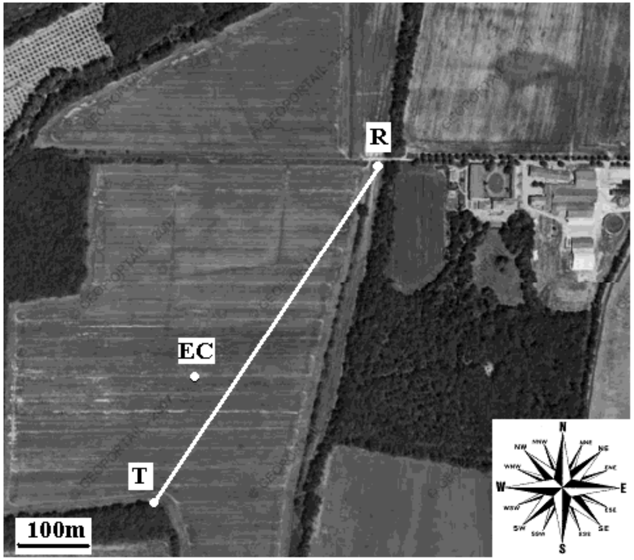

Fig. 1. Study area of Lamasquère. Location of the Eddy Covariance system (EC) with the scintillometer transmitter (T) and receiver (R).

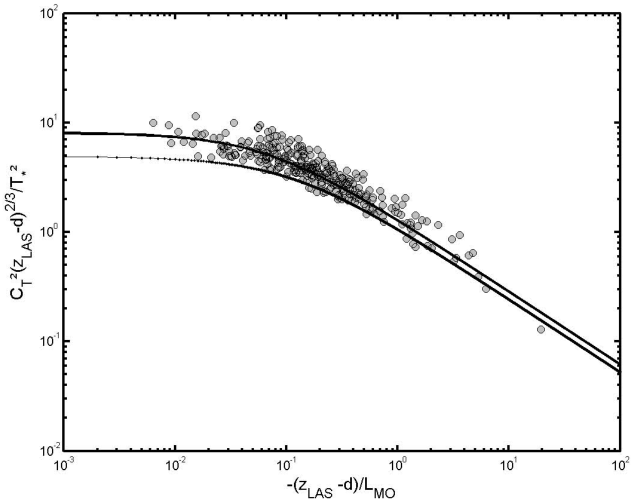

Fig. 2. Observed values of $C_{T^2}(z_{\text{LAS}}-d)^{2/3}/T_*^2$ plotted against observed $(z_{\text{LAS}}-d)/L_{MO}$ during the 3 periods. Data that diverges from MOST behavior are rejected. Solid line represents the scaling of Monin and Obukhov similarity function given by Hill (1992) and dotted line represents the one by de Bruin (1993).

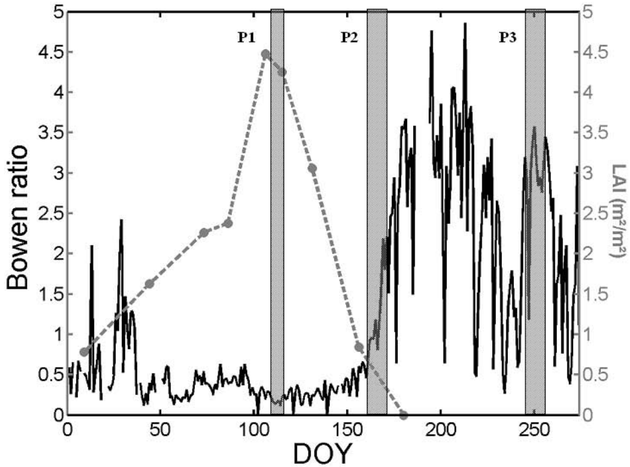

Fig. 3. Leaf Area Index (m^2/m^2) and mean daily values of the Bowen ratio according to the Day of Year (DoY) in 2007. The three periods are represented by grey boxes: P1 corresponds to Avril dataset (DOY 109 to 114), P2 to June one (DOY 163 to 169) and P3 to September one (DOY 248–254).

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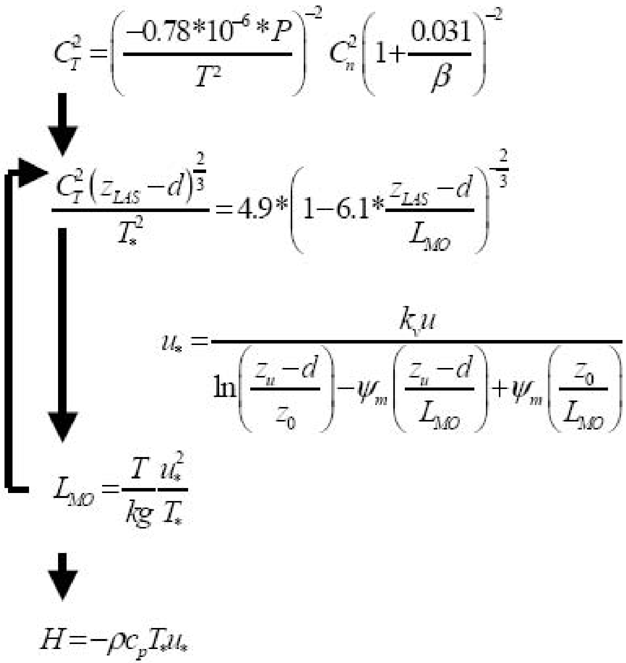

Fig. 4. Schematic description of the classical method process.

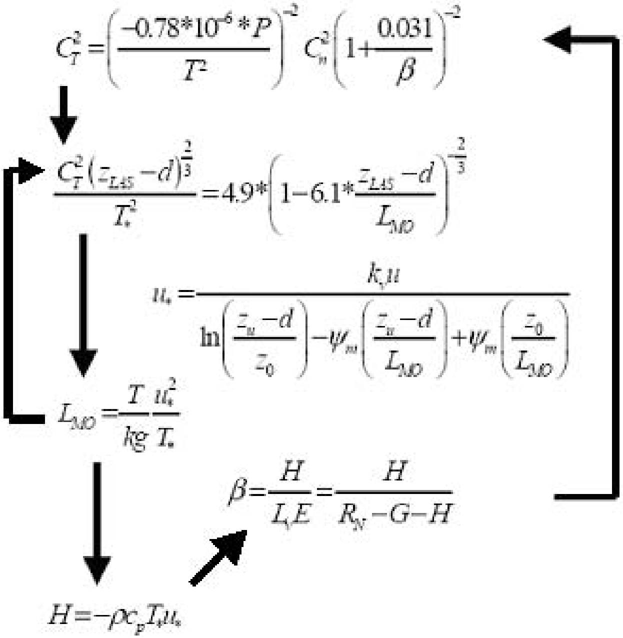

Fig. 5. Schematic description of the "β-closure method" algorithm. Here, the heat storage term, S due to vegetation, is included in the G term.

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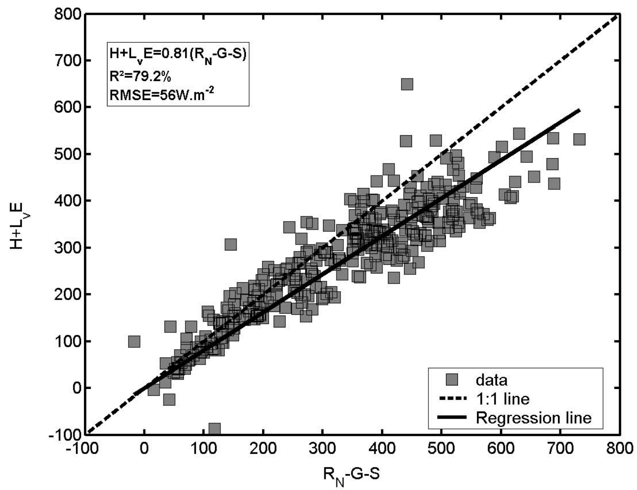

Fig. 6. Turbulent heat fluxes ($H+L_vE$) versus net radiation minus soil heat conduction and heat stockage (R_N-G-S) for the whole dataset. The best linear fit with a zero-origin is: $H+L_vE=0.81\cdot(R_N-G-S)$ with a correlation of $R^2=0.79$.

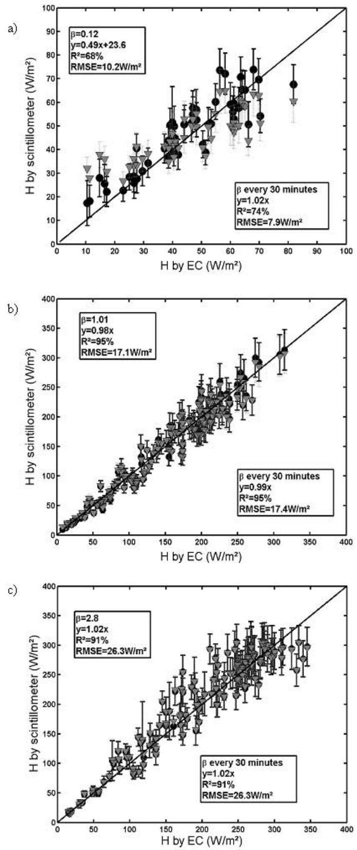

Fig. 7. Comparison between H calculated by Eddy Correlation, and H derived from scintillometer, and calculated with the classical method, during the three periods. Black circles correspond to the use of a β averaged on 30 min, and grey squares to a β averaged over 7 days: **(a)** April results (P1), **(b)** June results (P2) and **(c)** September ones (P3).

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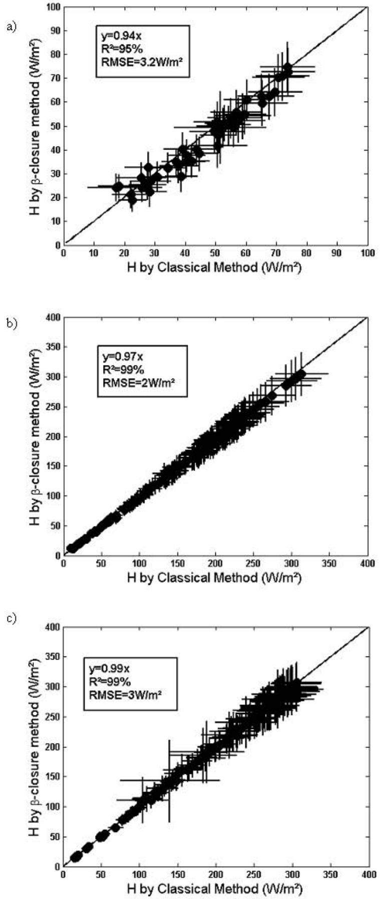

Fig. 8. Comparison of the sensible heat fluxes derived from the scintillometer H_{LAS} with the Beta closure method (BCM) versus the one derived with the classical method with 30 min averaged Bowen ratio: **(a)** April results, **(b)** June results and **(c)** September ones.