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 both in terms of flux estimates and uncertainty. When a high degree of precision is required for H_{LAS} 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 set-up 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

The Bowen ratio is first calculated with 30 min averaged values of H_{EC} and $L_v E_{\mathrm{EC}}$. Then, H_{LAS} is estimated 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 the corresponding 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%). In April, when fluxes are weaker, the correlation remains satisfying (H_{LAS}=1.02$H_{\mathrm{EC}}$$R^2$=74%).

Uncertainties related to the flux computation were also quantified. For the different periods, a 17.3% error in H_{LAS} was obtained in April, 11.7% in June, and 12.1% in September. The uncertainties in H_{LAS} increased as the value of the Bowen ratio decreased. It must be noted that in our case, 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_{LAS} is much higher (48% in April, 12.6% in June and 12.2% in September).

As we noticed formerly, the friction velocity can be either calculated iteratively or measured by the EC system. A comparison has been performed using measurements of the friction velocity (from the EC system) instead of iterative computation for the period P3 as both footprints (of the EC station and scintillometer) are superimposed in this period and β sensitivity of H_{LAS} is negligeable. Then, H_{LAS} fluxes were calculated with the classical method considering a measured friction velocity. Results show large discrepancies while using u_* from EC set-up, whereas u_* calculated by iterations computes H_{LAS} with greater accuracy (Fig. 8).

To sum up the results obtained with the classical method, it can be concluded that, for high Bowen ratio, the sensible heat flux derived from scintillometer H_{LAS} is well correlated with H_{EC} (R^2 >0.9). For low Bowen ratio, this correlation is weaker, due to the strongest sensitivity of C_{T^2} to

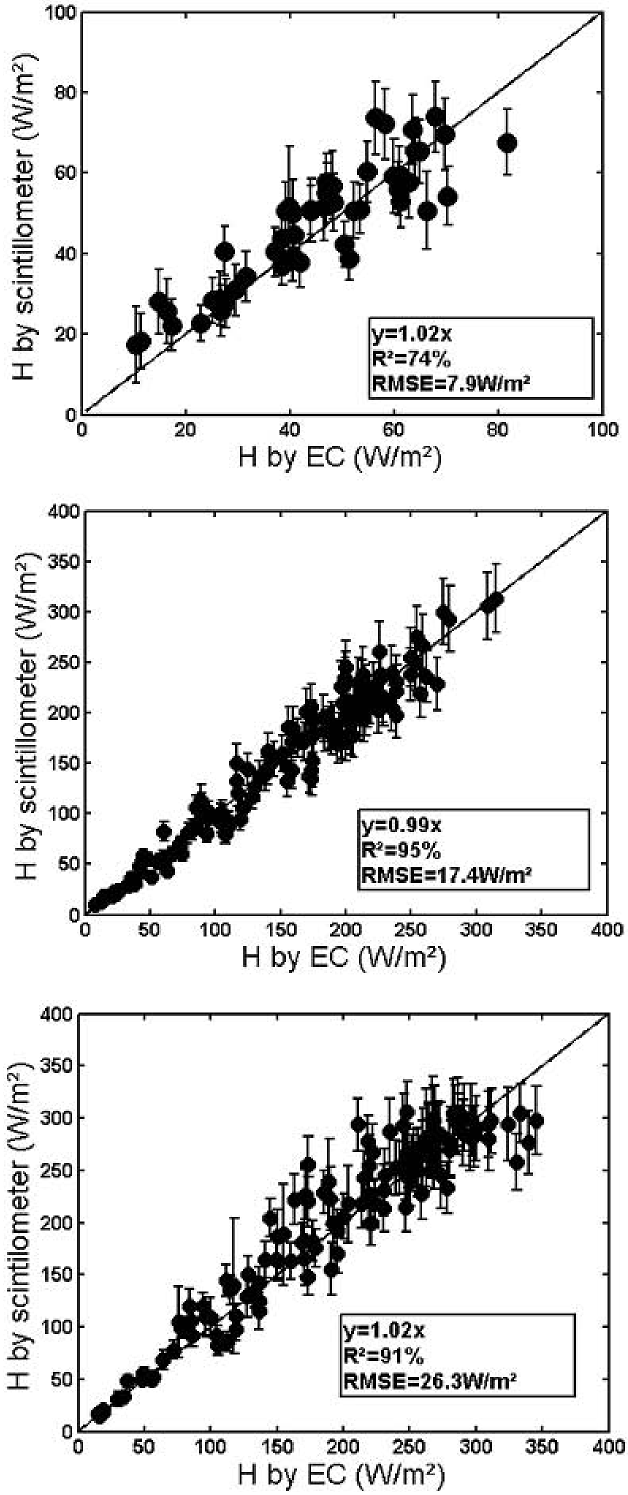

Fig. 7. Comparison between H_{EC} calculated by Eddy Correlation, and H_{LAS} derived from scintillometer, and calculated with the classical method, during the three periods: **(a)** April results (P1), **(b)** June results (P2) and **(c)** September ones (P3).

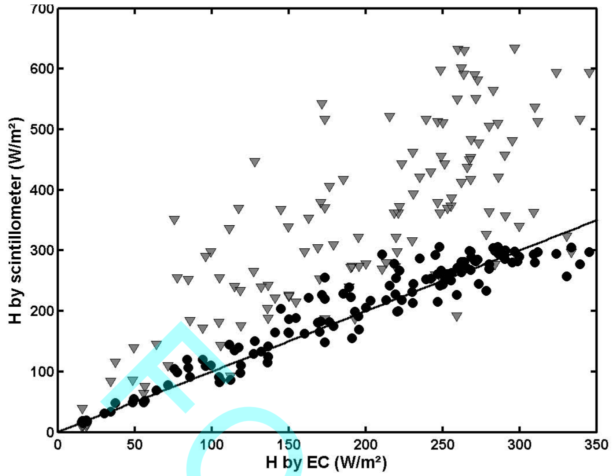

Fig. 8. Comparison between H_{EC} (H by EC) and H_{LAS} (H by scintillometer) calculated by the Classical method (black circles) or by the same method using u_* calculated by EC set-up (grey triangles) during the period P3. Black line stands for the 1:1 correlation.

the correction term in β (Eq. 4) but remains acceptable. Besides, sensible heat fluxes derived from scintillometer measurements suffer from high measurements uncertainties that range from 17% to 48% of the flux values. Moreover, as $\beta = H_{EC}/L_v E_{EC}$, depends on H_{EC} and that H_{LAS} is also compared to H_{EC}, the independence of the results can be discussed. Besides, EC set-up are often the only source of information available for turbulent parameters as β (Hartogensis et al., 2003; Kohsiek et al., 2006; Von Randow et al., 2008), which imposes to consider slight dependence of H_{LAS} to 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

Table 2. Correlation (R^2) and linear fit between H_{LAS} estimated with the scintillometer according to both methods (the classical one and the BCM) and H_{EC} measured with ECstation.

	Classical Method	BCM	γ	β
April	1.02×(R^2=74%)	0.95×(R^2=57%)	78.5%	0.12
June	0.99×(R^2=95%)	0.96×R^2=94%)	79.7%	1.01
September	1.02×(R^2=91%)	1.01×(R^2=91%)	98.7%	2.8

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.

Performances of scintillometers to estimate H flux have already been studied in the case of homogeneous surface and showed high correlation with H_{EC} (McAneney et al., 1995; De Bruin et al., 1995; Hoedjes et al., 2002). Then, the discussion is focused on the comparison of both methods.

In a preliminary analysis, it can be observed that the "β-closure method" tended to give the same results as, classical method, especially during the June and September periods (Fig. 9). However, γ and β seemed to affect the results of the "β-closure method" : H_{LAS} by BCM diverges from H_{LAS} by Classical method, when both parameters decreased. The influence of β on this divergence is more stringent, as shown by the comparison of the April and June results (where γ is approximately the same). It is evident that the decrease in β was followed by an underestimation of H_{LAS} 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_{LAS} estimates by less than 1%. Thus, this term can be neglected while using the "β-closure method" without significant error.

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_{LAS} uncertainty was approximately 1%.

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. 9). Furthermore, the BCM computation 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.

4.3 Moisture influence

Further analysis has been performed to include the moisture effect (R_{Tq}) in H_{LAS} computation with both methods. Moene (2003) estimated the possible error due to the approximation of $|R_{TQ}|$=1 in Eq. (4), to be up to 40% when the Bowen ratio is low, and advised to neglect the correction term in β. Furthermore, Lüdi et al. (2008) showed that R_{TQ} is dependent upon the Bowen ratio. The lowest the Bowen ratio is, the worst the temperature and humidity are correlated. Then, according to this criteria the period P1 is the most sensitive period to R_{TQ} fluctuations and needs to be further investigated to quantify the influence of the lack of correlation between temperature and humidity. Besides the influence of R_{Tq} is negligeable in June and September (Moene, 2003).

R_{TQ} has been calculated for the three periods, at the time scale of 30 min. The averages values of R_{TQ} for each period is 0.76 for P1, 0.66 for P2, and 0.59 for P3, which are comparable with other authors. For instance, Sorbjan (1993) sums up the results of different experimentations and conclude that R_{TQ} is between 0.6 and 0.8 in the surface boundary layer.

The sensible heat flux has been calculated with experimental values of R_{TQ}, and was then compared to previous results (where $|R_{TQ}|$=1 is assumed) for the period P1 (Fig. 10). The results show a relative underestimation of H_{LAS} in April due to the approximation of R_{TQ}=1 of 6% (±3%) with the Classical method and 9% (±4%) with the BCM.

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 Eddy Covariance (EC) stations provide local measurements, scintillometers are able to estimate the sensible heat flux from measurements of the structure parameter of refractive index, 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_vE 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.

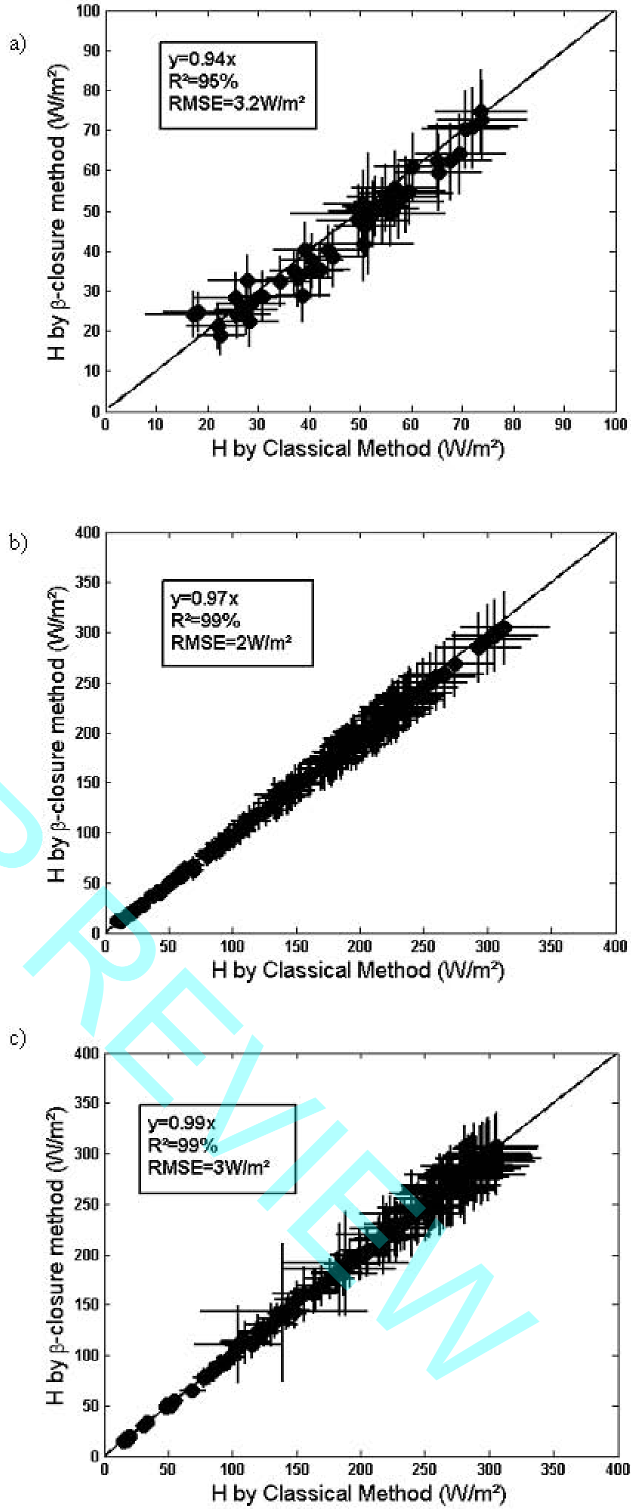

Fig. 9. Comparison of the sensible heat fluxes derived from the scintillometer H_{LAS} with the "β-closure method" (BCM) versus the one derived with the classical method: **(a)** April results, **(b)** June results and **(c)** September ones.

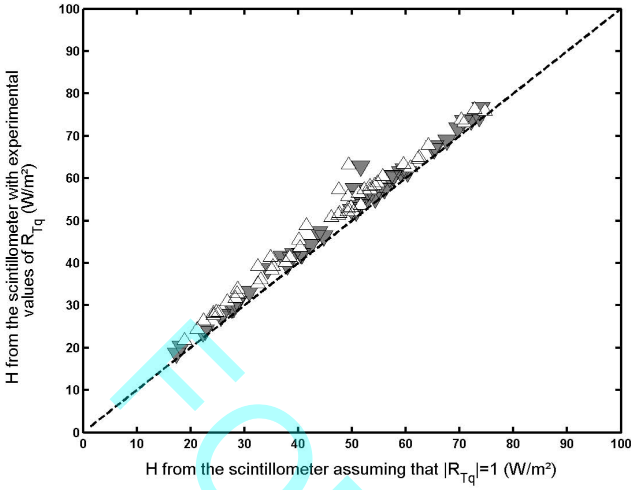

Fig. 10. Comparison between H calculated with the scintillometer considering a perfect temperature/humidity cross-correlation (R_{TQ}=1), and with the measured one, for the period P1. Classical method is represented by grey triangles, and BCM by white triangles.

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 sensible heat flux H was calculated with 30 min-averaged values of β measured using an EC flux system. In June and September, when β>1, H_{LAS} and H_{EC} are well correlated, and the uncertainty on H_{LAS} measurement is around 12%. In April 2007, when the Bowen ratio was smallest (β=0.12), the correlation between H_{LAS} and H_{EC} decreases (71%) due to the strongest sensitivity of H_{LAS} to the correction term in β. Moreover, the lack of accuracy on β measurement for low β values 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_{LAS} (<6%) even when the Bowen ratio was small. Furthermore, the uncertainty in H_{LAS} 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.

The approximation of a perfect correlation between temperature and humidity (R_{TQ}=1) has been discussed in low Bowen ratio conditions (April) which is the most sensitive case to R_{TQ} fluctuations. R_{TQ} values have been integrated over 30 min and included into each computational method. It results in a relative underestimation of H_{LAS}, using $|R_{TQ}|$=1, between 6 and 9% in comparison with H_{LAS}, using experimental values of R_{TQ}.

When using a scintillometer as an autonomous device, it is advisable to employ the "β-closure method", 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.

Edited by: G. Ehret

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

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