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Exploring eddy-covariance and large-aperture scintillometer measurements in an Amazonian rain forest

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ABSTRACT

A large-aperture scintillometer (LAS) is used to estimate the surface sensible heat fluxes in an Amazonian rain forest site, and these fluxes are compared with an eddy-covariance system (EC) to analyze conditions of low-frequency modulation in the surface layer. The results show that the flux estimates from the EC are often lower than from the LAS. The differences between EC and LAS tend to increase with decreasing correlation between vertical wind and temperature (r_{wT}). Using different averaging times on EC calculations, we observe that the largest differences between the LAS and the EC fluxes are found for 10-min averages, less so for 30-min averages, while 1-h averages give the smallest differences. The results are attributed to the spatial averaging effect of the LAS. Generally, the results suggest that r_{wT} can be used as an indicator of the importance of low-frequency motions in the surface layer. Evaluating the energy balance for different ranges of r_{wT}, we found that its closure improves when data with increasingly higher r_{wT} are used. In addition, a methodology has been developed to correct the scintillometer signals for the effect of tower vibrations.

1. Introduction

For several years now, the energy and carbon fluxes between the surface and the atmosphere have been measured in a rain forest area in the central Amazon (the LBA K34 site), located about 60 km north of Manaus, Brazil, using the eddy-covariance (EC) technique. However, just as in several other complex terrain sites in the world, the flux measurements are still subject to large uncertainties, especially due to the heterogeneous aspect of the topography in the region (*terra firme* plateau areas dissected by valleys with very wet soils). The limitations and uncertainties in flux measurements over complex surfaces have been discussed in recent papers (e.g. Mahrt, 1998; Finnigan et al., 2003; Kruijt et al., 2004).

The atmospheric boundary layer over Amazonian forest frequently contains slowly moving large eddies caused by strong convective motions and/or local circulations induced by the heterogeneity of the surface. These motions occur at time scales longer than the usual turbulent time scales and are here referred to as *low-frequency motions*. Unfortunately, it is still difficult to quantify their effects on the turbulent exchange processes in the surface layer. In some cases,

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especially those characterized by poor turbulent mixing of the atmosphere, there are indications that the low-frequency variations contribute up to 30% of the total covariance in Amazonian forests (Von Randow et al., 2002; Finnigan et al., 2003). However, it is not always clear to what extent these variations represent actual transport that should be accounted for to evaluate the total exchange in budget studies, or non-stationarities in the signals that should be disregarded in the flux calculations.

In the presence of slowly passing eddies, it is therefore not easy to choose an averaging time scale to define the 'mean' and 'fluctuation' parts in eddy-covariance calculations. The time scale should be long enough to sample a sufficiently large number of eddies passing by the sensors to provide stable statistics of the exchange. However, the longer the averaging time chosen, the bigger the uncertainties in the flux calculations will be, due to non-stationarity of the signals. In literature, typical averaging time values used are 30 or 60 min. In certain conditions, however, these time scales might be too short to properly sample slow moving turbulent organized structures (TOS) (Kanda et al., 2004). Using numerical experiments with large eddy simulation, the latter authors showed that the temporally averaged flux based on a single tower measurement systematically underestimates the spatially averaged heat flux. They explained the underestimation by the behavior of turbulent organized structures. Non-homogeneity in surface heat flux or topography may cause convective cells to lock into fixed positions on the landscape (Malhi et al., 2004).

An alternative method to estimate the surface heat fluxes that may have advantages over single-tower eddy-covariance is the *scintillometry* method. A scintillometer is an instrument that can measure the amount of scintillations in the air by emitting a beam of light over a horizontal path of the order of a few meters to 10 km (Hill, 1992; De Bruin, 2002). The scintillations recorded by the instrument can be related to the structure parameter of the refractive index of air (C_n^2), which is mainly dependent on fluctuations in air temperature and humidity. The main advantage of the scintillometer is that it provides a measurement that represents a *spatial* average of the turbulent eddies along the whole path. For this reason, it is not necessary to use a long time scale to sample a large number of eddies, and we expect a better estimate of the turbulence structure by the scintillometer in conditions of poor mixing.

The theoretical basis and initial applications of the scintillometer method to estimate fluxes were developed in the 1970s; see for example papers by Wesely (1976a,b), Wingaard and Clifford (1978), Wang et al. (1978) and an overview by Hill (1997). Different scintillometer types have been developed, providing information on the inner scale of turbulence (l_0) and the structure parameter of the refractive index of air (C_n^2). To estimate heat fluxes from the measured C_n^2, however, a similarity relationship between the two quantities is necessary. Measurements using different types of scintillometers have been successfully made over relatively uniform sites (e.g. Andreas, 1989; Hill et al., 1992; De Bruin et al., 1995) using the Monin-Obukhov similarity (MOS) theory, but in more complex sites, MOS theory must be applied with caution. Cain et al. (2001) highlighted that LAS flux estimates agreed with EC fluxes only when an 'effective' displacement height (d) – properly derived from their sonic anemometers – is used in the calculations, even though their estimated d was higher than the vegetation height. Meijninger et al. (2002) presented experimental evidence that above a concept blending height, MOS yields good results above a heterogeneous flat surface. But still, even below the blending height, the results of Meijninger et al. (2002) indicated only relatively small violation of MOS and satisfactory estimates of the fluxes, if they carefully considered the weighted footprint of the scintillometer.

Recently, Nakaya et al. (2006) and Nakaya et al. (2007) used a displaced-beam small-aperture scintillometer (DBSAS), with a path length of 86 m, in combination with an EC system above a deciduous forest canopy and found that the DBSAS measures higher dissipation rates than the EC when the wind is perpendicular to the scintillometer path, especially in conditions of poor mixing. The authors attributed the results to the larger footprint area of the scintillometer better sampling the spatial variability of turbulent eddies. A disadvantage of the DBSAS is that saturation of the signal occurs at path lengths longer than 250 m. For large-aperture scintillometers (LAS) saturation occurs at much longer path lengths (~5–10 km, see for example Ochs and Wilson, 1993; Kohsiek et al., 2006), and for that reason, the LAS is more appropriate to be used at greater heights and longer path lengths above tall forests.

The objective of this paper is to present measurements of a LAS, with a path length of 1140 m, installed next to the EC system at the K34 site in central Amazonia, analyzing the conditions of low-frequency variations and discussing the capability of the LAS to spatially average turbulent signals. We also present a methodology to correct the scintillometer measurements for the effect of vibrations in the tower.

2. Theoretical background

2.1. Fluxes using scintillometry

The estimation of fluxes with the scintillometer is based on the measurement of the fluctuations of intensity of an electromagnetic radiation beam, also known as *scintillations*. Detailed descriptions of the measurement principle and of different types of scintillometers are found in many papers (e.g. Wesely, 1976a; Andreas, 1989; Hill, 1992, 1997).

A large-aperture scintillometer consists of a transmitter and a receiver, installed at a certain height z_{LAS}. The relationship between the measured variance of the logarithmic intensity fluctuations $\sigma_{\ln I}^2$ and the structure parameter of the refractive index of air C_n^2 is obtained from the equation of propagation of a spherical wave through a medium with random refractive index fluctuations. For a LAS with equal transmitting and receiving apertures, Wang et al. (1978) derives

$$C_n^2 = 1.12\sigma_{\ln I}^2 D^{7/3} L^{-3} \quad (1)$$

where D is the aperture diameter of the LAS and L the distance between the transmitter and the receiver.

The scintillations are primarily the result of fluctuations in air temperature and humidity. Strictly speaking, the measured