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# Is friction velocity the most appropriate scale for correcting nocturnal carbon dioxide fluxes?

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ABSTRACT

The use of friction velocity $u_*$ as the turbulence scale for correcting eddy-covariance carbon dioxide fluxes in low-mixing conditions is questioned. This is done because $u_*$ is, itself, a flux and, therefore, its value is highly dependent on the temporal scale used for the analysis. The multiresolution decomposition is applied to data from three different ecosystems in Brazil, to show that $u_*$ is well behaved and related to the turbulent mixing only up to the scale that separates the turbulent mixing from the low-frequency exchange. For larger temporal scales, mesoscale fluxes may induce large variability in the friction velocity, so that time series with low turbulent mixing may show an elevated value for $u_*$, and vice-versa. We propose, as an alternative, the use of $\sigma_w$, the standard-deviation of the vertical velocity fluctuations. It is shown that $\sigma_w$ has no variability within the mesoscale range and that, therefore, it is a much better scale to quantify the turbulent exchange than $u_*$. The relationship between the two velocity scales is shown to depend on the scale and to be universal for the scales of the turbulent exchange. It is shown that curves of the turbulent carbon dioxide fluxes as a function of the turbulence scale are smoothed when using the friction velocity. Using $\sigma_w$ instead of $u_*$ in data filtering procedures has two main consequences: easier determination of the threshold for filtering and larger respiration rates of the series classified as turbulent. The improvement is larger for sites where very stable conditions are common.



## 1. Introduction

The eddy-covariance technique has become an essential tool to quantify the exchange of properties between the surface and the atmosphere. Particularly, its application in carbon dioxide flux measurements has linked micrometeorological and ecological communities (Baldocchi, 2003). Though the technique is widely used by an increasingly large number of researchers around the Globe, it is not capable of completely capturing the total $CO_2$ exchange from a given ecosystem, and a number of corrections are necessary (Massman and Lee, 2002). One of the most important difficulties is associated with the determination of nocturnal respiration rates in conditions of weak turbulent mixing. For this reason, gap-filling methods have been proposed and are extensively used for the determination of ecosystem carbon budgets (Goulden et al.,

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1996; Aubinet et al., 2000). These methods essentially consist of replacing data from nights with low turbulence intensity with those measured in nights with similar soil characteristics, but enough mixing. The turbulence scale used for this classification is the friction velocity $u_*$ and the procedure is commonly known as the $u_*$ correction. Papale et al. (2006) list a number of problems associated with this method. First, it is only justifiable if the $CO_2$ respired during the calm periods is removed from the observation site, by processes such as horizontal drainage flows, which have been observed and described by Staebler and Fitzjarrald (2004), Aubinet et al. (2005), and Feigenwinter et al. (2008), among others. Otherwise, it requires careful determination of the $CO_2$ vertical profile evolution. Furthermore, the criterion, and its results, is subjective, as the $u_*$ threshold for filtering can be arbitrarily chosen. In fact, Miller et al. (2004) showed that the annually integrated carbon exchange of a primary forest in Amazonia can vary from $-4$ (uptake) to 1 (emission) Mg C ha$^{-1}$ year$^{-1}$ for $u_*$ thresholds varying from 0 to 0.3 m s$^{-1}$. Finally, Papale et al. (2006) argue that the mere idea of substituting the observations under calm conditions for those during windy periods is not proven to be valid and that flux errors under windy conditions will propagate to other periods if this correction is carried out. In the present study, we want to call the community's attention to another difficulty of such procedure: uncertainties in the $u_*$ value, itself.

Vickers and Mahrt (2003) showed the existence of a cospectral gap, that separates the scales of the turbulent exchange, which is organized and well described by similarity relationships, from larger scales, where the fluxes are more erratic, larger in magnitude and of either sign. The gap is generally well defined in individual series of well-developed turbulence, but its existence is not so clear when the turbulence is intermittent (Acevedo et al., 2006). Average cospectra, however, have a very well-defined gap. The larger scale fluxes are generically referred to as "mesoscale fluxes", believed to be unrelated to local processes, such as the local turbulent intensity. While the turbulent portion of the momentum flux is always negative, in the mesoscale range it can be frequently positive. Recently, Mahrt and Vickers (2006), showed that the organized turbulent mixing exists even in very stable conditions, and that it can be properly determined if the appropriate averaging windows are used. Acevedo et al. (2007) used the same technique for the determination of carbon dioxide fluxes, showing that the averaging windows can be as small as 5 or 10 s in the most stable conditions.

Here, we call attention to the fact that the most common scale used to classify nighttime turbulent fluxes, the friction velocity $u_*$, is a flux and, as such, is subject to large variability in the mesoscale range. As a consequence, nights with little turbulent exchange can be classified in the traditional gap-filling schemes as turbulent, if the mesoscale transport is large enough. On the other hand, turbulent nights can be classified as non-turbulent if the mesoscale momentum transfer is positive. As a result, the classification of turbulent fluxes as a function of $u_*$ is smoothed: the exchange is overestimated for low turbulence and underestimated for cases with enough mixing. As an alternative, we propose $\sigma_w$, the standard deviation of the vertical velocity fluctuations, be used for this classification. Not constituting a flux, this scale is not subject to the problems associated with the friction velocity.

## 2. Datasets

Three datasets, originating from different land covers, and under different nocturnal stability regimes are considered.

The most stable site will be referred to throughout this study as Santarém (3.012°S, 54.537°W). It is a deforested site in Amazonia, which was set up as part of the LBA project (Large-Scale Biosphere–Atmosphere Experiment in Amazonia). It is located on an open field of approximately 500 ha, surrounded by primary and secondary forest. The site operated continually from 2000 to 2006, but in this study we will look at 3 months of data during the wet season of 2001. At this time, the surface was pasture. The data were collected on a 20-m micrometeorological tower, and the flux measurements were performed using an eddy-covariance system, consisting of a 3D sonic anemometer (SATI/3K Applied Technologies, Inc., Longmont, CO, USA) and a closed-path infrared gas analyser (IRGA, Licor 6262, Licor, Inc., Lincoln, NE, USA). The eddy-covariance system was at 8.75-m height above the surface. The vertical $CO_2$ profile was determined, obtained from inlets located at 0.5, 2.7, 5.3 and 11.8 m. The sonic anemometer and the IRGA sampled at 10 Hz, and a 3-s lag correction needed to be applied to the closed-path analyser. Sakai et al. (2004) give further details on the quantities measured, land practice at the site, calibration procedures, data quality management and the power system.

A total of 61 nights from the Santarém site were analysed, the same days used by Acevedo et al. (2007). These were all the nights from January to March 2001, for which spikes, gaps due to system failure and rainfall were absent. In each night, 8 h of data, from 2100 to 0500 local standard time (LST) were considered.

A forest site, again from the LBA project, was also considered. This is the Manaus site (2.609°S, 60.115°W), located at the Cuieiras reserve area, 60 km north of the city of Manaus. The data were sampled at a 50-m high micrometeorological tower, and the flux measurements were made using an eddy-covariance system consisting of a 1012 R2 3D sonic anemometer (Gill Instruments, Lymington, UK) and a LI-6262 infrared gas analyser. Both were located at a 53.1-m height above the ground. Both sampled at a 10-Hz frequency. The average canopy height at the site is approximately 30 m and the leaf area index measured at nearby sites ranges from 5.7 to 6.6 (see Harris et al., 2004). A detailed description of the site, local weather, terrain, vegetation and the measurements carried out is given by Araújo et al. (2002). In the present study, we use data from 71 nights, from January to April 2006. The same criteria applied for the Santarém site, of using complete nights, free of spikes or gaps, was applied.

Finally, we consider a dataset obtained above a rice field, in southern Brazil, which will be referred as the Paraíso site (29.744°S, 53.15°W). A micrometeorological tower operated at this location from June 2003 to December 2004 as part of the CT-HIDRO project, a country-wide study that had the purpose of describing the surface conditions for different ecosystems in Brazil. The eddy-covariance system was located at 10 m