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CHARACTERIZING TURBULENT TRACE GAS EXCHANGE ABOVE A DENSE TROPICAL RAIN FOREST USING WAVELET AND SURFACE RENEWAL ANALYSIS

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1. INTRODUCTION

The oxidized nitrogen species, nitric oxide (NO) and nitrogen dioxide (NO_2), play a key role in the regulation of tropospheric photochemical oxidants like ozone and the hydroxyl radical (OH) (Crutzen et al. ,1979). Soils are an important natural source of oxidized nitrogen due to the microbial production of NO. As a potential counterpart to the high NO_x ($NO+NO_2$) levels of industrialized areas, net NO_x emissions from large tropical ecosystems may be crucial for the global ozone budget. Uptake processes and chemical reactions specific for the radiation distribution within the canopy affect the soil emissions on their way to the atmosphere. The influence of these processes is mainly controlled by the residence time of air within the canopy. In this paper wavelet and surface renewal analysis of high resolution trace gas time series was used to determine in canopy residence times in order to compare it with chemical time scales, relevant for the NO_x exchange.

2. EXPERIMENT

The experiment was part of the EUSTACH-LBA campaign (Andreae et al., 2002) carried out in April and May 1999. The experimental site (10°04.92' S, 61°55.80' W) was located in a biological reserve 90 km north of Ji Paraná (Rondônia), south west Amazonia, Brazil. Beside concentration profiles of NO, NO_2, O_3, H_2O, and CO_2, air temperature was measured at 8 heights within and above the canopy. Eddy covariance measurements of O_3 and sensible heat fluxes were performed both at 11 m height within the stem space and together with latent heat and CO_2 fluxes above the canopy at 53 m. The canopy was 32 m high (average) with an integrated one-sided leaf area index of about 6 (Fig. 4).

3. METHODS

In most plant canopies, the exchange of momentum, heat, and trace gases is dominated by large-scale, intermittent, coherent turbulent eddies (Gao et al., 1989). These structures appear in time series of temperature and trace gases as 'ramp' patterns with a slow, nearly constant, increase or decrease, followed by a rapid, step like change back to the initial level (Fig. 1). Surface renewal analysis (Paw U et al.,1995) makes use of the concept that these ramp patterns arise from an idealized air parcel motion. An air parcel of volume V_0 is assumed to originate above the forest and instantaneously penetrate the canopy. During the residence time of the parcel, it is in contact with leaves and other canopy elements, exchanging thermal and chemical properties. These diffusive processes result in the gradual increase (e.g. temperature for a warmer canopy) or decrease (e.g. ozone) of the quantity until the parcel is replaced by another one (expressed in the following step change). The flux density F_X of a scalar X from the surface is then the average rate of change of storage in the canopy volume associated with these structures within the measuring period, resulting in:

$$F_x = \frac{1}{2}\frac{dX}{dt}\frac{V_0}{A} \qquad (1)$$

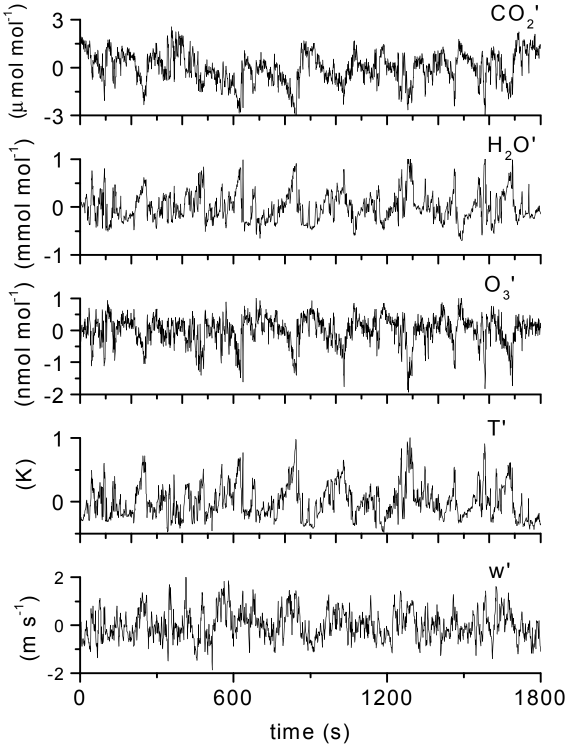

Figure 1. Half hour time series of different scalars and the vertical wind component measured at 53 m height, 21 m above the mean canopy height.

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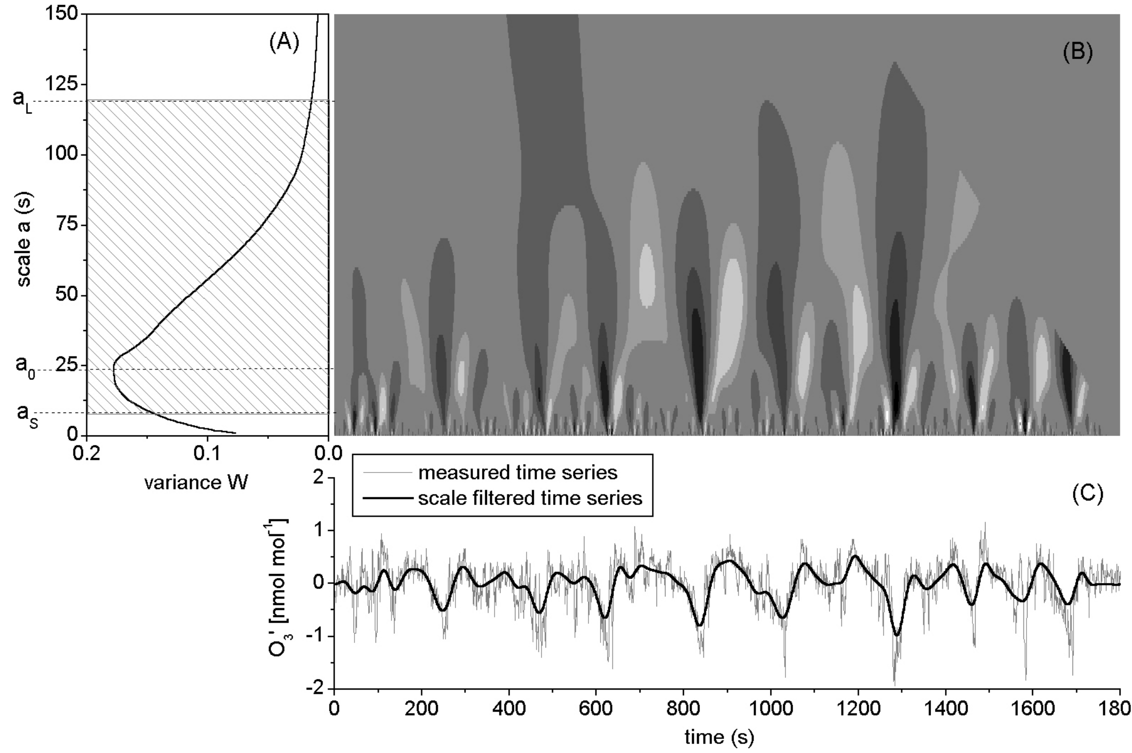

Figure 2. Wavelet transform $T_p(a,b)$ (B) of an ozone time series ((C); gray curve). The white areas display scales of maximal correlation. Integrating $T_p(a,b)$ over time results in the variance spectrum (A) which shows a distinct maximum at scale a_0. The gray shaded area (A) marks the width (between a_S and a_L) of the applied scale filter, resulting in the time series (black curve (C)), used for the surface renewal analysis.

where dX/dt is the average total derivative of the measured scalar, V_0 and A are the parcel volume and ground area approximated by $V_0/A \approx z_m$ (measuring height). The factor 1/2 accounts, in an idealized form, for the vertically uneven source distribution within the canopy air volume (Paw U et al.,1995) and seems to be fairly constant if the volume above a tall canopy up to the sensor height is included in the renewal analysis (Chen et al.,1997).

Using a fixed sensor only the partial derivative $\partial X/\partial t$ is measured, including advective effects. Paw U et al. (1995) and Katul et al. (1996) showed that normally the advective term, the difference between the total and the partial derivative, is of higher frequency than the partial derivative of the scalar. Therefore, a filtering scheme can be applied on the measured time series, approximating dX/dt in order to identify and extract the organized ramp structures in the measured scalar time series.

For that purpose, considering the intermittent nature of these structures, we used a combined filter and detection scheme based on continuous wavelet transform (Grossmann et al., 1989):

$$T_p(a,b) = \int_{-\infty}^{\infty} X(t)\, g_p(a,b,t)\, dt \qquad (2)$$

$$g_p(a,b,t) = \frac{1}{a^p}\left[1-\left(\frac{t-b}{a}\right)^2\right] e^{\left(\frac{t-b}{a}\right)^2} \qquad (3)$$

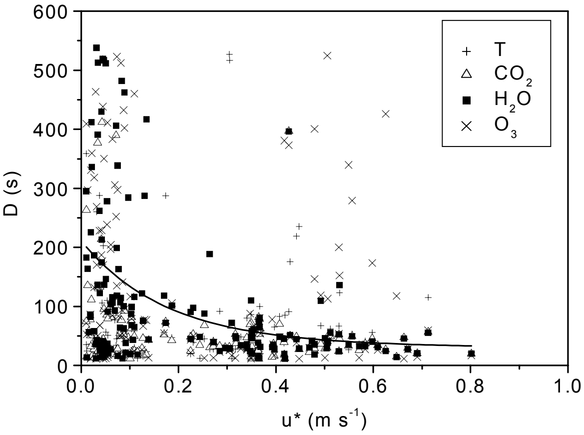

Figure 3: Dependence of the mean temporal structure duration $D = (\pi/\sqrt{2})a_0$ on u^* for all scalars measured at 53 m.

Here a convolution between the scalar time series $X(t)$ and the wavelet $g_p(a, b, t)$ is calculated for each scale a. Therefore, the wavelet transform, in contrast to the global Fourier transform also preserves the information about the localization of the structures in the time domain. Following Collineau and Brunet (1993), the power coefficient p was set to 1. All calculations were performed using the 'Mexican Hat' wavelet (3), taking advantage of its property as second derivative of a Gaussian function which can be used for structure detection without empirical calibration (Collineau and Brunet, 1993).

In the scale domain a one-decade wide filter window is applied, including the maximum a_0 of the variance spectrum (Fig. 2A) and removing long term trends as well as high frequent fluctuations. The wavelet coefficients $T_p(a,b)$ are set to zero for scales $a < a_S$ and

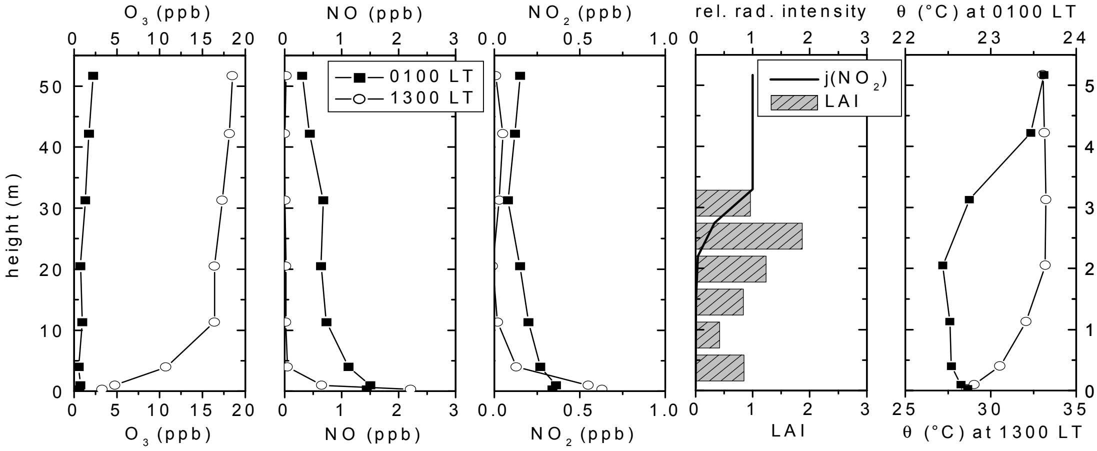

Figure 4. Profiles of potential temperature and concentrations of O_3, NO, and NO_2 at 0100 LT and 1300 LT (21 May 1999). Vertical distribution of the leaf area index *LAI* and the photolytic relevant radiation *j(NO_2)*.

$a > a_L$ (5) before the inverse wavelet transform is applied on $T_p^{\,f}(a,b)$ (4).

$$T_p^{\,f}(a,b) = T_p(a,b)\,\delta(a_S,a_L) \qquad (4)$$

$$\delta(a_S,a_L) = \begin{cases} 1 & a_S < a < a_L \\ 0 & else \end{cases} \qquad (5)$$

The filter window is slightly shifted towards larger scales for low u^* values and vice versa, to account for the tendency displayed in Fig. 3.

The filtered time series is used for the flux calculation according to (1), considering the direction of the flux determined by third-order structure functions (van Atta, 1977).

4. RESULTS AND DISCUSSION

The profiles of potential temperature in Figure 4 indicate totally different turbulent regimes during night and day. At night a slightly unstable stratification can be observed in the stem space up to 20 m as radiative cooling is the largest in the crown layer. At 1300 LT the stratification of the upper canopy and the roughness sublayer above is unstable, whereas the lower canopy is dominated by extreme stability. An ozone concentration difference of only 2 ppb between 51 m and 10 m indicates effective transport mechanisms during day (Fig. 4). Within the lowest 5 meters all soil emitted NO seems to react with O_3, forming NO_2 (Rummel et al., 2002). The bulk of this NO_2 is obviously deposited back on the soil and taken up by the stomata in the crown layer of the forest.

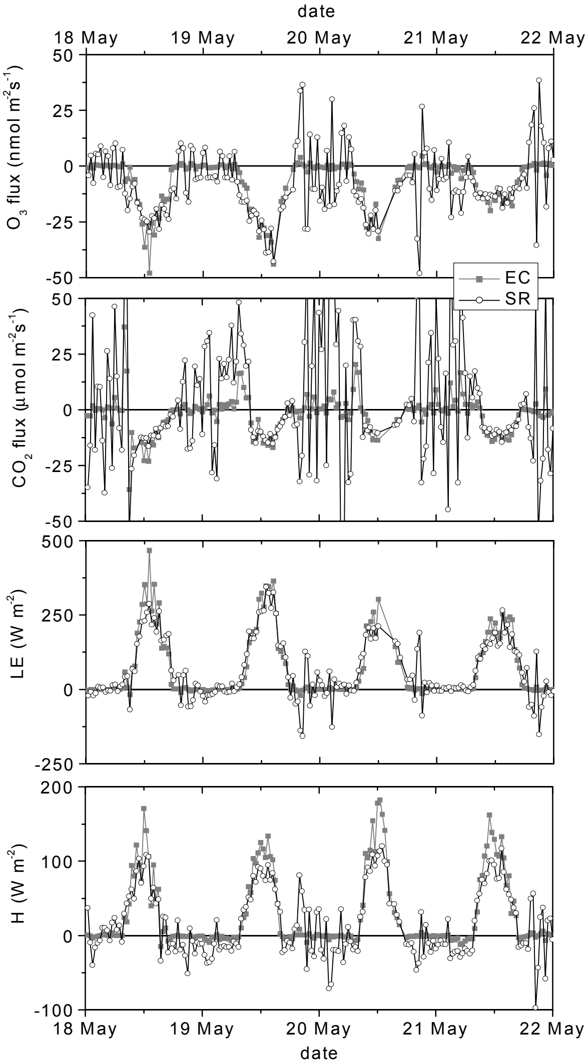

Figure 5. Comparison of heat and trace gas fluxes above the canopy determined by eddy covariance (full squares) and surface renewal approach (open circles).

A crucial point for the quantification of the internal nitrogen cycling is the estimation of both, the residence time of air within the canopy and the chemical time scale of NO reacting with O_3 to NO_2. The photolysis ($NO_2 + h\nu \rightarrow NO + O(^3P)$) is negligible in the lower part of the canopy due to a highly attenuated short wave radiation at that height (Fig. 4). If the turbulent transport between the canopy and the boundary layer is dominated by coherent structures penetrating down to the lowest meters of the canopy, the mean residence time can be estimated by the time lag of consecutive ramp structures detected in the high frequency time series via wavelet analysis. A test for this assumption is the applicability of the surface renewal approach. Figure 5 shows a comparison over 4 days between all scalar fluxes determined above the canopy by eddy covariance measurements and the results of the surface renewal method. During day the agreement between the two methods is quite good (Table 1), partly with a slight underestimation of the diurnal maximum especially for the heat fluxes. This is, together with a distinct spatial correlation between time series measured at 53 m and 11 m (Fig. 6) an indication, that the main part of the canopy air is renewed by relative short intensive turbulent events. At night, during periods of low mechanically produced turbulence, only sporadic correlation can be seen between the two heights in addition to large deviations between the fluxes obtained by the two methods (Fig. 5). Therefore a mean residence time or turbulent timescale representative for the main part of the canopy, can only be estimated during day.

Table 1. Regression between scalar fluxes determined by eddy covariance and surface renewal approach (daytime values only, 0800-1700 LT)

Scalar	*R^2*	*slope*	*Intercept*
Sensible heat flux	0.88	1.29	-1.18
Latent heat flux	0.87	1.23	-35.00
CO_2 flux	0.63	1.19	1.13
O_3 flux	0.72	1.08	3.05

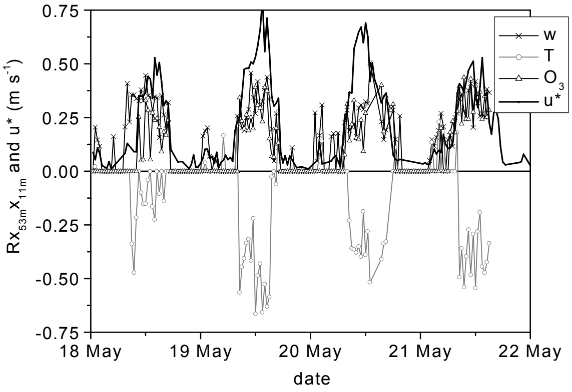

Figure 6: Spatial correlation with optimum time lag between time series measured above the canopy (53 m) and within the stem space (11 m). For orientation u* above the canopy is also shown.

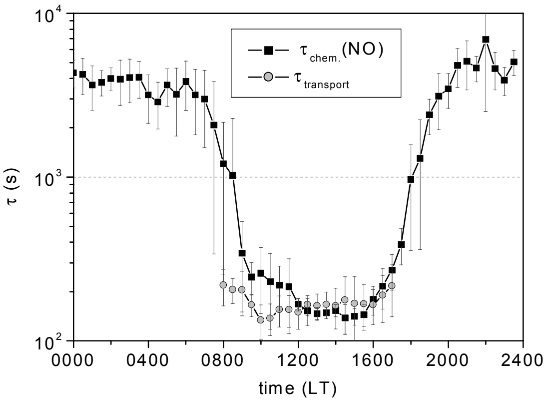

Figure 7. Mean diurnal course of the chemical timescale for NO ($NO + O_3 \rightarrow NO_2 + O_2$) at 11 m in comparison to the mean residence times ($\tau_{transport}$) derived by ramp detection via wavelet analysis (18…21 MAY 1999).

Figure 7 shows, that the mean residence times during daytime are between 100 s and 250 s and in the same order of magnitude than the chemical timescale for NO within the lower part of the canopy. This supports the (more qualitative) findings from the gradient measurements. During daytime almost any soil emitted NO is trapped within the canopy. This is due to strong intrusions of air from aloft loaded with high ozone. These are frequent enough to reduce NO within the lowest 5 meters.

The penetration depth of these coherent structures also has a large effect on the net NO_x emission. The height of NO_2 formation (O_3 reacting with NO) controls which canopy layers are involved in the deposition process of NO_2.

5. CONCLUSION

During day residence times for trace gases could be determined by a combination of wavelet and surface renewal analysis, because daytime exchange between this tropical rain forest and the atmosphere is dominated by coherent structures penetrating deep into the canopy.

Comparison to the chemical time scale shows, that almost no soil emitted NO is able to leave the canopy during daytime.

Due to the deep penetration of the structures, most of the canopy layer is involved in the stomatal uptake of NO_2. Therefore the net NO_x exchange is also regulated by coherent structures.

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