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Aircraft assessment of trace compound fluxes in the atmosphere with Relaxed Eddy Accumulation: Sensitivity to the conditions of selection

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Abstract. The Relaxed Eddy Accumulation (REA) technique, implemented aboard aircraft, may be used to measure a wide variety of trace gas fluxes at a regional scale. Its principle is rather simple: air is sampled at a constant rate and the flux is calculated by multiplying a constant β (0.58 in field experiment and 0.62 in simulations) by the standard deviation of the vertical velocity and by the difference between the average concentrations of the scalar (trace gas) for updrafts and downdrafts. The storage of the chemical compound in reservoirs allows for trace gas analysis in laboratory, when in situ measurement with fast response and high sensitivity sensors are not available. The REA method was implemented on the Avion de Recherche Atmosphérique et de Télédétection aircraft during the Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO) campaign. The main requirement for accurate flux determination is the measurement of the vertical component of wind velocity in real time. A simulation technique was developed to evaluate the performance of an aircraft REA. The influence of the time lag between the vertical velocity (W) measurement and REA control was tested, as well as the offset of W, the threshold, and the filtering imposed on W. Correction factors, used in a deployment of aircraft REA, were deduced from this study. An additional simulation was performed to evaluate the influence of spatial or temporal drifts on the scalar. The simulation showed that the REA method is not more disturbed than the Eddy Correlation method by low frequencies of physical origin, such as topography. The REA method was used during EXPRESSO for the measurement of isoprene fluxes over the wet savanna and the evergreen rain forest.

1. Introduction

Trace gas and energy balance between the surface and atmosphere can be assessed by the determination of sources and sinks at the surface and by the transfer of compounds from the surface to atmosphere (and vice versa). Identical constraints, concerning stationarity and homogeneity, are applied for trace gas fluxes and energy fluxes. These fluxes may be measured with Relaxed Eddy Accumulation (REA) and Eddy Correlation (EC) techniques, both based on atmospheric turbulence.

Constraints differ if they are applied at local (fixed point) or regional scale. For fixed points (e.g., towers) the situation is rather simple: flux measurements (like the gradient method, the Bowen ratio method, or the Eddy Correlation (EC) method) may be made above homogeneous surfaces. In the case of aircraft flux measurements, however, since these have much larger horizontal fetch, homogeneous surfaces must be defined statistically.

Aircraft flux techniques, including REA, are especially suited for the determination of fluxes at a regional scale and

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Paper number 2000JD900186. 0148-0227/00/2000JD900186\$09.00 from diverse ecosystems. This is particularly important in inaccessible regions, such as tropical forests and savannas, which usually have a strong energetic activity, high and uncharacterized species diversity, and significant importance in biogeochemical cycles.

Surface fluxes were measured from aircraft during the Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO) campaign over two important ecosystems: the woodland/savanna mosaic and the evergreen rain forest. Two flux methods were employed on the Avion de Recherche Atmosphérique et de Télédétection (ARAT) aircraft: the EC method and REA method. The EC method had already been used to measure ozone fluxes [Lenschow et al., 1980] and has been validated aboard the ARAT [Affre et al., 1999], with a complete methodology and a validation made using the water vapor flux as a reference. Methods and results obtained with the EC method during EXPRESSO are presented by Delon et al. [2000], concerning the surface energy budget and the turbulent kinetic energy budget, and were developed by B. Cros et al., (personal communication, 2000), concerning the ozone turbulent flux measurements.

The REA method depends on the standard deviation of the vertical wind velocity σ_w , the difference of the mean concentrations between updrafts and downdrafts, and an empirical constant β . The REA method is often used to

measure fluxes of diverse components whose measurement with the EC method is problematic [e.g. *Zhu et al.*, 1998] and several technical and theoretical problems have been discussed [Kramm *et al.*, 1999]. This paper examines the calculation of the vertical velocity *W* in real time, an essential condition for the measurement. After presenting the implementation of the REA in the ARAT, we will assess several constraints which are imposed on the REA system in the estimation of real time vertical winds. Simulations allow the evaluation of conditions of selection and of their influence on the β constant and, consequently, on the evaluation of the flux.

 CO_2 fluxes have been calculated with the EC method and the REA fluxes have been deduced from these calculations, in order to evaluate the accuracy of the latter [*Oncley et al.*, 1993]. During the EXPRESSO campaign in Central African Republic (CAR) and in the Republic of the Congo (Congo) a REA technique for isoprene fluxes [*Greenberg et al.*, 1999] was deployed. This EC/REA comparison assesses the suitability of REA for aircraft chemical flux measurements and illustrates the influence of spatial drifts upon the scalar.

2. Presentation of the REA System Used for the Experiment

2.1. Theory

The Eddy Accumulation method, proposed by Desjardins [1972], relies on the conditional sampling of air in proportion to the vertical wind velocity (positive or negative). This method was modified by Businger and Oncley [1990] by collecting air at a constant rate for updrafts and downdrafts and was called REA. The major inconvenience of turbulent flux measurements of chemical compounds is that they require high-frequency sensors. Conditional sampling methods, like the REA, require, as with the EC method, the measurement of the turbulent component of the vertical velocity but require only average measurements of the concentration, for which slower and selective detection techniques exist. If the analysis cannot be performed "in situ", samples can be transported to the laboratory for analysis. which allows the measurement of vertical fluxes of a great number of constituents [Nie et al., 1995].

The air is then collected at a constant rate, depending on the vertical velocity sign, and the vertical flux Φ is calculated according to (1):

$$\Phi = \beta \sigma_{u} \left(\overline{C + -C -} \right)$$
 (1)

where σ_w is the standard deviation of the vertical velocity. $\overline{c_+}$ ($\overline{c_-}$) is the mean concentration of the measured chemical compound calculated for the sampling period in the reservoir corresponding to the positive (negative) vertical velocity selection. Variable β is a constant, approximately 0.58 in field experiments [*Pattey et al.*, 1993] and 0.62 in simulations [*Businger and Oncley*, 1990; *Wyngaard and Moeng*, 1992]. Simulations show that β is weakly dependent on the stability [*Businger and Oncley*, 1990; *Andreas et al.*, 1998].

2.2. Implementation in the ARAT Aircraft for the EXPRESSO Campaign

The REA method has been widely used on ground [e.g., Baker et al., 1992; Guenther et al., 1996b; Bowling et al., 1998]. It requires, among other conditions, a homogeneous

emission source and high-frequency measurement of vertical velocity, usually with sonic anemometers. REA ground measurements have been performed for several chemical compound fluxes, for example, isoprene (nonmethane hydrocarbons) (*Guenther et al.*, 1999; *Zhu et al.*, 1999] or ozone [*Katul et al.*, 1996].

An REA was installed in the French ARAT research aircraft for the EXPRESSO campaign, which took place in CAR from November 15 to December 2, 1996 (an overview of the experiment is given by Delmas et al., [1999]). EXPRESSO was an interdisciplinary experiment, whose purpose was to study exchange processes between biosphere and atmosphere in tropical regions, and to quantify the impact of emissions on atmospheric chemical composition at a regional scale. Three different experimental platforms were used in EXPRESSO: a 60-m-high walk-up tower situated in the undisturbed primary forest of the northern Congo, dedicated to local-scale measurements (N'Doki, 2°12N, 16°23E); the ARAT instrumented aircraft, for regional-scale measurements, and two stations receiving signals at a continental scale from the National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer (NOAA-AVHRR) satellite. There were 11 research flights, 4 above wet savanna vegetation and 5 above evergreen rain forest vegetation. Two additional flights were made over the forest/savanna interface. The flights were carried out daily between 0930 and 1230 local time. The installation of the REA in the ARAT is detailed in Figure 1.

2.3. Cycle of the REA Measurement

A cycle of measurement was composed of the following sequence: (1) 4 min for sampling of eddies into up- and down-draft reservoirs along a constant attitude and altitude leg; (2) 1 min for transfer of aliquot of air from the reservoirs onto adsorbent cartridges, for later analysis of isoprene; (3) 30 s (+30 s) for analyzing the positive selection (+ negative selection) for CO₂; and (4) 2 min, 30 s for evacuating the reservoirs and reinitializing the cycle.

For |w| greater than the threshold the sampled air was forwarded (through two Teflon tubes) to two Teflon reservoirs, situated at the back of the plane (corresponding to point 1 in the detail of the cycle above). Air from each reservoir was sampled onto solid adsorbent cartridges for later analysis of isoprene (point 2). Reservoir air was analyzed for CO₂ using a Licor LI-6262 CO₂/H₂O Analyzer (point 3). When the Licor analyzer was not taking air from the reservoirs, it took air from outside (point 4). This allowed the measurement of the mean CO₂ concentration during the whole flight, except during the minute of analysis when the analyzer took air from the reservoirs. The cycle and the position of the system in the ARAT are schematized in Figure 1.

3. Real Time Vertical Velocity Measurement

One of the most important technical problems of the REA method in the aircraft is the real-time determination of vertical velocity W. The first attempts made by *MacPherson and Desjardins* [1991] were not conclusive. Thus in the ARAT aircraft the first objective was to calculate an instantaneous W, since W, computed by the standard aircraft data system, contributed an unacceptable delay of approximately 0.25 s, due to the transfer rate of the numerical message (Figure 2).



Figure 1. Scheme of the REA system aboard the ARAT. Open circles correspond to the three-way switching valves, and gray ellipses correspond to inlet (\rightarrow) or outlet (\leftarrow) pumps. The two reservoirs are represented by open rectangles. R+(R-), reservoir corresponding to the selection of positive (negative) vertical velocity.

3.1. Calculation of the Simplified W_{REA}

The Inertial Navigation System (INS) aboard the ARAT provides position, velocity, and acceleration data. These data are transmitted in a numerical form to a computer called Système de Fabrication d'Instruments de Mesure, SFIM, Figure 2). SFIM receives analog signals coming from the different sensors (detailed by Delmas et al. [1999]), transforms them into numerical signals, and classifies and transmits to the data acquisition system of the aircraft. This acquisition system calculates a vertical velocity of air with high resolution, but the data are stored and transmitted every quarter second, too long a delay for the REA control in real time. A separate computer was thus inserted to calculate a simplified vertical velocity, W_{REA} . This "REA computer" takes information concerning the pitching (θ) and the vertical velocity of the aircraft (Wa) from the INS and transfers air speed and incidence from the SFIM to compute W_{REA} , according to the expression

$$W_{_{\rm HA}} = (i - \theta)u + Wa + l\,\theta \tag{2}$$

where $l\theta$ is the vertical velocity induced by rotation, l(16 m) is the distance between the boom extremity and the gravity center;

Wa is the aircraft vertical velocity related to the ground; *Wa*=(*dz/dt*) where z is the coupled barometrial height (*Wa* is given by the INS); $(i - \theta)u$ is the air velocity related to the aircraft. During stable flight, $i = \theta$ (attack angle = pitch angle). If the aircraft is influenced by gales, *i* differs from θ . Almost all information concerning the turbulence is contained in this term. Variable $u = v_p + v_p'$, where v_r is the average air speed of the aircraft (ranging from 80 to 100 m/s) and v_r is the horizontal velocity fluctuation (around 1 m/s).

The calculated W_{REA} has to be converted from numerical to analog data needed by the REA control computer. This analog signal is then transmitted to the W_{REA} computer through a bandpass filter (between 0.02 and 10 Hz). A 10-Hz (0.1 s) low-pass filter is necessary to remove the noise induced by the calculation and the conversion from analog to numerical data (and vice versa), and to limit the electrovans (solenoid valve) switching frequency. A 0.02 Hz (50 s) high-pass filter is essential to reject low-frequency components (whose scale is greater than 5 km) and to eliminate the offsets induced by the calculation (see below).

The REA control computer is programmed to execute and control the cycle of measurement and operation of the electrovans for the wind selection. The air selection, depending



Figure 2. Scheme of the calculation of the simplified REA velocity (W_{REA}) from the reference velocity (W_{REF}) calculated by the central computer on board.

on the vertical velocity direction, is made above a threshold equivalent to $0.1\sigma_w$ (where σ_w is the standard deviation of W). If the threshold is greater than $0.1\sigma_w$, the deadband effect is too large to ensure an accurate flux measurement (deadband is a range of vertical wind velocity when no sample is collected). In the interval of $\pm 0.1\sigma_w$, the sign of the vertical velocity is ambiguous, and the selection of air is not representative of the flux direction. Variable σ_w can be either specified for each leg, depending on the preceding measurement, or fixed between 0.6 and 1 m/s (values usually encountered in the convective boundary layer [*Caughey and Palmer*, 1979]). This simplified and filtered velocity W_{REA} is re-injected into the SFIM in order to be compared to the reference velocity W_{REF} . The comparison gives a good correlation on low-level legs (Figure 3) and allowing W_{REA} to be used without systematic error for the air selection.

3.2. Simulated Functions

The REA method is called a "blind" method because of the impossibility of controlling the conditions of selection (i.e., vertical wind velocity over $0.1\sigma_w$). Several technical problems may occur, depending on these conditions of selection (switching frequency, delays, etc.). Computational time may also interfere and influence the delay in the calculation of the vertical velocity, the band-pass filtering, or the threshold used for the selection of the vertical velocity. The calculation of



Figure 3. W_{REA} (REA vertical velocity) and W_{REF} (reference vertical velocity) in m/s during a 5-min lowlevel leg (310 m) of flight 45 (savanna flight performed during the EXPRESSO campaign on November 24, 1996). The equation corresponds to the regression between W_{REA} and W_{REF} , and R^2 is the correlation coefficient.



Figure 4. (a) Simulation of functions from an energy spectrum: x axis, frequency in Hz; y axis, arbitrary units. The gray rectangle gives the position of the frequency band around the spectrum peak. (b) W (vertical velocity) and X (scalar) are shown as examples of functions: x axis, time; y axis, arbitrary units.

fluxes of chemical compounds with the REA method assumes that $\overline{W} = 0$. But in real conditions of selection, this is not always the case. Computations, made from simulated variables, were used to assess the influence of different problems encountered in real conditions, such as the difference from zero of the average vertical velocity (offset), the threshold imposed on the vertical velocity sampling, the time lag between reference vertical velocity calculated by the aircraft (W_{REF}) and simplified vertical velocity calculated for. the REA command (W_{REA}), and the filtering of REA vertical velocity.

The quality of the REA measurement is modeled from a collection of simulated variables, where homogeneity and stability are controlled statistically. In each simulation, the product $\sigma_w(C+-C-)$ is compared to the covariance directly calculated with the EC method, which allows the determination of the β constant and an evaluation of its dependence on each parameter (offset, threshold, or time lag). Four variables are represented for each simulation: (1) the β constant, (2) the concentration in the reservoir corresponding to updrafts (C+) minus the mean concentration, and (3) the concentration in the reservoir corresponding to downdrafts (C-) minus the mean concentration, both normalized by the standard deviation of the concentration, and (4) the flux $(\beta\sigma_w(C+-C-))$ normalized by a reference flux Φ_0 . This reference flux is constant and does not vary when β , C+ and C- change. All these variables are nondimensional (normalized) and therefore represented on the same y axis (see Figures 5, 6, and 7).

The simulation method used here relies on random time series with known statistical properties. The turbulent functions correspond to the ones found in the boundary layer. W and X (vertical velocity and scalar, respectively) are built from a theoretical spectrum shape (Figure 4a). The turbulence scale corresponds to the nS(n) maximum (where n is the aircraft frequency). S(n) has a -5/3 slope in the inertial subrange, and nS(n) has a +1 slope in the low-frequency range. The correlation between W and X is defined by the frequency band around the spectrum peak (Figure 4a). The bandwidth allows the determination of the value of the correlation coefficient between W and X. An example of times series of W and X is shown in Figure 4b.

A sensitivity study for two different conditions of turbulence was conducted to describe the influence of constraints imposed on flux measurement. The first case corresponds to a flight performed for the evaluation of surface fluxes (Z = 50 m, aircraft speed = 90 m/s), and the second case corresponds to the evaluation of entrainment fluxes, near the top of the boundary layer (Z = 1200 m, aircraft speed = 100 m/s). Zi = 1500 m is the thickness of the boundary layer.

The REA characteristics depend on the wavelength of the spectrum peak of the vertical velocity. Near the surface (50 m) this wavelength λ is about 5 times the altitude where the aircraft flies ($\lambda = 5 \times Z = 5 \times 50$ m = 250 m) and then tends toward 1.5Zi when the aircraft flies at the top of the boundary layer ($\lambda = 1.5 \times 1500$ m = 2250 m) [*Caughey and Palmer*, 1979; *Druilhet et al.*, 1983]. The contribution of coherent structures is not treated here, because these may reach scales



Figure 5. Sensitivity of the REA variables to the vertical velocity offset for two flight levels: (a) 50 m (0.03Zi) and (b) 1200 m (0.8Zi). The offset is given proportionally to σ_w (standard deviation of the vertical velocity). The REA variables are the β constant, C_{+}/σ_c , C_{-}/σ_c , and Φ/Φ_0 . Variable σ_c is the standard deviation of the concentration.

about 3 to 6 times the thickness of the boundary layer [Lohou et al., 1998], far above the actual aircraft sampling altitudes.

3.2.1. Sensitivity to the vertical velocity offset. Approximations of aircraft vertical velocity and attack angle are needed in the calculation of W in real time. The aircraft vertical velocity is calculated from INS data, which depends on the baroinertial coupling and may produce an offset of the order of 10 cm/s. W is difficult to control in practice, since the attack angle is difficult to define accurately. However, if the calibration is made off-line, the average components can be removed by a filtering or by stating the condition that $\overline{W} = 0$.

Figure 5 illustrates the influence of the offset on the REA variables β , $C+/\sigma_C$, $C-/\sigma_C$, and Φ/Φ_0 near the surface (0.03Zi)

on Figure 5a and near the top of the boundary layer (0.8Zi) on Figure 5b. The offset of W is given proportionally to σ_w . The result depends strongly on the statistical characteristics and the nonstationarity of the variables. For surface fluxes the variables are stationary and close to Gaussian variables. When the offset is negative (positive), the positive (negative) fraction increases. Consequently, the slightest skewness on the vertical velocity will produce a discontinuity on the result, through the effect on C+ and C-, related to the dependence of β on σ_w .(Figure 5a).

The nonstationarity of β (and Φ/Φ_0) increases with the spectral scale. In Figure 5b, as the offset decreases, β and Φ/Φ_0 increase, while C+ and C- decrease. In figure 5b (where



Figure 6. Sensitivity of the REA variables (same as in Figure 5) to the threshold (a) at 50 m (0.03*Zi*) and (b) at 1200 m (0.8*Zi*). The threshold is given proportionally to σ_w .

Z=1200 m) the spectral scale is greater than that near the surface (Figure 5a), and β and Φ/Φ_0 increase rapidly when the offset is negative. To avoid these effects, the average vertical velocity must be kept equal to zero. On the ARAT, a bandpass filtering was imposed on the W_{REA} in order to meet this condition.

3.2.2. Sensitivity to the vertical velocity threshold. In order to limit the electrovan switching frequency and avoid sampling around weak vertical velocities (so as to increase the concentration difference subsequently measured in the reservoirs), a threshold is fixed on the vertical velocity selection and air is not sampled into up or down reservoirs when the vertical winds are less than the threshold (deadband). Figure 6 illustrates the influence of the threshold on the REA variables (the threshold is proportional to σ_{w} , and ranges from 0 to $0.5\sigma_{w}$), near the ground (Figure 6a), and at

0.8Zi, (Figure 6b). A similar result was reported by Pattey et al. [1993] and Katul et al. [1996] for ground fluxes measurements: β decreases as the threshold increases. When the threshold increases the REA variables are influenced the same way near the ground and near the top of the boundary layer. In both cases the flux decrease is about 10% for a threshold equivalent to 0.1 σ_w . The difference in concentrations measured in the reservoirs increases significantly with the threshold. Consequently, the sensitivity of the measurement will be improved in the limit of $0.1\sigma_w$. Beyond this limit the diminution of the REA variables does not involve a realistic value of the flux anymore.

3.2.3. Sensitivity to the vertical velocity selection delay (time lag). The dependence of the REA variables with the time lag is illustrated on Figure 7 (0.03Zi on Figure 7a and 0.8Zi on Figure 7b). Near the surface the REA variables,



Figure 7. Sensitivity of the REA variables (same as in Figure 5) to the vertical velocity delay (time lag, in seconds) (a) at 50 m (0.03Zi) and (b) at 1200 m (0.8Zi).

especially β and Φ/Φ_0 , are strongly dependent on the increase of the time lag. Indeed, when Z = 50 m, the time needed to run the spectral scale ($\lambda = 250$ m) is T = 250/90 = 2.8 s, which is not negligible against the time lag (e.g. 0.2 s). As the delay increases, a point of discontinuity is involved (Figure 7a). On the contrary, at the top of the boundary layer, the increase of the delay has practically no influence. When Z=1200 m ($\lambda = 2250$ m), T = 2250/100 = 22.5 s is far greater than the time lag: the point of discontinuity is not reached. The influence of this point of discontinuity on the flux is very bad and leads to an unrealistic result. The importance of obtaining the smallest delay between W_{REA} and W_{REF} is emphasized. Consequently, the delay did not exceed 0.1 s during the EXPRESSO campaign.

3.2.4. Sensitivity to the low-pass filtering. Low-pass filtering is essential to the calculation of vertical velocity in real time: it smoothes the digital noise, applied by the REA computer, and it limits the switching frequency. A high-pass

filtering ensures that the mean vertical velocity W is equal to zero. Near the surface the REA variables are very sensitive to the low-pass filtering, whose effect is the same as the one of the increasing time lag. At the top of the boundary layer the influence of the low-pass filtering is rather weak (the filtering has also the same influence as the time lag). Precise real time vertical velocity measurements are, consequently, required to restrict the effect of the low-pass filtering on REA control.

4. Influence of Space-Dependent Drifts

The REA may be affected by several technical problems referenced above but may also be influenced by the physical characteristics of the scalar. In order to illustrate the influence of a nonstationary scalar, we used CO_2 fluxes data measured by EC and REA techniques during the EXPRESSO campaign. The calculation of CO_2 fluxes with the REA method and with the EC method could be simulated thanks to the high quality



Figure 8. Spatial drift of the CO₂ concentration on three low-level legs of flight 47 (forest flight performed during the EXPRESSO campaign on November 26 1996). (a) CO₂ concentration (in ppm) is plotted according to the distance covered by the aircraft. (b) The three CO₂ plots correspond to the three legs of the aircraft, whose altitude is represented. The fourth plot corresponds to the averaged ground level during the legs.

of the CO_2 concentration recorded during the flights. This simulation allows the evaluation of the influence of spatial drifts (which may be associated with physical low frequencies), encountered on the scalar. This evaluation is made by comparison between the directly measured CO_2 concentration and this same signal after a high-pass filtering.

Most of the spatial drifts are the result of the aircraft motion. Figure 8 illustrates the evolution of CO₂ concentration (Figure 8a) on three low-level legs performed during flight 47 (forest flight, top part of Figure 8b). The fourth line in the bottom part of Figure 8b shows the ground level topography. The legs are performed at three different altitudes, above the same ground path and using contrary directions. The 10 ppm decrease (or increase, depending on the direction of the leg) in the CO₂ concentration recurs from one leg to the other (on a 20-km horizontal path). REA CO₂ simulated fluxes are compared to CO₂ fluxes computed with the EC method in order to evaluate the influence of spatial drifts. A delayed filtering is applied on REA fluxes to remove the low-frequency CO₂ fluctuations. The calculation of a turbulent flux (with the EC method) is made in two different ways: the raw calculation uses all the spectral characteristics of the scalar and the filtered calculation eliminates all the wavelengths greater than 3Zi.

These functions were also used for the comparison of CO_2 fluxes with the REA method. Raw and filtered fluxes of both methods are compared on Figures 9a and 9b for 15 aircraft legs performed in the boundary layer at different altitudes. The REA constant β is 0.58 in the calculation (this value is usually used with physical functions).

Regressions values are good: 0.96 and 0.72 for filtered and raw fluxes, respectively. Although the regression value is weaker for raw fluxes, the correlation between the two fluxes remains favorable. This highlights an important and new result: it is well known that the EC method is weakly affected by low frequencies on the scalar; this comparison shows that the REA method is not more affected by spatial drifts than the EC method. Fluxes calculated with the experimental REA (and not simulated) are raw, and, consequently, low frequencies do not increase the uncertainty of the fluxes.

The raw flux/filtered flux ratio evaluated with the EC method for another scalar presenting the same kind of low frequencies as for the CO_2 can be easily calculated. An estimation of filtered REA fluxes can then be calculated, by applying it to raw REA fluxes. This ratio, calculated during the EXPRESSO campaign for water vapor, is close to 1 near the surface and reaches 1.5 at the top of the boundary layer, where the role of low frequencies induced by entrainment processes is enhanced.

5. Isoprene Flux Measurements During the EXPRESSO Campaign

The isoprene measurement was performed by a team from the National Center for Atmospheric Research, Atmospheric Chemistry Division [Greenberg et al., 1999]. Isoprene was trapped onto solid adsorbent cartridges and then analyzed in the laboratory after the experiment. The cartridges were a three-stage combination (from weakest to strongest adsorbent) glass beads, Carbotrap®, and Carbosieve S-III® of [Greenberg et al., 1999]. Cartridges were stored at approximately -30°C before and after flights, except during transport to and from the CAR. During transport, the cartridges were kept in an ice chest (0°C-5°C); transport time was approximately 30 hours. Samples were analyzed by gas chromatography with flame ionization and atomic emission detectors for quantitation and mass spectrometry for peak identifications. Details of analytical procedures and techniques are given by Greenberg et al. [1994].

Isoprene fluxes are plotted on Figure 10 for each type of ecosystem. This ecosystem classification was made from the analysis of AVHRR satellite data. The areas where REA



Figure 9. (a) REA raw fluxes compared to EC raw fluxes. (b) REA filtered fluxes compared to EC filtered fluxes. All the fluxes are in ppb.m.s⁻¹. The equations correspond to the regression line (solid black line). R^2 is the correlation coefficient.



Figure 10. Isoprene flux measurements made above the forest and the savanna, according to the latitude. As the vegetation varies with latitude, the x axis could have also been related to the vegetation. Two points only are available for each ecosystem, but each point is an average of several measurements. Consequently, vertical bars correspond to error bars, and horizontal bars correspond to the extension in latitude of the ecosystem.

isoprene fluxes were made were of two types. The savanna near Boali (coordinates: 4°N, 18°E) was very similar to the surrounding savanna over which REA measurements were made, so these measurements were included as one average value for savanna isoprene flux. The same was true for the tropical forest: the landscape surrounding Envélé (coordinates: 2°N, 17°E) was indistinguishable from other forest landscapes where we made REA measurements. So an average forest isoprene flux was also calculated. The savanna is actually classified as degraded woodland, which means that it was formerly tropical forest but has been subjected to repeated burns. The satellite vegetation database shows that the area where REA measurements were made corresponded to one land use classification (degraded woodland). The forest REA area was a mosaic of two land use categories: seasonal tropical forest and primary rainforest. The forest and degraded woodland landscapes can also be reclassified into approximately 20 sublandscapes each, but these mostly contain varying amounts of the same species. This may explain some of the variability of emissions measured over the landscapes, especially the forest area.

Isoprene fluxes over the Enyélé forest are about 980 $\mu g/m^2/h$ (0.27 $\mu g/m^2/s$), while they are about 900 $\mu g/m^2/h$ (0.25 $\mu g/m^2/s$) over all forests flown over during EXPRESSO. (These quantities are similar because of the similarity of the studied ecosystems.) Isoprene fluxes over the savanna are about 550 $\mu g/m^2/h$ (0.15 $\mu g/m^2/s$).

Isoprene fluxes were also measured on the N'Doki tower a few meters above the canopy. Mean midday fluxes (1000 LT and 1400 LT) were about 1400 μ g/m²/h in March and 460 μ g/m²/h in November (D. Serça et al., personal communication, 2000). These above-canopy and aircraft measurements were compared to the results of model evaluations [*Guenther et al.*, 1999]. The results of the model prediction were in good agreement (within a factor of 2) with experimental data, but field measurements are needed to parameterize the model for tropical landscapes.

6. Conclusion

The REA system deployed on the ARAT aircraft for the EXPRESSO campaign allowed the measurement of isoprene fluxes over the savanna and the forest. The REA method allows the direct measurement of vertical eddy fluxes, where fast-response physicochemical analyzers for EC measurements are unavailable. The accuracy of REA depends most critically on the accurate determination of vertical velocity of air in real time. A parallel and independent calculation vertical velocity algorithm (W_{REA}) was developed for the EXPRESSO campaign, and offline comparisons between the two vertical velocities, W_{REA} and W_{REF} show a very good agreement. Constraints, linked to the introduction of filtering imposed to obtain $\overline{W} = 0$ were evaluated in order to define their influence on the measurement accuracy.

Two conditions of turbulence, at the surface (0.03Zi) and in the entrainment zone (0.8Zi), were simulated. Four points were developed:

1. The offset on W_{REA} , the vertical velocity which controls the REA, may introduce an error in the resulting flux, which is corrected, in part, by a band-pass filter. This error may reach 15% at 0.8 Zi for an offset of 0.2 σ_{μ} (Table 1 and Figure 5).

Table 1.	Error	Rate of	the Flux	When	the (Offset,	the
Threshold	i, and	the Tim	e Lag Ind	crease			

	Error Rate, %						
	0.03 Zi	0.8 Zi					
Offset, Fraction of σ_w							
-0.2	3	15					
-0.1	1	5					
+0.1	2	3					
+0.2	4	8					
Threshold, Fraction of σ_w							
0 05	5	3					
0.1	8	6					
0.2	15	11					
Time Lag, s							
0.125	4	1					
0 25	29	5					

Variable σ_{ν} is the standard deviation of the vertical velocity.

2. The introduction of a threshold on the REA vertical velocity helps to enhance the method sensitivity (Table 1 and Figure 6).

3.For the entrainment flux the time lag (between vetical velocity measurement and REA selection) does not have a big influence up to 1 s, but this delay must not exceed 0.1 s for the surface flux (the error rate increases up to 29% when the delay exceeds 0.125 s (Table 1 and Figure 7)).

4. The low-pass filtering effect is similar to the time lag: the filtering does not have a big influence at 0.8Zi, but the influence is very important near the surface.

The only way to avoid these effects is to ensure a W_{REA} the closest to W_{REF} . These simulations, made a posteriori, may eventually improve the calculation of W_{REA} , made in real time. The correction factors can be deduced directly from the error rates reported in Table 1. Additional simulations made with CO₂ concentrations show that the REA method is not more affected by low frequencies (spatial or temporal drifts of the scalar) than the EC method. The determination of a filtered flux/raw flux ratio of water vapor by EC, for instance, allows the evaluation of REA off-line filtered fluxes. The solving of technical problems encountered when the vertical velocity is measured is an additional step to ensure the accuracy and the reliability of REA flux measurements. Results obtained by REA isoprene fluxes are similar to isoprene REA tower fluxes made during the same period and area of the EXPRESSO campaign.

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