COMPARISON OF FLUX MEASUREMENTS WITH OPEN- AND CLOSED-PATH GAS ANALYZERS ABOVE AN AGRICULTURAL FIELD AND A FOREST FLOOR

(Research Note)

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Abstract. Comparison was made of the flux measurements of a closed-path CO_2/H_2O analyzer and an open-path H_2O analyzer above a clover field and the forest floor of a Douglas-fir stand. The attenuation of the gas concentration fluctuations caused by the sampling tube of the closed-path analyzer resulted in underestimation of the H20 flux above both surfaces. The degree of underestimation above the clover field depended on wind speed, but was smaller than that calculated from the transfer function for laminar flow in a circular tube and the scalar cospectrum in the neutral and unstable surface layer. Above the forest floor CO_2 fluctuations led those of H_2O by $\sim$0.7 s. The implications of this are discussed regarding the determination of the time delay caused by the sampling tube of the closed-path analyzer. The day-time CO_2 efflux from the forest floor, averaged over three days, was 0.043 mg/(m^2s).

1. Introduction

A prerequisite for the study of exchange processes of gases such as H_2O, CO_2 and CH_4 in the biosphere and atmosphere is the accurate measurement of their fluxes. For some gases (e.g., H_2O), the measurement can be made using the eddy correlation technique with a velocity sensor and an adjacent open-path gas analyzer. For trace gases such as CO_2 and CH_4, the measurement is frequently made using the eddy correlation technique with a closed-path analyzer. In this case, air is transported from the sampling point near the velocity sensor through a tube to the analyzer sample cell. To ensure accuracy, corrections must be made for fluctuations in humidity and the time delay and damping of fluctuations along the sampling tube. Recently, several papers have addressed these corrections (Lenshow and Raupach, 1991: Leuning and King, 1992: Leuning and Moncrieff, 1990; Massman, 1991). But there are few experimental studies comparing flux measurements with both closed- and open-path analyzers in outdoor environments (e.g., Leuning and King, 1992), and the result regarding the damping correction is not conclusive. In order to address these issues further, we present a comparison of flux measurements made with an open-path H_2O analyzer and a closed-path CO_2/H_2O analyzer above both an agricultural field and the floor of a coniferous forest.

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2. Experimental Methods

2.1. Sites and Instrumentation

The first experiment was performed above a level clover field in Delta, 15 km south of Vancouver, from 18 to 20 August, 1992. The clover canopy was about 20 cm tall and covered about 10% of the ground surface. The instrument tower was located at the centre of the field, which was 500 × 200 m. An eddy correlation unit was operated at a height of 1.42 m in the daytime. It consisted of a 3-dimensional sonic anemometer/thermometer (Applied Technologies Inc., Boulder, CO, Model SWS-211/3V) for measuring the three velocity components and air temperature, an open-path infrared analyzer (Campbell Scientific Inc., Logan, UT, Model K20 hygrometer) for H_2O vapour density, and a closed-path CO_2/H_2O infrared analyzer (LI-COR Inc., Lincoln, NE., Model LI-6262 with a time constant of 0.1 s) for CO_2 and H_2O vapour density. The closed-path analyzer was operated in absolute mode. A 12 V DC pump (Brailsford Co. Ltd., Rye, NY, Model TD-4X2N) was used to draw air from the sampling point near the open-path analyzer and the sonic anemometer/thermometer through a Dekaron tube 1.91 m in length and 4.5 mm in radius (Eaton Corp., OH), an external filter (Gelman Acro 50) and an internal Bev-a-line tube about 30 cm in length and 1.6 mm in radius, to the sample cell of the analyzer at a flow rate of about 4.5 l/min. Another pump of the same type was used to circulate the air in a closed loop connecting the reference cell and an acrylic tube containing a desiccant and a scrubber to remove H_2O and CO_2 in this cell for absolute mode operation.

The second experiment was performed with the same apparatus above the forest floor within a Douglas-fir stand in Pacific Spirit Park, Vancouver, from 21 to 27 September, 1992. The stand was about 100 years old, with dominant tree height of about 30 m and a density of about 600 stems/ha. There was no understory vegetation in an area of at least 60 m in radius surrounding the instrument tower. The surface organic layer was 2–5 cm thick. The eddy correlation unit was operated at a height of 2.3 m above the ground.

The analogue signals from the two analyzers were digitized by a 12-bit A/D board built into the electronics of the sonic unit, resulting in a total of 7 data channels sampled at 9.9 Hz. The raw digital data were sent via a serial port to a lap-top computer with a 20 Mb hard drive. Calculations of the eddy fluxes and other turbulence statistics were done after completing the field measurements.

Supplementary measurements included air temperature near the sampling point, temperature of the closed-path analyzer sample cell, and soil temperature at the 5 cm depth. Barometric pressure was obtained from the weather station at Vancouver International Airport.

After the first experiment was completed, it was realized that while the resolution of the A/D converter was adequate for measuring H_2O flux above the clover field with the closed-path analyzer, it was not for CO_2 flux. Therefore, in the second experiment the CO_2 signal was first offset by a constant voltage of 2.005 V and then amplified by a factor of 10 (Neff Instrument Corp., Duarte, CA, amplifier Model SC019, cut-off frequency set at 10 Hz), prior to the A/D conversion.

The open-path analyzer was calibrated in July, 1992, with a dew point generator (LI-COR Inc., Model LI-610). For the closed-path analyzer, factory calibrations were used, but the span and zero potentiometers were set before each of the two experiments. H_2O span was set with the dew point generator using a dew point of about 20 °C and the CO_2 span was set by passing a calibration gas with a concentration of 369 ppmv through the sample cell. The factory calibrations were then checked against measurements with the dew point generator at several dew points below 20 °C and against various CO_2 concentrations less than 369 ppmv obtained with a gas diluter (Analytical Development Co. Ltd., Hoddesdon, England, Model GD-601). Excellent agreement was obtained.

2.2. Data analysis

An averaging time interval of 30 min was used in the calculations of the fluxes. Corrections were made to the H_2O flux measured with the open-path analyzer for the effects of mean H_2O density and fluctuations in air temperature, and to the CO_2 flux with the closed-path analyzer for fluctuations in H_2O concentration (Webb *et al.*, 1980). No correction was made to the closed-path H_2O flux for the mean H_2O density effect (the $\mu\sigma$ term in Equation 25 of Webb *et al.*, 1980). The error introduced by this is negligible (<0.5%). Correction was also made to the fluxes measured with the closed-path analyzer for the difference in pressure (gauge pressure) between the sample cell and the ambient environment. This was done by measuring the concentration of H_2O in a large sealed room at flow rates used in the field and at zero flow rate. The ratio of the concentration without flow to that at field flow rates was 1.044 and was used for the gauge pressure correction.

3. Results and Discussion

3.1. Determination of time delay

The time delay caused by the sampling tube of the closed-path analyzer was determined as the lag at which the maximum cross-correlation over a 5-min interval occurred in the H_2O signals from the closed- and open-path analyzers. It was 1.72 and 2.22 s for the first and second experiments, respectively, and was incorporated into the program for calculating H_2O and CO_2 fluxes. The difference was a result of a slight change in the configuration of the sampling pump.

The time delay can be calculated from simultaneous measurements of the same gas using both open- and closed-path analyzers, as in the present study, with the former positioned near the inlet of the sampling tube. In many cases, however, there are no duplicate measurements of the same gas, and measurements of some other passive scalar have to be used in the cross-correlation calculation. For example, in a study of CO_2 exchange over an open bog, Neumann *et al.* (1992)

estimated their time delay based on the CO_2 signal from a closed-path and H_2O signal from an open-path analyzer. This method assumes that the fluctuations in the two scalars chosen for the cross-correlation calculation are exactly in phase (or out of phase) in the natural environment so that the estimated time lag is the time of travel of air from the tube inlet to the closed-path analyzer sample cell.

This assumption is generally true in the surface layer, because the ground is the only source/sink for all passive scalars. To confirm this, we calculated time lags between the closed-path CO_2 and open-path H_2O signals and between closed-path H_2O and sonic temperature signals, based on the cross-correlation technique, for the clover field experiment. The resulting values differed mostly by 0.1 s from 1.72 s, the value determined from correlation between the two H_2O signals.

The assumption is, however, unlikely to be appropriate above the forest floor due to differences in the source/sink distributions among the scalars. An extreme case is that of sensible heat and H_2O near the forest floor in a tall forest: H_2O flux is usually upward and originates from the forest floor while sensible heat flux in the daytime is generally downward and originates from the overstory (in the present study 30 out of 44 daytime runs had downward sensible heat flux; see also Lee and Black, 1993). Consequently, fluctuations in the two constituents may not be exactly in phase or out of phase. The assumption may not even hold for H_2O and CO_2. An asymmetry existed between these two gases during the daytime in the present study: the forest floor was a source and the overstory a sink of CO_2 while both were sources of H_2O. A visual inspection of the closed-path analyzer signals indicates that CO_2 fluctuations led H_2O fluctuations (Figure 1). The phase difference between the two signals at the beginning of each hour in the daytime, using the cross-correlation technique, was determine to be, in order, 0.3–0.9, 0.4–1.8 and 0.5–0.7 s for 22, 25 and 27 September, with an average value of 0.7 + 0.4 s ($n = 27$: mean + one standard deviation). To test the sensitivity of flux estimation to the time delay, we also calculated fluxes with a delay of 1.62 s for 22 September, This resulted in an overestimation of CO_2 flux by an average of 30% and an underestimation of H_2O flux by 25% compared to those with the delay of 2.22 s, the true travel time of air along the sampling tube. It is therefore important to estimate the time delay accurately for flux calculations with closed-path analyzers.

3.2. Comparison of the Fluxes

Figure 2 compares the H_2O flux measured with the two analyzers. The attenuation of the fluctuations along the sampling tube of the closed-path analyzer resulted in an average underestimation of the flux by 11 and 7%, respectively, above the clover field and the forest floor. The scatter for the clover field was large and was mainly caused by the change in mean wind speed from run to run (see below). The correlation between the two measurements above the forest floor was remarkably good, considering that the magnitude of H_2O flux was very small (less than 0.007 g/(m^2s), corresponding to latent heat flux of 16 W/m^2).

The attenuation of the fluctuations in a fluid drawn through a circular tube is a

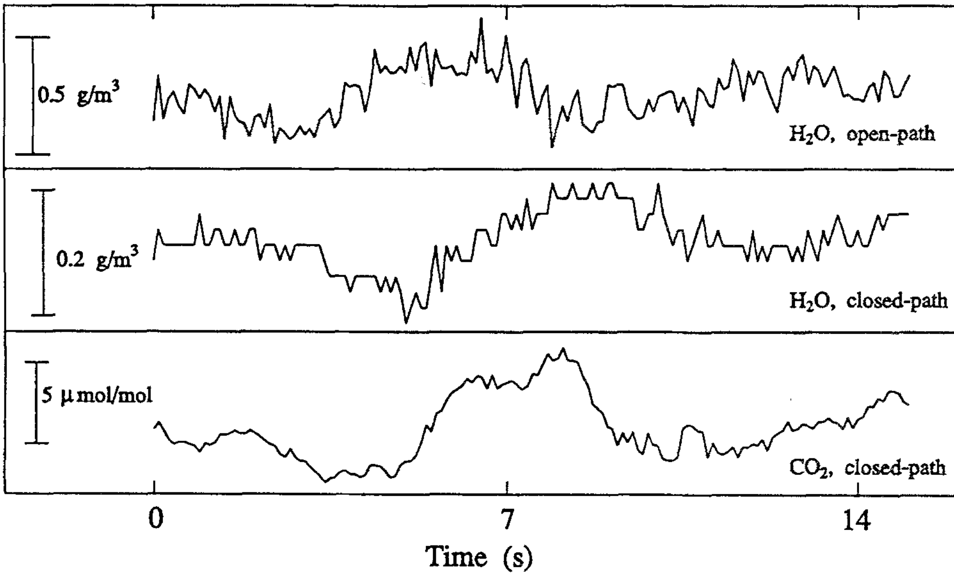

Fig. 1. A segment of 15 s time series of H_2O and CO_2 fluctuations near the forest floor within the Douglas-fir stand in Pacific Spirit Park starting at 9 h 39 min 50.5 s on 27 September, 1992.

frequency-dependent transfer function with attenuation increasing with frequency. Using a transfer function for circular tubes and the cospectra for sensible heat flux in the atmospheric surface layer, Leuning and Moncrieff (1990) predicted that the flux loss due to the tube attenuation would increase with wind speed in the surface layer. The main reason for this behaviour is that scalar flux spectra shift to higher frequencies at higher wind speed (Kaimal *et al.*, 1972). As shown in Figure 3, the attenuation depends on wind speed. The flux loss approaches 20% at a wind speed of 4.5 m/s but is negligible at about 2 m/s. In contrast, Leuning and Moncrieff's calculation for their sampling tube and flow rate suggests that there is still significant flux loss at wind speed as low as 1 m/s at a height of 1 m above the zero plane. The calculation made for our system, using the transfer function recommended by Leuning and King (1992, their Equation (12)) for laminar flow and the cospectra of scalar flux in the unstable surface layer (Kaimal *et al.*, 1972), also overestimates the flux loss, the ratio of closed-path to open-path flux being 0.81 at a wind speed of 2 m/s and 0.69 at 4 m/s.

Above the forest floor, the ratio varied between 0.75–0.95 for the runs with a flux magnitude >0.0025 g/(m^{2}s), and did not show wind speed dependence (wind speed in the range 0.3–0.7 m/s). The variation was greater for the runs with a smaller flux magnitude. For example, the 30-min run including the time series segment shown in Figure 1 had H_2O flux of 0.0016 g/(m^{2}s) and experienced as much as 50% damping of H_2O fluctuations by the sampling tube (Figure 1). The

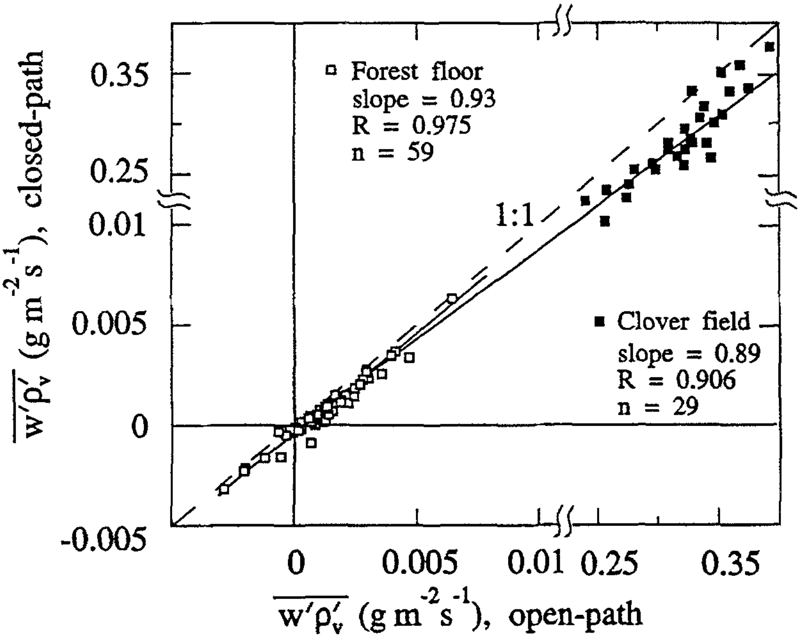

Fig. 2. Comparison of H_3O flux ($\overline{w'\rho_v'}$) measured with closed- and open-path analyzers above the clover field (■) in Delta and the forest floor (□) within the Douglas-fir stand in Pacific Spirit Park in 1992. The solid lines are for best fit equations. Also indicated are the number of runs (n), correlation coefficient (R) and the slope of the regression lines.

above transfer function approach is not applicable in the environment of this type, because the dynamics of scalar flux cospectra is not well understood, even though a few studies have reported the cospectra within vegetation canopies (e.g., Baldocchi and Meyers, 1991).

Figure 4 plots the diurnal course of the CO_2 flux above the forest floor, with the 7% correction made for the tube attenuation. The mean CO_2 flux in the daytime for 22, 25 and 27 September, was, in order, 0.033, 0.047 and 0.048 mg/(m^{2}s). The magnitude reported here is similar to that above the floor of a deciduous forest (Baldocchi and Meyers, 1991). There was no obvious diurnal pattern, possibly due to the small diurnal change in soil temperature (peak-to-peak value less than 1 °C).

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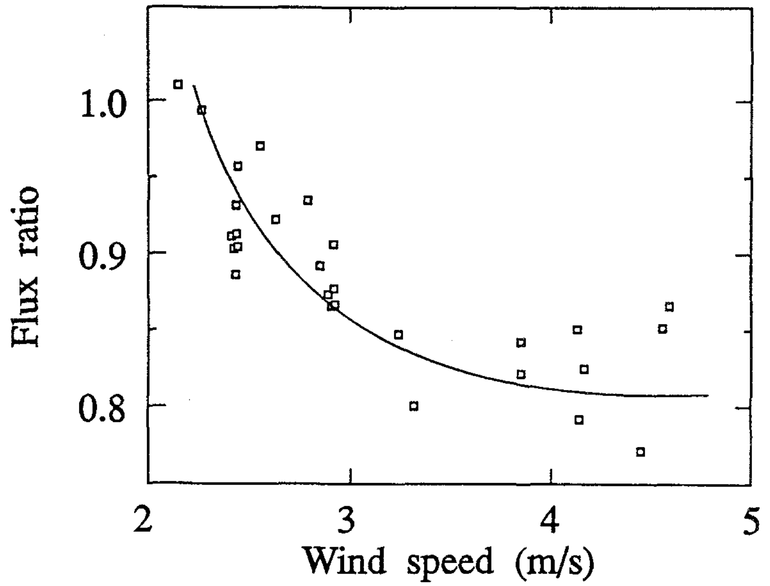

Fig. 3. Dependence of the ratio of H_2O flux measured with the closed-path analyzer to that with the open-path analyzer on wind speed above the clover field in Delta in August, 1992. The solid line is fitted by eye.

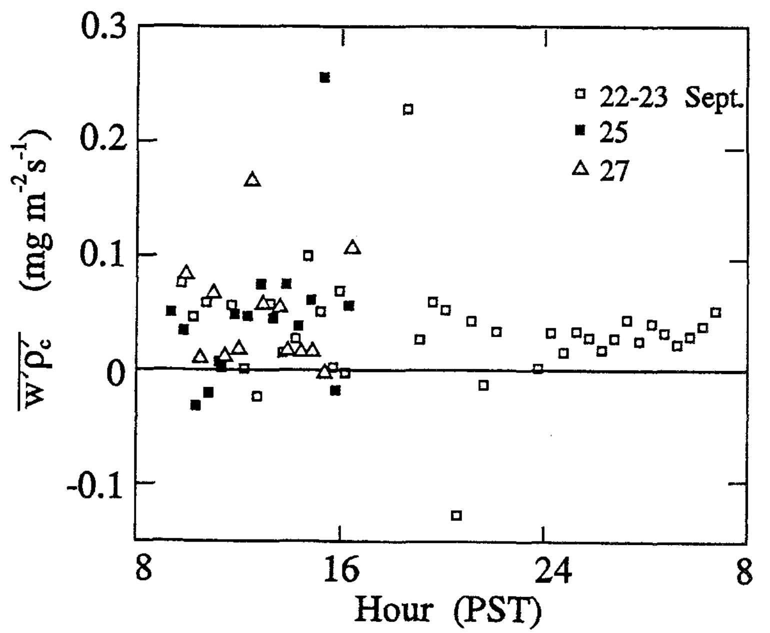

Fig. 4. Diurnal course of CO_2 flux ($\overline{w'\rho_c'}$) above the forest floor within the Douglis-fir stand in Pacific Spirit Park in September, 1992.

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