

# Damping of humidity fluctuations in a closed-path system

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**Abstract.** A Nafion pipe was added to a closed-path system used for eddy-covariance measurement of CO<sub>2</sub> in order to bypass density corrections of the flux in the post processing. The system was tested onboard R/V Aranda in the Baltic Sea during early spring 2009. It was found that by letting the air pass through a 0.3 m long Nafion pipe before reaching the gas analyzer the humidity fluctuations were reduced by a factor of 10. This damping in combination with the damping of the temperature fluctuations in the entire tube from inlet to analyzer was enough to omit the density correction during these environmental conditions.

Key Words: Eddy covariance, WPL-correction, closed-path sensor, air-sea flux

## 1. Introduction

The eddy-correlation method is a direct way to measure the turbulent fluxes of CO<sub>2</sub> between the surface and the atmosphere. It has the advantage of yielding the immediate fluxes averaged over 10-60 minutes. Thus, this method allows for a direct study of variables that influence the magnitude of the flux at relatively short time scales, which is appealing. However, corrections need to be applied to the measured fluxes in order to get any usable data from the measurements.

One of the corrections that need to be applied to the measured CO<sub>2</sub> fluxes is the so called Webb-Pearman-Leuning (WPL) correction (Webb *et al.* 1980). This corrects the measured CO<sub>2</sub> fluctuations for simultaneous fluctuations of density (sensible heat and water vapor). If a closed path sensor is used, the system can be designed in such a way that the sensible heat flux term in the correction can be

omitted (see e.g. Rannik *et al.* 1997 and Sahlée and Drennan 2009). However, the CO<sub>2</sub> flux still needs to be corrected for the water-vapor flux, which can be very large in the marine environment. Although the WPL-correction is a physically correct correction, it may be uncomfortable to apply a correction that may be as large as the measured flux, sometimes even changing the sign of the flux. In addition, the sensible and latent heat fluxes used in the WPL-correction are in themselves associated with uncertainties which thus add to the uncertainty of the CO<sub>2</sub> flux.

In this study we have evaluated a method of damping also the humidity fluctuations in a closed-path system, thereby removing the entire need of the WPL-correction thus reducing the uncertainty of the measured CO<sub>2</sub> flux.

## 2. Theory

Currently available gas analyzers used for fast response measurements of CO<sub>2</sub> measure the CO<sub>2</sub> density in the ambient air. Thus, these measurements can't directly be used to calculate the mass flux of CO<sub>2</sub> since CO<sub>2</sub> density fluctuations also arise by simultaneous fluctuations of temperature and water vapor, adding an "artificial" component to the measured flux.

The first thorough derivation of equations for the density corrections of the flux was presented in Webb *et al.* (1980), the WPL-correction. Their equation corrects the vertical CO<sub>2</sub> flux in the post-processing of the data according to the following:

$$F_c = \overline{w'\rho'_c} + \mu \frac{\overline{\rho_c}}{\rho_d} \overline{w'\rho'_v} + (1 + \mu\sigma) \frac{\overline{\rho_c}}{T} \overline{w'T'} \quad (1)$$

where  $F$  is the total corrected mass flux,  $\rho$  is the mass density, subscripts  $v$  and  $c$  refer to water vapor and CO<sub>2</sub> respectively,  $w$  is the vertical velocity,  $\overline{w'\rho'_c}$  is the uncorrected mass flux of CO<sub>2</sub>,  $\overline{w'\rho'_v}$  is the uncorrected mass flux of water vapor,  $\sigma$  is the ratio  $\frac{\rho_v}{\rho_a}$  (subscript  $a$  refers to the ambient air),  $T$  is the absolute air temperature (K),  $\overline{w'T'}$  is the vertical turbulent temperature flux and  $\mu$  is the ratio  $\frac{M_d}{M_v}$  where  $M$  is molar mass, subscript  $d$  refers to dry air. The usual notation is used in the Reynolds decomposition, i.e. an overbar denotes a mean value and the prime denotes a deviation from the mean value.

Alternatively, instead of correcting the fluxes in the post-processing, a corrected flux can be calculated directly by first converting the measured densities to mixing ratio using simultaneous measurements of water vapor and temperature

(Sahlée *et al.* 2008).

A full correction (Eq. 1) needs to be applied to measurements made with open-path gas analyzers. If a closed path sensor is used, i.e. where the gas has passed through some distance of tubing before reaching the analyzer, the sensible heat flux term may be omitted if the tube is long enough so that the temperature fluctuations are sufficiently damped (Sahlée and Drennan 2009, Rannik *et al.* 1997).

If a long enough Nafion pipe is added to a closed-path system then the water vapor flux term in the correction may also be omitted, removing the need for the density correction. In a Nafion pipe the sample air flow is separated from a counter flowing purge gas by a permeable Nafion membrane which lets only water vapor molecules pass through. Thus, by using dry air as a purge gas, the water vapor concentration difference between the sample air and purge gas will drive a transport of water vapor from the sample air flow to the purge gas, effectively drying the air that is sampled.

### 3. Experiment

A side-by-side test was setup on board the R/V Aranda during a cruise in the Baltic Sea in April 2009, comparing an open-path system with a closed-path system where a Nafion pipe had been included. The instrument used in the open-path system was a LI-75000 (Licor, Lincoln, Nebraska, USA), measuring the CO<sub>2</sub> and H<sub>2</sub>O density, mounted next to a Metek-1 sonic anemometer (Elmshorn, Germany), measuring the three wind components, on the bow mast at 16.2 m height above sea level. The closed-path system consisted of a LI-7500 operating in a “closed mode” by pumping air to the LI-7500 calibration chamber installed in the sensor head. A similar setup was first used in boundary-layer studies from low-level flights in hurricanes during CBLAST (Drennan *et al.* 2007). This setup was found to be well suited for the marine environment with a moving platform and risk of sea spray contamination of the sensor.

The sensor head was strapped down to minimize the risk of vibrations influencing the measurements and enclosed in a PVC casing, which was attached to the bow mast. A pump (Thomas G6/04) drew air from the tube inlet, placed at the sonic base, to the gas-analyzer through 1.5 m of plastic tube (Bev-A-Line IV, 3mm inner diameter, 6 mm outer diameter) and a 0.3 m long Nafion pipe. This tube length is enough to sufficiently damp the temperature fluctuations (Sahlée and Drennan 2009).

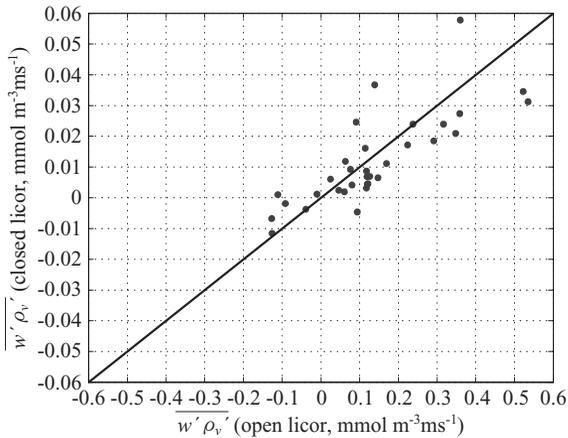
The instruments were sampled at 10 Hz. During the measurements the ship was kept at a fixed position, only moving to keep the bow facing into the mean wind direction. The wind measurements from the sonic were corrected for ship

motion in the post-processing. A crosswind correction according to Liu *et al.* (2001) was applied to the sonic temperature. To correct for the sensor separation between the gas analyzers and sonic anemometer, for each half hour run the time series of the CO<sub>2</sub>/H<sub>2</sub>O measurements was shifted step-wise until the maximum correlation with the vertical wind speed was reached.

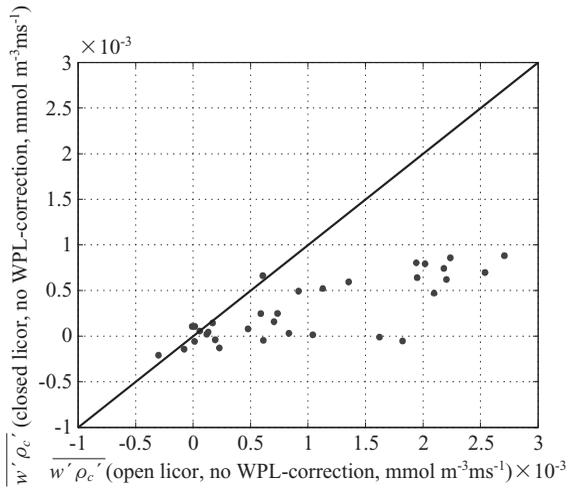
Additional instrumentation for measurements of mean wind speed and direction, relative humidity and air temperature was mounted above the bridge at 25 m height, this instrumentation is a part of R/V Aranda's permanent meteorological observing system. During the flux measurements the wind speed was low to moderate, never exceeding 10 m s<sup>-1</sup> and the atmospheric stratification was mainly stable, mean  $z/L=0.35$ , where  $z$  is the measurement height and  $L$  is the Obukhov length  $L = -u_* T_0 / (gk\overline{w'T_v'})$  where  $u_*$  is the friction velocity,  $T_0$  is the absolute temperature of the atmospheric surface layer,  $g$  is the acceleration of gravity,  $k$  is the von Karmán's constant (0.4) and  $\overline{w'T_v'}$  is the vertical turbulent virtual heat flux.

## 4. Results

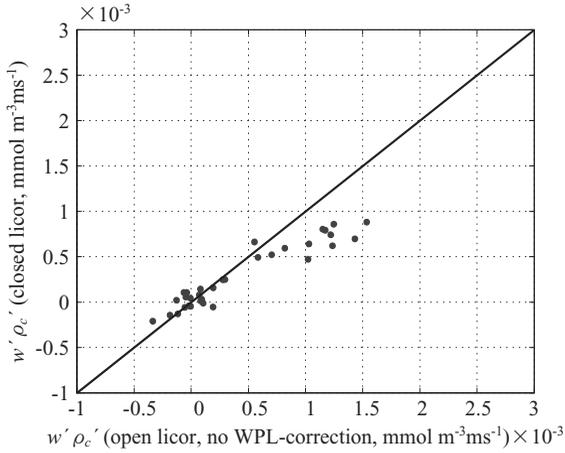
Figure 1 shows a scatter plot with the water vapor flux from the closed-path system on the vertical axis and the water vapor flux from the open-path system on the horizontal axis. The solid line has a 1:10 slope. From this figure it is clear that the Nafion pipe in the closed system has the effect of damping the water vapor flux



**Figure 1** vertical flux of water vapor as measured by the closed-path system with the Nafion pipe plotted against the vertical water vapor flux from the open-path system. Solid line indicated a 1:10 relation.



**Figure 2a** vertical flux of CO<sub>2</sub> measured by the closed system (without any WPL correction) as a function of vertical CO<sub>2</sub> flux measured by the open system, also without WPL correction.



**Figure 2b** as Figure 2a but WPL correction has been applied to the open-path system.

by a factor of 10.

Comparing the humidity variances,  $\sigma_q$  between the systems shows that  $\sigma_q$  in the closed-path system is reduced to about 20% of the open-path  $\sigma_q$ .

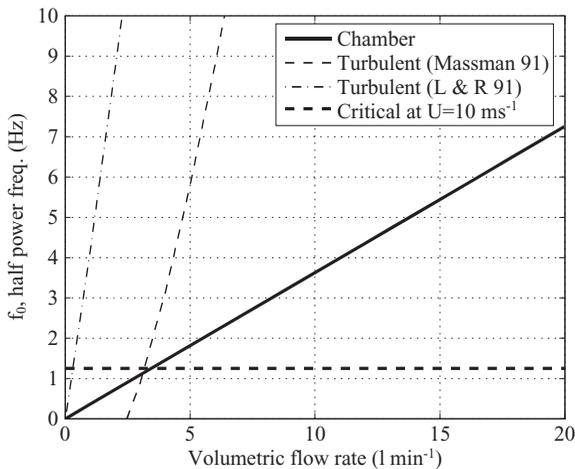
In Figure 2a the vertical flux of CO<sub>2</sub> measured by the closed-path system including the Nafion pipe is compared to the vertical flux of CO<sub>2</sub> measured by the

open-path system without applying the WPL-correction. As expected there is a rather poor agreement, due to the missing correction. In Figure 2b the WPL correction has been applied to the open-path system, and the comparison is improved significantly.

The remaining disagreement between the fluxes from the two systems is not due to the 10% remaining water vapor flux in the closed-path system. No change in the comparison is seen if the WPL correction is applied also to the closed system using the remaining water vapor flux (not shown). However, this might not be surprising since the water vapor flux was rather low during the measurements. The main part of the WPL-correction was due to the heat flux.

The disagreement might be explained by limitations in the bandwidth of the closed-path system, i.e. a flux loss due to attenuation of the measured signal in the tube and chamber. Leuning and Judd (1996) analyze the attenuation of a signal in a closed-path system by treating the system as a low-pass filter which is characterized by its half-power frequency  $f_0$ , i.e. the frequency at which the variance is reduced to one half. The same methodology has been applied when analyzing the bandwidth of the present system and is presented in Figure 3.

In Figure 3  $f_0$  for the tube and chamber is shown as a function of volumetric



**Figure 3** Analysis of bandwidth limitation in the closed-path system, illustrated as the half-power frequency,  $f_0$ , of the different components of the system (tube and chamber) as a function of volumetric flow rate. Two expressions for  $f_0$  for the tube are presented (dashed line, Massman 1991 and dash-dotted line, Lenschow and Raupach 1991). Horizontal bold dashed line marks the critical frequency that must be resolved in order to recover 95% of the true flux for neutral and unstable conditions (Kaimal *et al.* 1972).

flow rate. The pump used in this system had a flow rate of  $5 \text{ l min}^{-1}$  specified by the manufacturer, however no measurement of the flow rate was performed. The spectra presented in Kaimal *et al.* (1972) suggest that during neutral and unstable conditions 95% of the flux are present at normalized frequencies smaller than 2, where the normalized frequency is defined as  $f = nz/U$ , where  $n$  is frequency,  $z$  is measurement height and  $U$  is the wind speed. This frequency is calculated for the present measurement height and for a wind speed of  $10 \text{ m s}^{-1}$  and shown in Figure 3. Two expressions for  $f_0$  during turbulent tube flow are also shown in Figure 3, by Massman (1991) and Lenschow and Raupach (1991). As seen, both of these are well above the critical frequency for a volumetric flow rate of  $5 \text{ l min}^{-1}$ .

The half-power frequency for the flow through the chamber of the closed-path system is calculated according to:

$$f_0 = 3V_c / (2\pi v_a) \quad (2)$$

where  $V_c$  is the volumetric flow rate, and  $v_a$  is the volume of the measurement chamber ( $22.15 \text{ cm}^3$ ). Here it is assumed that the time to flush one volume of the calibration chamber is  $t_c = v_a / V_c$ . The half-power frequency is given by  $1/(2\pi\tau)$  where  $\tau$  is the time constant of the system. Assuming that  $t_c = 3\tau$  gives Equation (2). According to this analysis, the system should be able to resolve most of the flux, albeit  $f_0$  for the chamber is quite close to the critical frequency.

## 5. Discussion and conclusions

By adding a 0.3 m Nafion pipe to a closed-path gas analyzing system, the measured humidity flux is reduced by a factor of 10. This is sufficient to omit the WPL-correction in the flux calculation for the conditions encountered. However, the comparison between the closed-path system and the open-path reference system wasn't perfect: some discrepancy was seen for the larger  $\text{CO}_2$  fluxes. This might be due to limitations in bandwidth of the system, i.e. it is not able to resolve all important frequencies. According to theoretical considerations using the same analysis as in Leuning and Judd (1996) it appears that the bandwidth should be sufficient. However, no measurement of the volumetric flowrate was done, thus it is possible that the flow rate was lower than specified which could make the chamber volume a limiting factor for the system bandwidth. At lower flow rates it can also be questioned if the tube flow is fully turbulent; if not it would lead to large underestimation of the flux, which is seen in Figure 2b. Also, the critical frequency is presented for neutral and unstable conditions. During this experiment the stratification was mostly stable. Since the critical frequency increases with stability for stable stratification it's perhaps not a surprise that some flux loss was

experienced at the current flow rate.

Further development and testing is needed before routinely using the Nafion pipe in the closed-path system e.g. a larger flow rate is desirable. A 90% reduction of water vapor flux was enough for the conditions encountered during this particular experiment. However, the measured fluxes were very small. During conditions with larger vapor fluxes the damping might not be sufficient meaning that a longer Nafion pipe would be needed.

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