5.11 **EVALUATION OF UNCERTAINTY IN EDDY COVARIANCE MEASUREMENTS WITHIN FLUXNET-CANADA**

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1 INTRODUCTION

The Fluxnet-Canada Research Network (FCRN) is committed to rigorous quality assessment of the turbulent flux and climate data collected across the network. FCRN Protocols establish common procedures for measurements, processing of eddy covariance (EC) data and gap filling. All FCRN main sites are required to use a Gill R3 or CSAT3 sonic anemometer and an LI-7000 closed-path infra-red gas analyzer (IRGA) in a temperature-controlled housing designed by the UBC Biometeorology and Soil Physics Group. Furthermore, EC measurements at the sites must be checked against an inter-comparison EC (XSITE) system supplied by the University of British Columbia's Biometeorology and Soil Physics Group.

The objectives of this paper are to evaluate the suitability of the XSITE system for flux intercomparisons, establish what constitutes good agreement between to EC systems mounted close to each other and to present the results of the intercomparison experiments carried out at all main flux tower sites of the FCRN.

2 METHODS

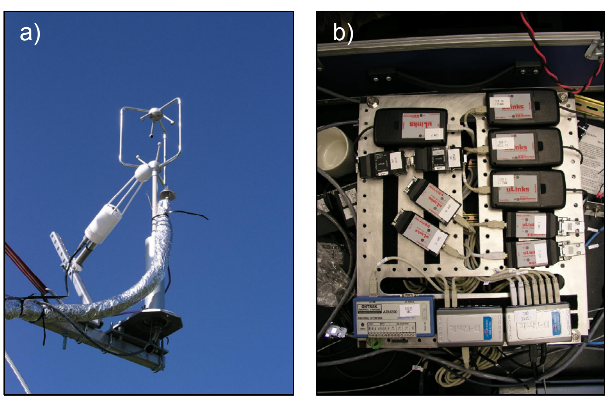

Figure 1: a) GillR3 sonic anemometer with LI-7500 open-path infra-red gas analyzer (IRGA) and closed-path sample tube. b) USB-to-serial (RS232) adapter set up for data logging.

During the field experiments, we followed a protocol for daily data analysis consisting of 1) visual inspection of high frequency data, 2) checking of diagnostic variables, 3) analysis of power and co-spectra, 4) regression analysis of processed fluxes and 5) calibration and delay-time checking of the closed-path system. Any problems discovered in the course of this daily analysis were solved and the measurements were continued until enough data points for a representative regression analysis were collected. Only measurement periods with good wind direction, no rain and air temperatures >5 °C were used in this analysis. Measurements were usually continued until at least 100 half-hourly periods were collected.

The XSITE system consists of a Gill R3 sonic anemometer and a LI-COR LI-7500 open-path IRGA as well as a LI-7000 closed-path IRGA (Figure 1a). All instruments are logged through serial RS232 communication (Figure 1b).

2.1 UBC Temperature controlled housing

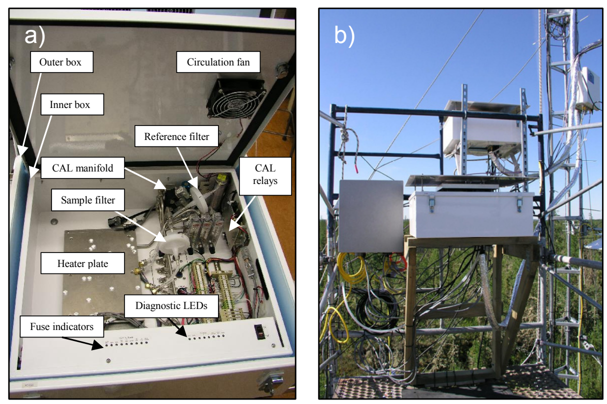

Figure 2: a) UBC temperature controlled housing (TCH) with the IRGA removed. b) Two TCHs mounted on a tower.

The IRGA is contained in a temperature-controlled housing (TCH) to provide it with a temperature-controlled environment and protect it from rain, dust or other outdoor hazards (Figure 2). The TCH controls the IRGA's optical bench temperature (not the air temperature in the housing) and maintains it at 38 °C. For ambient temperature between -25 °C and 30 °C bench temperature is maintained within 0.5 °C peak-to-peak.

The TCH also provides the interface for automated calibrations (Figure 3). Three different gases can be used for calibration (CAL0, CAL1 and CAL2). CAL0 is usually connected to a dry, CO_2-free gas (N_2) while CAL1 and CAL2 are connected to the tanks with known CO_2 mixing ratios.

The calibration gas is released at the sample tube inlet at a flow rate slightly higher than the sample flow rate (15 L/min), allowing the IRGA to be calibrated under working pressure and flow rate. This also provides an independent check of the closed-path system response time, given that these known gases travel the same path that the sample air travels, including the full length of the sample tube.

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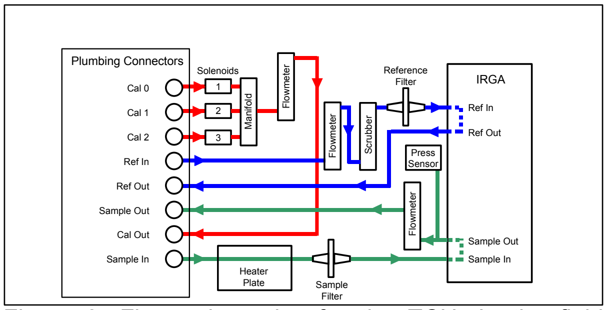

Figure 3: Flow schematics for the TCH. In the field *Sample In* is connected to a 4.5-m long heated sample tube and *Cal out* is connected to a line releasing the gas at the sample inlet.

3 MEASUREMENT UNCERTAINTY

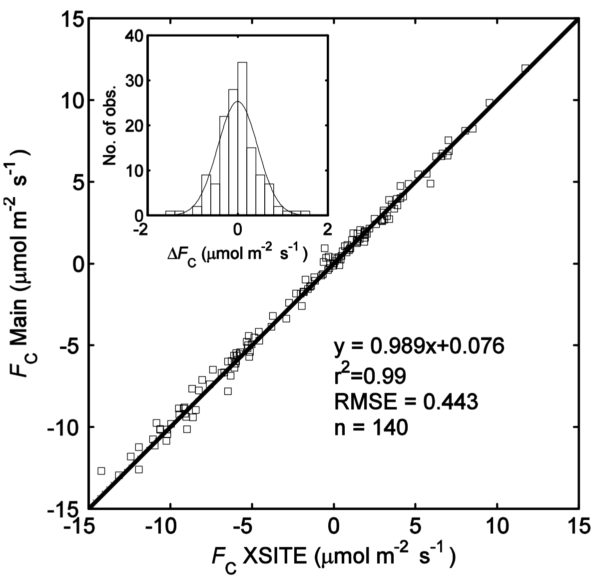

Figure 4: XSITE and site closed-path system CO_2 flux (F_C) measurements at QC-OBS (see Table 1). The inset shows the distribution of differences between measured and regressed values.

Figure 4 shows a comparison of CO_2 flux (F_C) measured by the XSITE and site EC systems at the QC-OBS site. The regression relationship from an orthogonal (Type II) regression is within error margins identical to the 1:1 line and the distribution of the differences ΔF_C between the two measured fluxes is close to Gaussian (Figure 4, inset distribution), albeit slightly leptokurtic, with a standard deviation of σ = 0.45 μmol m^{-2} s^{-1}.

For two EC systems with no instrument errors, variations between systems would mainly be caused by eddies on length scales smaller than the sensor separation because these cannot be simultaneously detected by both EC systems. Fortunately, above a forest canopy most of the covariance is contained in eddies on scales of tens to hundreds of metres, i.e. they are substantially larger than the distance between systems and will therefore be detected by both of them.

Figure 5 shows ensemble co-spectra of *w* and CO_2 for daytime half-hours with F_C < -2 μmol m^{-2} s^{-1} and *u* > 1 m s^{-1}, normalized by the total covariance (57 half-hours fulfilled these selection criteria). The vertical dotted line in Figure 5 is at n = 1/3 m^{-1}, corresponding to a length scale of about twice the distance separating the two systems. Overall, the ensemble spectra for both system agree quite well. However, deviations are present over the entire spectrum, not only for small length scales to the right of the vertical dotted line.

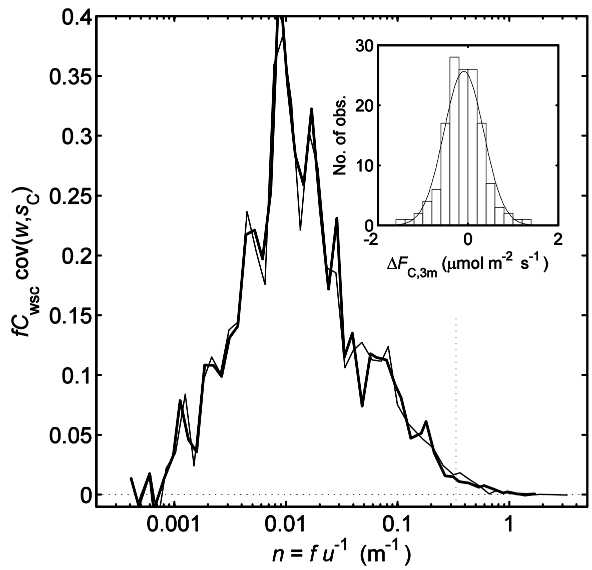

Figure 5: Ensemble CO_2 cospectra for the XSITE closed-path system (thin line) and the site closed-path system (thick line) at QC-OBS. See text for inset.

To quantify low-frequency contributions to the flux individual half-hourly spectra were integrated from the smallest frequency up to n = 1/3 m^{-1}. The results were then normalized with the integral over the entire spectrum. Multiplying the resulting fraction with the measured flux yielded an estimate of the flux $F_{C,3m}$ contained in eddies of scales larger than 3 m (typically 98% of the full-spectrum flux). The inset in Figure 5 shows the distribution of differences $\Delta F_{C,3m}$ between the XSITE and the site system. This distribution is very similar to the one in Figure 4, with σ = 0.44 μmol m^{-2} s^{-1} and a similar leptokurtic shape. This shows that random variability between the two EC systems is not caused by statistical error due to turbulent fluctuations at scales smaller than that of the system separation but rather by random instrument errors.

4 SYSTEM PERFORMANCE

Figure 6 shows the regression of F_C measured by the XSITE open-path system against that measured by the XSITE closed-path system for the ON-EPL comparison experiment. This data set was chosen because the site has short vegetation, making the comparison more demanding. The agreement is comparable to that shown in Figure 4. Since in this case both flux measurements use the same sonic, the only cause for differences is the IRGA measurement.

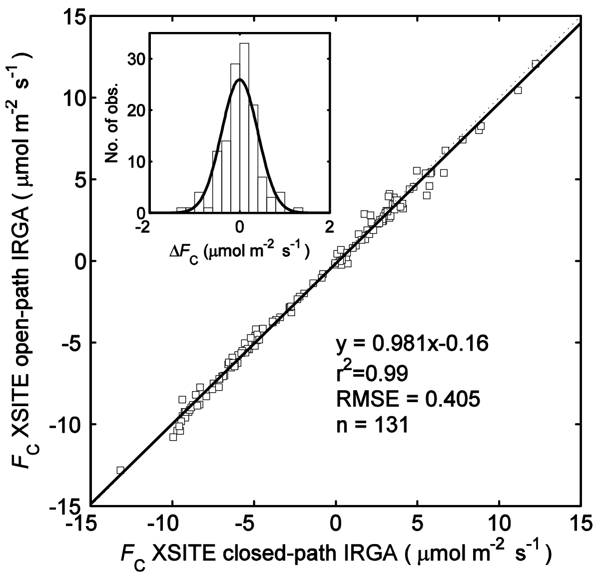

Figure 6: XSITE open to closed-path system CO_2 flux comparison at ON-EPL (see Table 1). Inset as in Figure 4.

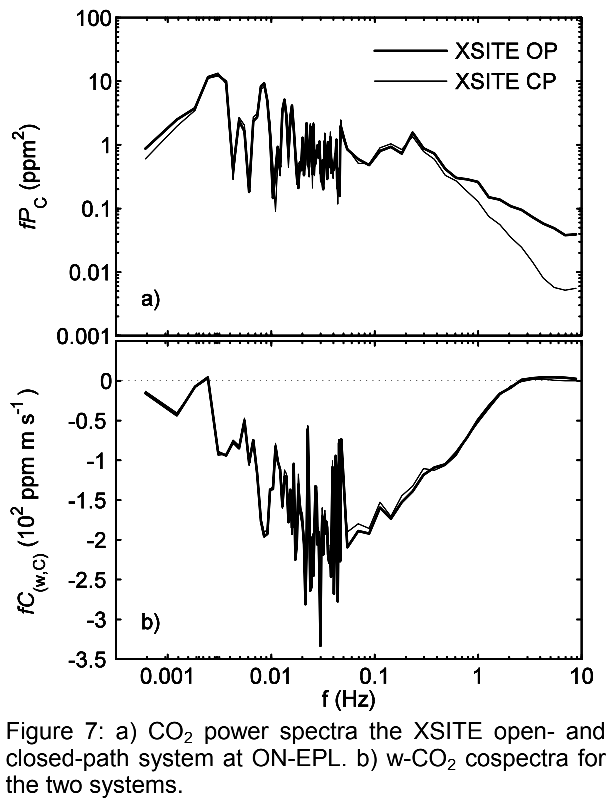

Figure 7: a) CO_2 power spectra the XSITE open- and closed-path system at ON-EPL. b) w-CO_2 cospectra for the two systems.

Figure 7 shows CO_2 power spectra and w-CO_2 cospectra for the open- and closed-path measurements. The closed-path system systematically underestimates variance above 0.5 Hz and the cospectra indicate that this frequency range contributes little to the flux. However, random variation between the cospectra are present at all frequencies, again showing that measurement errors are the main cause of half-hourly flux differences in our EC system comparisons.

The performance of the XSITE EC system was also assessed by estimating high-frequency losses from ratios of cospectra for w-T and w-CO_2 or w-water vapour, respectively. Since T is not subject to high-frequency losses, which for CO_2 and H_2O are due to the sampling system, the relative loss of covariance can be estimated, assuming that at middle frequencies (0.01 to 0.1 Hz) T as well as CO_2 and water vapour exhibit similarity. Transfer functions were calculated by fitting a logistic function to the ratio of mean cospectra and normalizing the result to 1 at f = 1/1800 s^{-1}.

Figure 8 shows transfer functions for the XSITE system during the comparison experiment at QC-OBS. For frequencies lower than 1 Hz, loss of covariance for CO_2 was less then 20 %. For water vapour, losses were similar for relative humidities (r_h) below 60 %. For r_h > 60 %, however, H_2O covariance at 1 Hz was reduced by 60 %. The loss in the measured flux can be estimated by integrating the w-T cospectrum before and after applying the transfer function. At QC-OBS, median losses were estimated to be 2 % for CO_2. Losses in water vapour fluxes were 2 % for r_h > 60 %, and 4 % for r_h > 60 %.

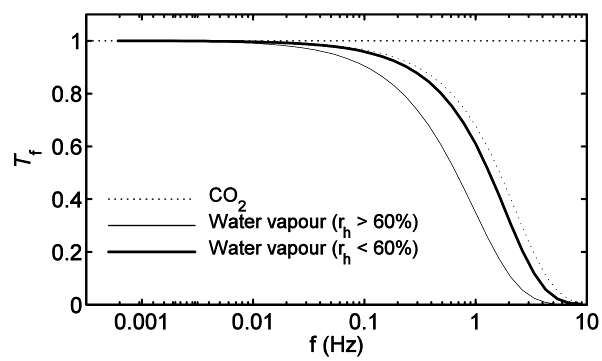

Figure 8: Transfer functions calculated from cospectral ratios of w-T and CO_2 and water vapour.

5 INTERCOMPARISON RESULTS

All FCRN stations have now been visited by the XSITE team (Table 1). Figure 9 summarizes the results of all intercomparison experiments carried out to date. The slopes of the regressions of the flux measurements from the site system vs. the XSITE closed-path system are given for sensible heat flux (H_s), latent heat flux (λE), CO_2 flux (F_C) and friction velocity (u_*). We analyzed only measurement periods with acceptable wind direction, no rain and air temperatures >5 ^oC. Measurements were usually continued until at least 100 half-hourly periods were collected.

Generally, the difference between fluxes from the XSITE and site system (with both systems operating properly) was less than 5 %, which was the threshold for acceptable agreement of the flux comparison. This value was chosen because instantaneous errors for anemometers (based on Gill and CSAT3 manuals) can be up to 6 % of the measured value depending on the attack angle, noise levels and calibrations. Gain errors

Table 1: Site visits carried out as part of the XSITE project.

Station	Site	XSITE comparison	Stand	Tower	Site EC system
BC	DF49	Apr 20 - May 25, 2005	Douglas-fir, h = 35 m	48-m 20'' triangular mast, z = 43 m	Gill R2/R3, LI-6262
BC	HDF89	Oct 1 – 20, 2004	Douglas fir, h = 8 m,	18-m 10'' triangular mast, z = 12 m	Gill R3, LI-7000
AB	WPL	Jun 16 – 21, 2004	Treed fen h = 4 m	9.5-m 10'' triamgular mast, z = 9 m	Gill R3HS, LI-7000
SK	OBS	Apr 30 – May 30, 2004	Black spruce h = 12 m	25-m walk-up scaffold tower, z = 28 m	Gill R3, LI-6262
ON	GR	Aug 1 - 14, 2005	Mixed forest, h = 23 m	45-m walk-up scaffold tower, z = 46 m	CSAT3, LI-7000
ON	TP	Jul 21 – 29, 2005	White pine, h = 22 m	28-m walk-up scaffold tower z = 28 m	CSAT3, LI-7000 in home-made TCH
ON	EPL	Jul 9 – 15, 2004	Raised bog h = 0.3 m	6-m 10'' triangular mast z = 2.5 m	Gill R3, LI-7000
QC	OBS	Jul 17 – 25, 2004	Black spruce h = 18 m	25-m walk-up scaffold tower z = 26 m	CSAT3, LI-7000 and LI-7500
NB	NL	Aug 23 – Sep 3, 2005	Balsam fir h = 13 m	18-m 20'' triangular mast z = 16 m	CSAT3, LI-7000

in the IRGA can be up to 1 % of the measurement and depend on instrument temperature. Based on these estimates and our experience with instrument comparisons in the field, we decided to use the 5 % threshold value to identify cases in which an attempt to improve measurements is justified.

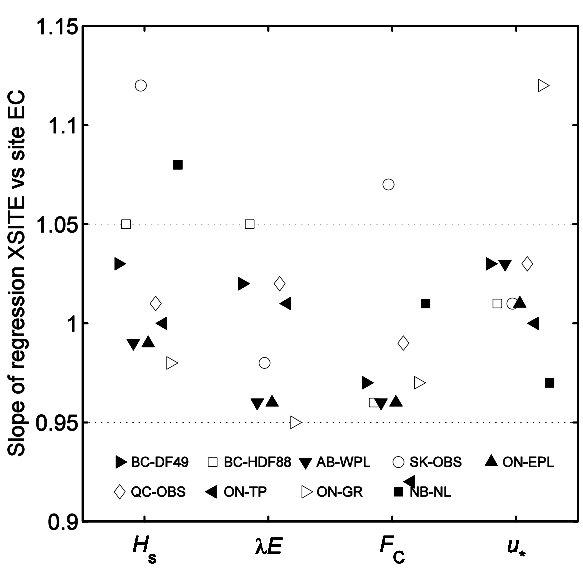

Figure 9: Slope values of orthogonal regressions of fluxes in all site system comparison after system adjustments (see Table 1). Value of the slope for NB-NL λE is 0.77.

In Figure 9, comparisons that exceeded this 5% threshold value were those for which the criteria for the number of data points and weather conditions had to be relaxed. At SK-OBS, the number of data points was small because the weather for the entire intercomparison period was generally cold and wet. At ON-GR, the wind direction regime during the comparison period was markedly different from averages recorded at the station, resulting in an excessive number of points that had to be excluded. At ON-TP, a sampling inlet funnel with excessive damping was replaced by a better one at the end of the comparison, but little time was left to properly test the funnel. However, in this case the improvement of measurements was obvious in the high frequency data when compared with the XSITE closed-path system. Finally, at NB-NL, electrical wiring and power problems combined with sonic anemometer positioning made it difficult to complete the evaluation even when the comparison period was extended.

However, generally the agreement between flux measurements from the two systems at all FCRN stations gives good confidence in the reliability of the results produced by the network.

6 CONCLUSIONS

Over the course of the three field seasons that the XSITE project has conducted experiments, we have drawn the following conclusions:

1) Sonic anemometers are the most common source of disagreement between site and XSITE EC systems;

2) The LI-7500 open-path IRGA, when carefully calibrated in the laboratory and used in favourable conditions (T_{air} > 5^{o}C, no rain), is reliable enough to detect most faulty IRGA behaviour;

3) Correct positioning of EC sensors with respect to the tower and dominant wind direction is essential to achieve good agreement between EC systems.