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A PERSPECTIVE ON CARBON DIOXIDE FLUX MEASUREMENTS USING AN OPEN-PATH INFRARED GAS ANALYZER IN COLD ENVIRONMENTS

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1. INTRODUCTION

Open-path infrared gas analyzers, such as the LI7500 (LICOR Inc, Lincoln, NE), have advantages for measuring fluxes of water and carbon dioxide over closed-path systems. The advantage is fast frequency response, lower power requirements and simplified system design because a pump is not needed to flow air through the sensor. Hence, they have become a common instrument for measurements in remote locations where power requirements are a major consideration. However, because the air measured is at ambient temperature, temperature fluctuations create density fluctuations which need to be accounted. Users employ the WPL adjustment (Webb et al. 1980) to account for density fluctuations caused by temperature and water vapour on the carbon dioxide concentration measurements. In theory, these adjustments are exact and allow for a correct determination of the CO_2 flux or net ecosystem exchange (NEE; sign convention of positive NEE is upward). Experiments have also shown that these adjustments work well in practical applications (Leuning et al. 1982, Ham and Heilman 2003). Many researchers have compared their open-path and close-path measurement systems and found good agreement. Also, most experiences with the LI7500 instrument have shown good stability between calibrations.

2. APPARENT PROBLEMS IN NEE MEASUREMENT IN COLD ENVIRONMENTS

Over the past few years, we have been puzzled by apparent downward day-time fluxes of carbon dioxide during winter at our sites in northern forests. The observations are inconsistent with our knowledge of biological activity in frozen landscapes, and are different from measurements made with a closed-path sensor, where small net respiration is observed. Figure 1 shows a pattern observed at threes sites in February 2005. The sites are within 70 km of each other with F98, F89 and F77 representing forest sites that had burned in 1998, 1989 and 1977, respectively. The pattern is for an apparent downward flux during the day. The magnitude shown here for the F98 and F89 sites is actually larger than normal, whereas the F77 behaviour is more typical. Also note that night-time fluxes should show net respiration, but often stay around zero. In all cases, the fluxes have been corrected for density (Webb et al. 1980). We show supporting data on incoming shortwave radiation, friction velocity (u_*) and air temperature in Figure 2. Maximum air temperatures are about -5C and it is unlikely that there will be a downward carbon dioxide flux at this temperature and time of year. This is especially true at the F98 site where most of the post-fire vegetation is under the snow and not well developed. The phenomenon actually appears to be as if the density correction is not sufficiently large.

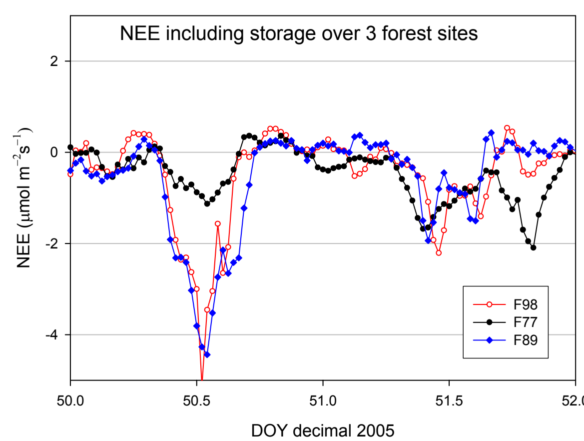

Figure 1. NEE measured at three forested sites in central Saskatchewan on February 19 and 20, 2005. The points are half-hour average fluxes, smoothed by averaging the point with the previous and following point (i.e., a 3-point filter). Storage is included and the fluxes have been corrected for density effects (Webb et al. 1980).

In Figures 1 and 2, air temperatures at a height of 1.5 m reach maxima of close to -5C. It is conceivable that canopy temperatures could be above freezing and that metabolic activity could occur. Hence, we show similar phenomena in Figure 3 where air temperatures remain below -20C. Although we understand that this temperature may push the specifications for the LI7500, it is important to note that similar patterns are observed in Figures 1 to 3.

This winter phenomenon has been difficult to diagnose. Several other researchers have also

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observed this at their sites, especially working in Alaska and northern Canada. This has caused many of these studies to not be able to report annual net ecosystem production values, because of suspect winter data (e.g., Amiro et al. 2006). In addition, researchers have largely been discovering this issue in a vacuum; i.e., it is not really documented, and researchers working in new environments are tempted to believe the results. To further complicate the issue, there does not appear to be a problem during warmer conditions, and summer-time comparisons between closed- and open-path sensors are usually satisfactory. Researchers working in warm desert conditions have not reported the issue. In our particular case, we have measured consistent net respiration using our open-path instrument over a barren field in summer (i.e., performs as expected).

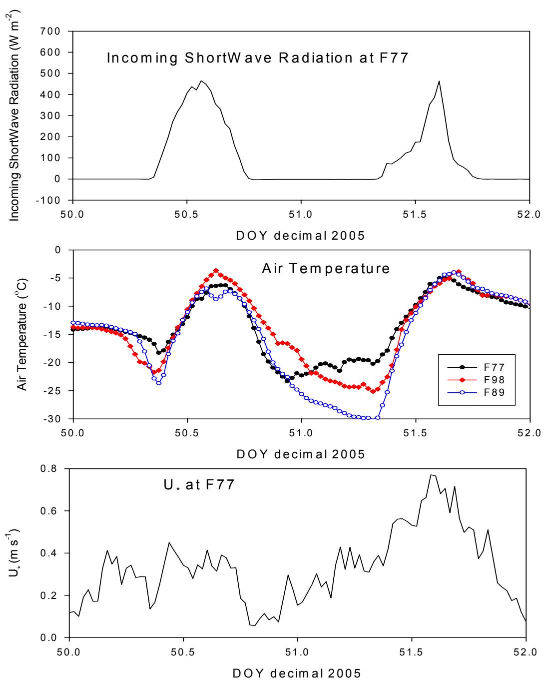

Figure 2: Incoming shortwave radiation, air temperature and friction velocity (u*) for February 18-19, 2005 at the sites in central Saskatchewan.

Our checks to date have included software and hardware investigations. The software has been checked many times, including sending our data to another group. In addition, the issue has been observed by independent researchers, using various software algorithms and data collection platforms. Hence, it is unlikely a problem caused by a single endemic software problem. Similarly, checks of the hardware have not explained the problem. We have checked calibrations in a cold room at -20C, and the instrument has performed well. Similarly, all of our four instruments have relatively recent serial numbers dated past an earlier light-dependent problem. We have also independently checked this. Much of the difficulty in diagnosis is related to the very low flux values in winter, making it hard to do intercomparisons without a wide dynamic range.

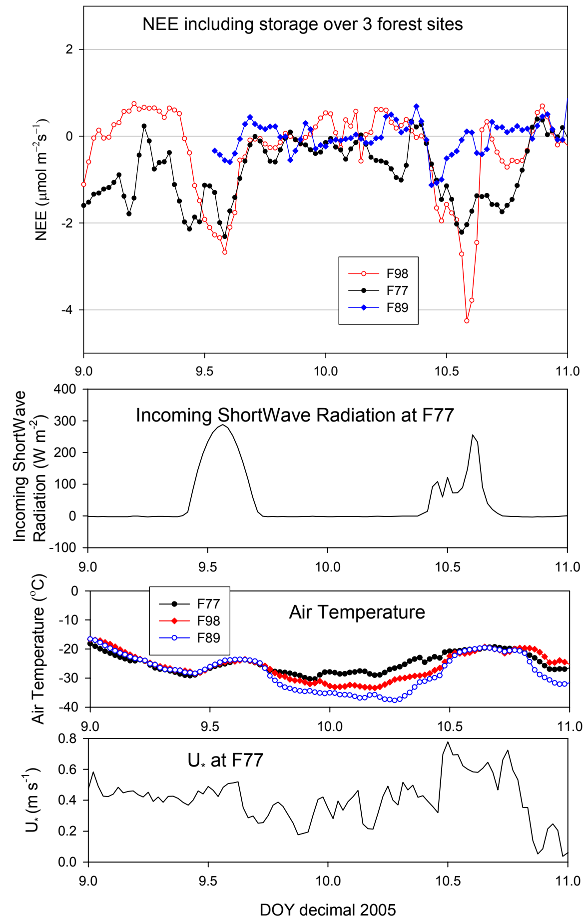

Figure 3: Similar information to Figures 1 and 2 except for two very cold days, January 9 to 10, 2005.

Recently, scientists at LICOR have been investigating potential effects caused by the heating of the open-path LI7500 sensor (Burba et al. 2005 a,b). The instrument uses a Peltier system to heat or cool the sensor head with an ideal operating temperature of 30 C. In principle, the instrument attempts to keep the sensor head near this ideal temperature. This should mean that maximum sensor head heating will occur during very cold conditions, and has the potential to create a local heat flux at the sensor head. Equation 1 describes the WPL adjustment where we normally calculate H at a nearby sonic anemometer (designated as H_a). This H_a assumes that H is the correct temperature fluctuation that is influencing the density of CO_2 at the sensor.

Equation 1:

$$NEE = \overline{w'\rho_C'} + \frac{\overline{\rho_C}\, H_a}{\overline{T} C_p\, \overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}\, M_a}{\overline{\rho_a}\, M_v}\right) + \frac{\overline{\rho_C}\, LEM_a}{\overline{\rho_a}\, M_v \lambda}$$

where w is the vertical wind velocity, ρ is a density with subscripts C for carbon dioxide, a for air and v for water vapour. M is the molecular weight for air (a) and water (v), T is air temperature, LE is the latent heat flux and λ is the latent heat of vaporization. Primes denote fluctuations and an overbar denotes a mean.

However, what if H_a does not estimate the correct temperature fluctuation at the sensor head? Instead, we really want to know the heat flux affecting the open-path density measurements, H_s. We recognize that there are other terms in Equation 1 that could be affected by this, such as the mean ρ_a, but let's assume that this effect is small.

So, with this reasoning, Equation 1 will be incorrect when $H_s \neq H_a$. In particular, under cold temperatures, we hypothesize that $H_s > H_a$. We have no direct measurement of H_s, so will assume that $H_s = H_a + H_h + H_r$, where H_h is a local heat flux generated by heating of the sensor head. We also introduce an additional term, H_r, which is a heat flux that could be potentially created by solar radiation impinging on the sensor head, and creating a local heat flux. H_h is a function of the heat control of the detector, which will increase as air temperature deviates from the ideal 30 C. H_r, in principle, should be real in any situation where the sensor absorbs incoming radiation and dissipates energy through convection. Although the sensor is painted to reflect much of the incoming solar radiation, it still has an albedo of less than unity and the potential to generate a local heat flux.

3. SOME IDEAS ON IDENTIFYING THE PROBLEM

Burba et al. (2005a,b) provide some ideas on possible corrections to heating of the sensor. This is based on heat transfer theory where the heat generated in the sensor head affects some portion of the path length where the CO_2 concentration is measured. The effect on the measurement path is estimated using heat transfer equations. This requires knowledge of temperature, wind speed, and radiation balance as well as the geometry of the instrument and its exposure. With sufficient information, exact heat transfer can be potentially determined such that the influence in the optical path can be corrected. This correction could be difficult in many field situations with an inherent uncertainty in the heat transfer parameterization caused by geometry. In turbulent flow, it is likely that warm eddies will move heat away from the sides of the instrument because heat dissipation is largely from this area (the sides of the cylinder are thinner than the top). We would expect that some of this heat will affect the path length of the LI7500 and the magnitude of effect will depend on orientation, wind speed and temperature difference.

In contrast to attempting to identify a correction based on heat transfer, we are exploring some approximate ideas to be used to quality control the data. First, let us focus on estimating the possible magnitude of H_h that would be needed to cause a measurement problem. Let's assume that the heating of the sensor head increases linearly with a decrease in temperature. This is likely not a linear function, but is a simple first approximation. Further, let's assume that the energy allocated to heating the sensor head increases from 0 W (at an isothermal condition of +30 C) to 15 W at -30 C (the maximum power consumption estimated by a LICOR engineer through personal communication). The difficulty is now to estimate what fraction of this heat could affect the path length. Without good physical reasons, we can arbitrarily investigate the effect of a small fraction of this heat, say if 2% of the energy escapes from the top surface of the sensor head and affects the optical path. For a top surface area of about 33 cm^2, this gives a maximum effect of 90 W m^{-2} at -30 C.

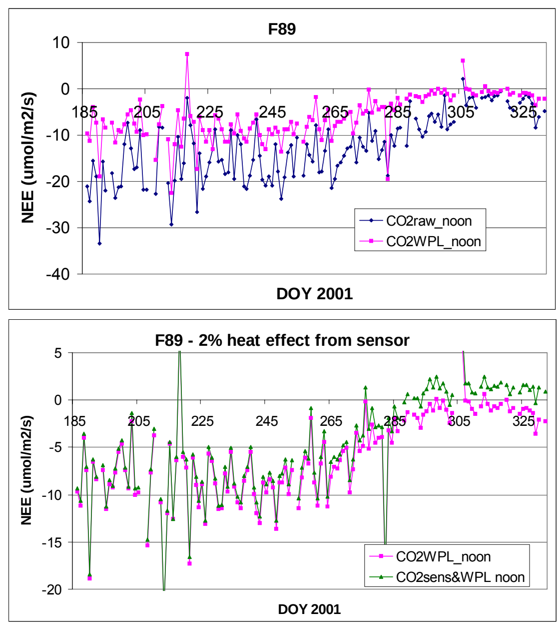

Figure 4: NEE at noon (half-hour mean) at the F89 site in 2001. The top graph shows the effect of the density correction: CO2raw_noon is the measured raw flux whereas CO2WPL_noon has the density correction (Webb et al. 1980). The bottom graph shows the effect if there was a small heating effect from the LI7500 sensor head, that becomes greater with cooler temperatures (CO2sens&WPL noon). Details of this calculation are given in the text.

In Figure 4, we present data from one of our sites collected in 2001 where the NEE at noon (half-hour mean) is plotted for each day. Here we show the data collected without the WPL adjustment and with the adjustment (top panel). With the WPL adjustment, noon NEE remains slightly negative for most days, even during the cold season where we expect no uptake past about DOY 300. In the bottom panel, we also plot the same data with an additional 2% of the energy effect as indicated in the preceding paragraph. This shows that the summer effect is small but that even a small heating correction can change NEE from negative to positive past about DOY 285. The resulting NEE of about +1 to 2 μmol $m^{-2}s^{-1}$ is in the range of our expectations for ecosystem respiration at this site. This arbitrary exercise demonstrates that even a small amount of heat loss can have a significant effect. In reality, we believe that the heating issue is not linear, and that the summer effect is less than shown in Figure 4. This is because the heating increases more steeply with decreasing temperature.

Inclusion of such a heating effect will essentially make NEE more positive in all cases because $H_s > H_a$. So for most days, the night-time correction will be slightly greater than the day-time correction. This would not explain our apparent day-time dip (i.e., more negative) in NEE as shown in Figures 1 and 3, although it could change day-time NEE from CO_2 uptake to net respiration (loss).

4. DISCUSSION

At this point, we still do not understand the phenomenon. The sensor heating effect is expected to be small. George Burba from LiCor Inc. reports only very minor heating when measurements near the sensor head have been measured using thermocouples (personal communication). Similarly, sensor heating cannot easily explain a diurnal pattern. However, it is interesting to note that we can sometimes see clear evidence of heating when frost has been deposited on sensors, as shown in Figure 5. In this particular instance, all other structures were frost coated but the LI7500 sensor base was clearly warmer and frost-free.

The potential for the term H_r, caused by an additional heat flux from local radiation intercepted by the head, would be consistent with the reasoning for a diurnal pattern. But such a phenomenon should be even greater in the summer or also show in data sets of researchers working in hot, dry environments. This does not appear to be the case (e.g., Leuning et al. 1982, Ham and Heilman 2003). It would laos need to be incrementally greater than H_a. We have not seen this pattern in our own data over a fallow field in the summer, where net respiration occurs (as expected).

We are currently working to see if we can find a quality-control procedure to know when some artefact is occurring. However, we have not been able to find good correlation with variables such as insolation, u_*, or air temperature.

We caution researchers working in new environments to make additional measurements to substantiate possibly new exciting findings. As an example, concluding that photosynthesis is occurring in cold environments through measurements of NEE with an open-path instrument needs to be substantiated with chamber or gradient measurements.

We welcome discussions with other researchers who have either observed this phenomenon or have developed solutions for it.

Figure 5. Photograph of an LI7500 sensor head during a frost event in November 2005. Note that all structures are frost covered except for the bottom part of the sensor. The wind direction is on an angle, but mostly from behind the sensor. Photo by Alberto Orchansky.

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REFERENCES

Amiro, B.D., A.G. Barr, T.A. Black, H. Iwashita, N. Kljun, J.H. McCaughey, K. Morgenstern, S. Murayama, Z. Nesic, A.L. Orchansky, and N. Saigusa. 2006. Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agric. Forest Meteorol.* (in press).

Burba, G.G., D.J. Anderson, L. Xu, and D.K. McDermitt. 2005. Solving the off-season uptake problem: Correcting fluxes measured with the LI-7500 for the effects of instrument surface heating. Part1:Theory. Poster presented at Ameriflux Annual Meeting, October.

Burba, G.G., D.J. Anderson, L. Xu, and D.K. McDermitt. 2005. Solving the off-season uptake problem: Correcting fluxes measured with the LI-7500 for the effects of instrument surface heating. Part1:Results. Poster presented at Ameriflux Annual Meeting, October.

Ham, J.M. and J.L. Heiman. 2003. Experimental test of density and energy-balance corrections on carbon dioxide flux as measured using open-path eddy covariance. Agron. J. 95: 1393-1403.

Leuning R., O.T. Denmead, A.R.G. Lang, and E. Ohtaki. 1982. Effects of heat and water vapor transport on eddy covariance measurement of CO_2 fluxes. *Boundary-Layer Meteorol.* 23: 209-222.

Webb E.K., G.I. Pearman, and R. Leuning. 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. *Quart. J. Roy. Meteorol. Soc.* 106: 85-100.