10A.6 SPATIAL VARIABILITY OF VERTICAL AND HORIZONTAL TURBULENT FLUXES ABOVE A BOREAL FOREST

Meelis Mölder[1,*], Christian Feigenwinter[2] and Anders Lindroth[1]

[1]Lund University, Sweden
[2]Gembloux Agricultural University, Belgium

1. INTRODUCTION

The exchange of momentum, energy and matter between ecosystems and the atmosphere is measured by the eddy covariance (EC) technique at numerous experimental sites in the frame of flux networks (e.g. FLUXNET). The measured annual sums of CO_2 uptake are considered to be representative for larger areas and for the respective plant species, despite the awareness of non-ideal conditions for the application of the EC method like insufficient fetch conditions, low turbulence during calm and stable nights, intermittent turbulence, etc.

The CarboEurope-IP advection group has under 2005 and 2006 carried out special wind velocity and CO_2 concentration measurements at three sites (Renon, Italy; Wetzstein, Germany; Norunda, Sweden) in order to estimate the non-turbulent vertical and horizontal advective fluxes of CO_2 (Feigenwinter et al., 2008). However the horizontal variability of vertical turbulent fluxes and the role of the horizontal flux divergence in the CO_2 conservation equation need to be investigated too.

The advection campaign at the Norunda site in summer 2006 provided an excellent opportunity to investigate the spatial variability of turbulent fluxes because three EC systems placed in line were operated during this campaign.

2. THEORY

The CO_2 conservation equation can be written:

$$NEE = z_r \frac{\partial \langle c \rangle}{\partial t} + \overline{w'c'}(z_r) + \overline{w}(z_r)\left(\overline{c}(z_r) - \langle c \rangle\right) + \\ + \int_0^{z_r} \left(\overline{u}(z) \frac{\partial \overline{c}(z)}{\partial x} + \overline{v}(z) \frac{\partial \overline{c}(z)}{\partial y} \right) dz + \int_0^{z_r} \left(\frac{\partial \overline{u'c'}}{\partial x} + \frac{\partial \overline{v'c'}}{\partial y} \right) dz$$

where $\langle c \rangle = \frac{1}{z_r} \int_0^{z_r} \overline{c}(z) dz$ is the vertically averaged concentration below the reference level and the CO_2 concentration c is given in μmol m^{-3}. The left side term, *NEE*, is the net ecosystem exchange in μmol m^{-2} s^{-1}. The first four terms on the right side of the equation are the storage change, the (vertical) eddy-covariance term, the vertical advective flux and the horizontal advective flux (Aubinet et al., 2003). The last term is the divergence term of the horizontal turbulent fluxes.

3. METHODS

The Norunda site (Lundin et al., 1999) represents a mixture of mature pine-spruce stands of 25 m height growing in a flat landscape. The main tower is 102 m tall. The surroundings of the tower are characterized by small inhomogeneous patches like large rocks, wet openings, roads, differences in stands etc.

For the advection measurement purposes the site was complemented with four additional towers, where the wind vectors, air temperatures and CO_2 concentrations were measured at four heights (1.5, 6, 12, 30 m) by the means of sonic anemometers and IR gas analysers. The four towers were installed in about 65 m diagonal distance from the central tower forming a 3D cube control volume. The central tower and two of the additional towers were equipped with EC systems at the 32-33 m level to estimate the spatial variability of turbulent fluxes. These three towers were in line in the SW to NE direction that was the dominant wind direction for the site. All the used gas analysers were of open-path type (LI-7500), two of the sonics were produced by Gill and the one in the central tower by Metek. The analysers were calibrated versus the same reference gases and dew-point generator at the end of the experiment. The measurements were carried out between July 7 and September 18, 2006.

Since different sonic anemometers were involved, a comparison of two systems was carried out in May 2008. One Gill system was mounted at nearly the same height as the Metek system in the central tower. The gas analysers were calibrated with the same gases and dew-point generator before the comparison experi-

* *Corresponding author address:* Meelis Mölder, Lund University, Dept. of Physical Geography and Ecosystems Analysis, SE-22362, Lund, Sweden; e-mail: meelis.molder@nateko.lu.se

ment began. It turned out that even the open-path gas analysers manufactured at different times were problematic.

The Metek anemometer included a factory set head (flow distortion) correction, but no such correction was applied to the Gill type sonics. It is known that the Gill's wind components can be underestimated at large attack angles. The Gill systems were operated at 20 Hz, but the Metek system at 10 Hz. The 2D rotation was applied on the wind velocity components. A maximum correlation was searched for between the vertical velocity and the CO_2 and water vapour concentrations in order to find the optimal time delay. The horizontal fluxes were calculated for the same time delay. A complete set of fluxes was calculated. In addition to $\overline{w'T'}$, $\overline{w'q'}$ and $\overline{w'c'}$ also $\overline{u'T'}$, $\overline{u'q'}$, $\overline{u'c'}$, $\overline{v'T'}$, $\overline{v'q'}$ and $\overline{v'c'}$ were calculated. Since the *u* component was along the mean wind, we do not consider the covariance with the *v* component here. The covariances involving temperature *T* and water vapour content *q* (thus sensible, *H,* and latent, *LE,* heat fluxes) have been converted to W m^{-2}, all the CO2 fluxes (vertical flux as F_c) are given in µmol m^{-2} s^{-1}.

The three systems are referred to as Lund, Metek and Jena, respectively. Both the Lund and Jena systems involved a Gill type sonic anemometer, but the Lund system was operated by the Lund University team and the Jena system by the Max Planck Institute team from Jena. The comparison in 2008 took place between the Metek and Lund systems.

4. RESULTS

4.1 *Comparison of systems*

For this comparison a five days long fair weather period (May 5–11, 2008) was available. Almost all wind directions were presented, but winds between the west and north still dominated. Those data, when wind blow through the tower, were excluded from wind component comparisons.

The standard deviation σ_w was considerably higher from the Metek sonic. But σ_u was somewhat larger from Gill sonic, however σ_v was smaller from Gill almost the same percentage. As a result of the correlation between *u* and *w*, the u_* was almost the same from the two. The σ_T tended to be smaller from Metek system, this combined with higher *w* gave almost equal sensible heat fluxes, *H*. For water vapour, the σ_q was slightly higher from Metek, but *LE* was still quite the same.

A problem that we were not aware of during the 2006 campaign was that the open-path gas analysers (LI-7500) were produced at different times. The oldest sensor in the Gill system was solar light sensitive. The newer

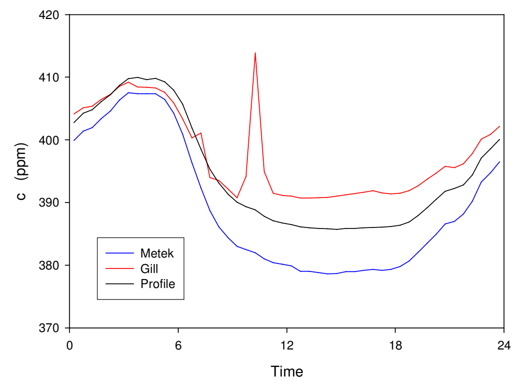

Figure 1. Average diurnal variation of CO_2 concentration, May 5-11, 2008

instruments in Metek and Jena systems should have been problem-free according to LiCor Inc. A comparison of average concentrations with a closed-path gas analyser operated at nearly atmospheric pressure shows a strong light effect on the Gill system (Figure 1), the daily amplitude being reduced. It also suggests an effect on the Metek system, with the daily amplitude being enhanced. Before the midday, when direct light could fall on the window, the concentration gives a spike. The standard deviation σ_c tended to be higher from Metek system, but not as much as the amplitudes of average concentrations would suggest. Possibly, the solar light changed also the offset of a LI-7500, even on the newer version of it. The F_c is always higher (more positive or negative) from the Metek system (Figure 2). All the horizontal fluxes, $\overline{u'T'}$, $\overline{u'q'}$ and $\overline{u'c'}$, are larger (absolute values) from the Gill system, possibly because of larger *w* component fluctuations.

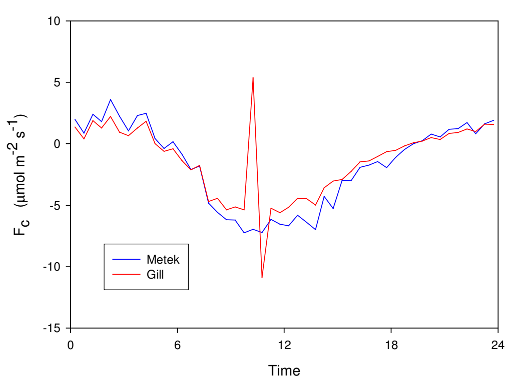

Figure 2. Average diurnal variation of CO_2 flux, May 5-11, 2008

4.2 Measurements during the advection campaign

Since all the EC systems were of open-path type, the CO_2 and H_2O data were extremely noisy (malfunctions due to wet conditions). For this study only three periods could be selected (6, 2 and 3 days long). Only during the first period (6 days between June 7 and 13) wind blow more or less along the line of the three towers. Regarding the other periods, even if there would have been detectable horizontal variations, they would not have contributed to the divergence. Here we present mainly the results from the first period.

During this first period, the σ_w was even larger from Metek than during the comparison period. However, σ_u values were quite similar. The σ_v relationship between Metek and Gill sonics was the same as during the comparison. As a result, u_* is considerably larger from Metek (Figure 3). During other periods they are quite similar. The sensible heat is higher

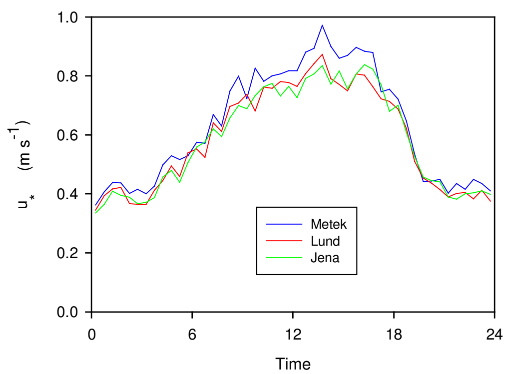

Figure 3. Average diurnal variation of friction velocity, June 7-9 and 11-13, 2008

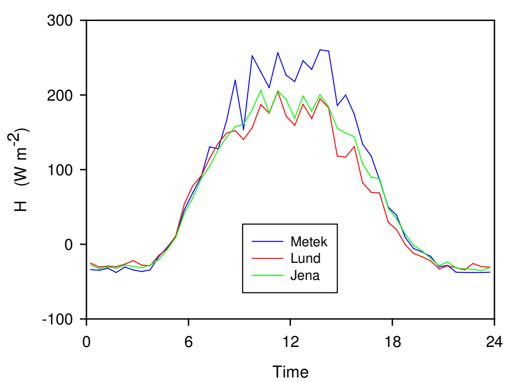

Figure 4. Average diurnal variation of sensible heat flux, June 7-9 and 11-13, 2008

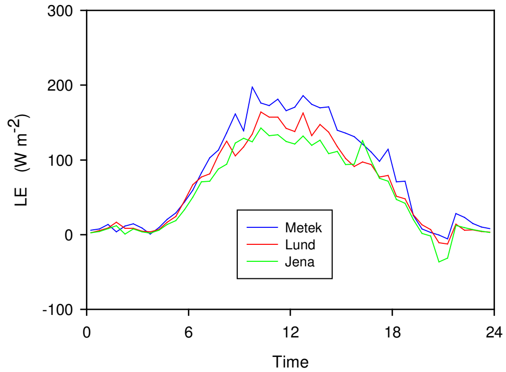

Figure 5. Average diurnal variation of latent heat flux, June 7-9 and 11-13, 2008

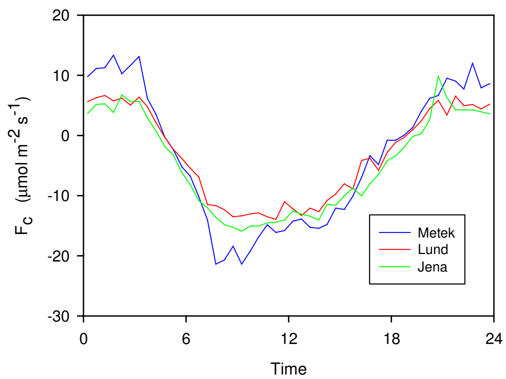

Figure 6. Average diurnal variation of CO_2 flux, June 7-9 and 11-13, 2008

from Metek when u_* was higher (Figure 4), otherwise quite similar. The latent heat flux tends to be higher all the time from Metek (Figure 5). The Jena system gives the lowest fluxes in the first half of the campaign. Those were reduced by 6% according to the calibration results after the campaign. The agreement would have been better without that correction, assuming that changes in calibration occurred later. For a later period the agreement is indeed better, but the fluxes themselves are smaller. Both σ_c and F_c tend to be larger from Metek like during the comparison period. F_c is especially large when u_*, H and LE were large too (Figure 6). Possibly it is not only an effect of differences in vertical velocity but also an effect of differences in concentration measurements. Even the Metek system gave (negative) spikes in the middle of the day during advection campaign, although it should not have been light sensitive. Nevertheless, the overall sun effect seemed to be milder during 2006. As seen already for the comparison period, all the horizontal turbulent fluxes are often larger from the systems with Gill sonic (Figure 7, 8, 9). Exception is the first period, when all fluxes involving CO_2 concentration, are larger from Metek and even $\overline{u'c'}$ is lager too (Figure 9).

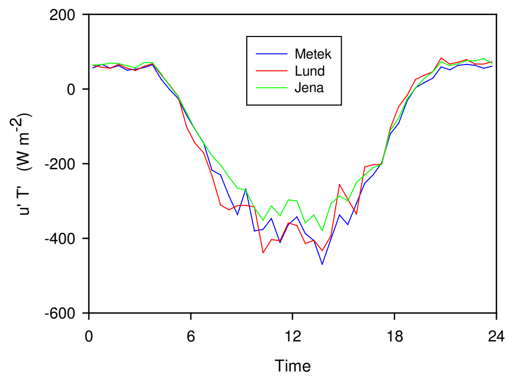

Figure 7. Average diurnal variation of horizontal sensible heat flux, June 7-9 and 11-13, 2008

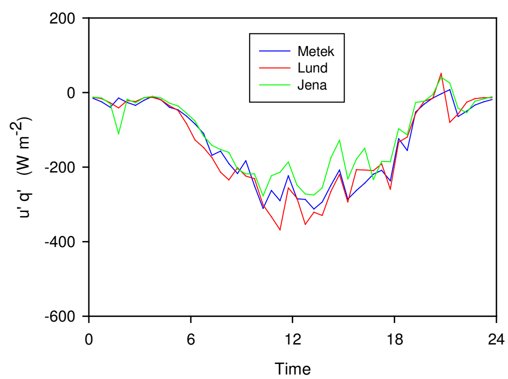

Figure 8. Average diurnal variation of horizontal latent heat flux, June 7-9 and 11-13, 2008

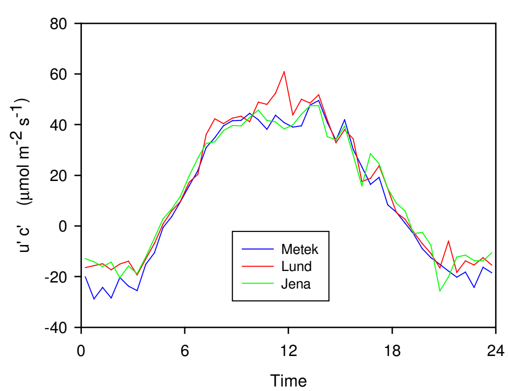

Figure 9. Average diurnal variation of horizontal CO_2 flux, June 7-9 and 11-13, 2008

What we see is that there are large differences in the fluxes, but most of them can be explained by instrumental differences. Also, the variations are larger during day because all the fluctuations are larger then. We know that advective fluxes occur more often during night. Discarding the Metek data and just considering Lund and Jena data, shows that we cannot distinguish any systematic differences from the natural variations during nights. The conclusion is that reliable and notable horizontal differences in the turbulent fluxes could not be detected in this study.

5. CONCLUSIONS

Spatial variations in both vertical and horizontal turbulent fluxes were studied using three EC systems placed in line above a boreal forest. There were remarkable differences but they could be explained by instrumental differences. It is clear that the wind components were measured differently by Gill and Metek type of sonic anemometers. Also, it turned out that the open-path analysers that were manufactured at different years gave different results. The oldest analyser being clearly sun radiation sensitive, but even the newer model showed some solar light effects. As a result we cannot detect any differences, larger than uncertainties, in the fluxes. Everything, fluxes themselves, their uncertainties and the differences are especially small during nights. A future experiment should make use of identical EC systems with closed-path gas analysers.

6. REFERENCES

Aubinet, M., Heinesch, B. and Yernaux, M., 2003: Horizontal and vertical CO_2 advection in a sloping forest. Boundary-Layer Meteorology, **108**, 397-417.

Feigenwinter, C., Bernhofer, C., Eichelmann, U., Heinesch, B., Hertel, M., Janous, D., Kolle, O., Lagergren, F., Lindroth, A., Minerbi, V., Moderow, U., Mölder, M., Montagnani, L., Queck, R., Rebmann, C., Vestin, P., Yernaux, M., Zeri, M., Ziegler, W. and Aubinet, M., 2008: Comparison of mean horizontal and vertical non turbulent advective fluxes at three CarboEurope forest sites. *Agricultural and Forest Meteorology*, **148**, 12 – 24.

Lundin, L.-C., Halldin, S., Lindroth, A., Cienciala, E., Grelle, A., Hjelm, P., Kellner, E., Lundberg, A., Mölder, M., Morén, A.-S., Nord, T., Seibert, J. and Stähli, M., 1999: Continuous long-term measurements of soil-plant-atmosphere variab-les at a forest site. *Agricultural and Forest Meteorology*. **98**/**99**, 53 – 74.