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RESULTS OF A PANEL DISCUSSION ABOUT THE ENERGY BALANCE CLOSURE CORRECTION FOR TRACE GASES

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TITLE: Atmospheric Transport and Chemistry in Forest Ecosystems

What: Panel discussion during the international conference focused on exhaustive efforts to determine the sources of the energy balance closure problem.

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The panel discussion on energy balance closure correction for trace gas fluxes was embedded into a conference on transport and chemistry in forest ecosystems. The discussion was a logical successor to a workshop held in 1994 in Grenoble (Foken; Oncley 1995), where the problem of the unclosed surface energy balance—which is where the observed turbulent fluxes of sensible and latent heat do not sufficiently account for the measured net available energy at the Earth's surface—was addressed after energy budget closure analyses in the 1980s and early 1990s (Bolle *et al.* 1993; Kanemasu *et al.* 1992; Koitzsch *et al.* 1988;

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Laubach; Teichmann 1996; Leuning *et al.* 1982; Tsvang *et al.* 1991). Many of the issues addressed in the 1994 workshop formed the scientific hypothesis for the special energy balance closure experiment EBEX-2000 (Oncley *et al.* 2007), but this campaign did not yield a complete solution to the problem. Since this time, much research has been done; at the beginning of the panel discussion Thomas Foken summarized many of these findings and the conclusions, mainly based on a presentation given at an iLEAPS workshop held in Boulder from January 26 to 28, 2006 on flux measurements in difficult conditions (Foken 2008).

- The different footprints of radiation, soil heat flux, and turbulent flux measurements including the storage terms, which were postulated earlier to be a reason (Culf *et al.* 2004), have no significant influence on the problem (Oncley *et al.* 2007). Of course, if the storage terms are not adequately calculated then their influence is significant (Meyers; Hollinger 2004; Oliphant *et al*. 2004).

- The eddy-covariance method can measure the turbulent transport of energy and matter accurately, provided all required corrections and conversions are applied properly (e.g. Foken et al. 2010; Mauder; Foken 2006; Mauder et al. 2006) and provided the underlying assumptions are fulfilled. These are, amongst others, frequency response (spectral) correction, stationarity (for spectral correction), corrections for sensor flow distortion (Cava *et al.* 2008; Nakai *et al.* 2006), and planar homogeneous flow and negligible local subsidence, because horizontal advection and a mean vertical mass flow are usually not determined.

- There are suggestions that in horizontally level terrain, where drainage flows are not an issue, the energy balance is usually closed at nighttime, when the turbulent fluxes are low. This indicates that the radiation and soil heat flux measurements are not the key issue. The quality of these measurements has been assessed carefully in the literature (e.g. Kohsiek *et al.* 2007; Liebethal *et al.* 2005). Care must be taken because of the large relative errors in measurements when the fluxes are of low magnitude, and indications that advection may still be major at some level sites at night (Paw U et al. 2000), even without drainage flows, when turbulence is low.

The energy balance is not closed at most of the FLUXNET sites (Aubinet *et al.* 2000; Wilson *et al.* 2002), even when the sites are horizontally level and flat, and plant canopies are short. There are, however, very homogeneous sites such as deserts where the energy balance can be closed under all conditions (Heusinkveld *et al.* 2004; Mauder *et al.* 2007b).

- These observations suggest that we fail to close the energy balance because we fail to account properly for *all of t*he mechanism*s of aer*odynamic transport of energy. Two important mechanisms which pose serious problems are horizontal divergence of the mean advective fluxes and transport by low frequency motions.

- Direct measurement of advection caused by drainage flows or complex topography has been shown to be ver*y diffic*ult (Aubinet et al. 2005; Feigenwinter et al. 2004; Paw U et al. 2004). Spatial averaging using a multi-tower set-up has been attempted by Mauder *et al.* (2008), but errors are still large. A combination of tower-measurements and modeling, whether it be analytical or large-eddy simulation, may assist in this analysis, in conjunction with better experimental designs (Dupont et al. 2008; Katul et al. 2006; Park; Paw U 2004; Yang et al. 2006a; Yang et al. 2006b). The ratio of vertical eddy-covariance and mean horizontal advective divergence fluxes can be related to a dimensionless number developed from theoretical derivations and supported by field experiments (Park; Paw U 2004).

- Over low vegetation, vertical transport by low frequency eddies appears to be unimportant as no significant additional flux contributions have been found for averaging intervals between 30 minutes and 240 minutes with ogive analysis, and only during the transition time of the day was an extension of the averaging period up to two hours able to increase the turbulent fluxes slightly (Foken et al. 2006).

- Over some tall towers, however, there is evidence from a range of sites that including low frequency contributions to the eddy flux, either by increasing the averaging time or using wavelet analysis to determine the fluxes, can close the energy balance (Finnigan et al. 2003; Mauder; Foken 2006; Mauder et al. 2007a; Sakai et al. 2001).

- Under convective conditions, we can identify several processes which can be responsible for this kind of low frequency vertical transport, such as slowly moving convection cells, coherent rolls, and transient changes in surface energy balance caused by passing clouds. The resulting low frequency motions are often sometimes referred to as “secondary circulations” particularly when they are quasi-stationary in space.

- This view is reinforced by recent Large-Eddy-Simulation (LES) studies above homogeneous and heterogeneous terrain in which organized turbulent structures and secondary circulations were investigated (Inagaki *et al.* 2006; Kanda *et al.* 2004; Steinfeld *et al.* 2007). All these papers have shown that the secondary circulations seriously affect the eddy covariance flux measurements and thus may contribute to the unclosed energy balance. As shown by Steinfeld *et al.* (2007), the effect of the secondary circulations increases with increasing observation height.

- Such secondary circulations can become fixed in space due to the heterogeneity of the surface. At border lines between heterogeneities, model and experimental studies have found higher energy fluxes (Klaassen et al. 2002; Schmid; Bünzli 1995). Because covariance systems are usually located in a uniform footprint area these enhanced fluxes at the interface are not measured (Foken 2008; Foken et al. 2010). The local energy balance at the tower is satisfied by adding the advective fluxes to or from the interface to the eddy fluxes but, of course, these advective fluxes are not usually measured, and it is still unclear how they can be measured at all (Aubinet et al. 2010).

- We note however, that spatial averaging techniques such as scintillometry (Meijninger et al. 2006) and airborne measurements (Mauder et al. 2007c) are able to capture these fluxes (Foken et al. 2010).

We are left with an apparent paradox in which some observations on towers over tall forest canopies are affected by low frequency contributions to eddy flux but can be corrected by increasing the averaging time (albeit with some practical difficulties). In contrast, eddy flux observations closer to the ground, which ogive analyses extending to periods as long as 4 hours show to have little or no low frequency contribution, still often fail to close the energy balance. Based on the LES simulations noted above we suggest the following testable hypothesis:

Even very close to the surface, under certain meteorological and geographic conditions, the spatial pattern of vertical energy transport may be modulated by the large scale circulations in the atmospheric boundary layer. Regions of *higher-than-average* transport are found near the interfaces between these circulations. As the circulations pass slowly over the surface, a tower may be located most of the time in the region of *lower-than-average* transport between these interfaces. During these times, the local energy balance is satisfied by unsteady advection to or from the regions of large transport, a term which cannot be measured on single towers. When an interface and a time of high transport passes over a tower, sensors may fail to capture this transport, either because analysis systems register it as mean vertical advection and many protocols routinely rotate to force $\overline{w}$ (i.e., mean vertical wind velocity) to zero or simply because the sensors are statistically unlikely to register many such events. This hypothesis can be tested readily using large eddy simulation results and by investigating the skewness of transport measured at towers.

From all these findings it follows that there is no simple way to correct the energy balance closure. Accordingly, the energy balance closure cannot be readily used to assess the accuracy of trace gas flux measurements, nor can it be used to correct them.

A related issue which must be addressed is that of correcting the unclosed energy balance artificially by allocating the residual [residual=(Rn-G)-(H+LE)] to the sensible and latent heat fluxes according to the Bowen-ratio (Twine *et al.* 2000). At least two major concepts must be assumed for this; one is that of scalar similarity. For higher frequencies, and when measured a sufficient distance away from the scalar sources, the transport of all gases seems to be similar (Pearson jr. *et al.* 1998) but for lower frequencies this scalar similarity may not be always fulfilled (Ruppert *et al.* 2006). If there is no scalar similarity between the sensible and latent heat flux, Bowen-ratio based correction fails. At least for some sites it appears that the proportions of the sensible and latent heat fluxes carried by low frequency eddies is different (Finnigan *et al.* 2003, Mauder, personal communication). A second assumption is that the sensors for temperature and humidity and their covariance with vertical velocity are equally affected by any sensor limitations, such as frequency response. But the lower frequency response, and great difficulty of maintaining calibration of humidity sensors, when compared to temperature sensors, may result in a greater error in latent heat flux measurements than those of sensible heat flux.

To solve the energy balance closure problem, this issue must first be taken much more seriously by the eddy-flux community. It is not only a problem of the measurement of sensible and latent heat flux but also of all trace gas fluxes. There is wide agreement among micrometeorologists that one major reason for the energy balance closure problem is unmeasured advective fluxes, sometimes associated with spatially stationary secondary circulations that can also be considered as unmeasured low frequency contributions to the vertical component of the eddy transport (Foken 2008; Mahrt 2010). If there are turbulent structures which cannot be measured with single point measurements, these affect not only the energy balance but also all trace gas fluxes.

The entire **FLUXNET** (Baldocchi *et al.* 2001) **community** should discuss the influence of the energy balance closure on tower-based trace gas data not as a measure of data quality (Aubinet *et al.* 2000) as is normally done at the moment, but as a reason for a possible flux bias, mainly during day time when spatially stationary circulations and secondary circulations exist, and when energy balance closure analysis is more accurate. In the same way the problem is of course relevant for all flux measurements in **atmospheric chemistry**.

Failure to close the energy balance is also a significant problem when the data are used to validate soil-vegetation-atmosphere transport (**SVAT) models** or simpler land surface boundary conditions for weather and climate models. Often such models appear to be in good agreement with the experimental data, but attribute the energy budget residual to the ground heat flux or storage (Kracher et al. 2009). This results in a ground heat flux/storage term that becomes too high so that a coupling with a soil model is difficult. In other cases, models distribute the residual simply according to the Bowen ratio. Both techniques have a significant, potentially inaccurate, influence on the water balance or the prediction of the air temperature.

Methods for analyzing the reasons for the lack of energy balance closure and its implications for different trace gas fluxes are still under discussion. They include:

- LES and higher-order closure model studies of low frequency circulations and mean advection
- theoretical studies in fluid dynamics,
- investigation of the effect of surface heterogeneities on advective flows,
- finding the optimum measuring locations in heterogeneous flows,

- investigations of similarity between the latent and sensible heat fluxes and other trace gas fluxes,
- statistical character of fluxes and averaging procedures.
- long-term integration of turbulence data
- improved measurements and estimation of storage terms

The panel discussion was not able to give an answer on all open questions but it stated that since the conference in 1994 much progress has been made towards finding the reasons for the energy balance closure problem. However, the panel felt it important to bring this issue to the attention of all affected scientific communities once again and to discuss and study methods for robust correction techniques to remove this source of uncertainty in eddy flux measurements of energy and other trace gases.

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