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

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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, France (Foken and 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; Laubach and 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 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 Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) workshop held in Boulder, Colorado, from January 26–28, 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

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influence on the problem (Oncley et al. 2007). Of course, if the storage terms are not adequately calculated, then their influence is significant (Meyers and 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 and Foken 2006; Mauder et al. 2006) and the underlying assumptions are fulfilled. These are, among 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 not usually 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 flux network (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. 2007c).
- These observations suggest that we fail to close the energy balance because we fail to account properly for *all* of the mechanisms of aerodynamic transport of energy. Two important mechanisms that 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 very difficult (Aubinet et al. 2005; Feigenwinter et al. 2004; Paw U et al. 2004). Spatial averaging using a multitower setup 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 and 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 and 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 and 240 min 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 and Foken 2006; Mauder et al. 2007b; Sakai et al. 2001).
- Under convective conditions, we can identify several processes that can be responsible for this kind of low-frequency vertical transport, such as slow-moving convection cells, coherent rolls, and transient changes, in surface energy balance caused by passing clouds. The resulting low-frequency motions are often referred to as "secondary circulations," particularly when they are quasistationary in space.
- This view is reinforced by recent large-eddy simulation (LES) studies above homogeneous and heterogeneous terrains 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 because of the heterogeneity of the surface. At border lines between heterogeneities, model and experimental studies have found higher energy fluxes (Klaassen et al. 2002; Schmid and 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; however, 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. 2007a) 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 they 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 four hours, have little or no low-frequency contribution, and 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 mean vertical wind velocity $\overline{w}$ 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 that 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 of which is 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 et al. 1998); however, 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 fluxes, then the correction based on the Bowen-ratio fails. At least for some sites, the proportions of the sensible and latent heat fluxes carried by low-frequency eddies appear to be different (Finnigan et al. 2003; M. Mauder 2008, personal communication). The second concept 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 the 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 fluxes 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 that cannot be measured with single-point measurements, then 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 daytime 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 transfer (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 they 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 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 the following:

- 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
- investigation of the optimum measuring locations in heterogeneous flows
- investigation of the similarities 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
- improvement of 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 toward 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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