Quality control of eddy-covariance measurements, Workshop at Castle Thurnau, November 15-17.
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Annotated review; H. Loescher, Oregon State University

This workshop focused on instrument calibration and classification, and data quality control criteria. The criteria were applied and assessed across several research studies. The workshop also included discussions on the current eddy covariance technique, as well as some innovative approaches to emerging issues, for example; u* corrections, nighttime advection, and using LES to address the spatial heterogeneity of energy balance. A new technique linked a QA/QC software package with source area models to determine which locations within the source area contribute to differing qualities of data was also introduced. Much of these results are to be considered as preliminary, and are presented here to invoke thought and feedback. Many presentations are available at; http://www.geo.uni-bayreuth.de/mikrometeorologie/QC_Workshop/

Foken-*overview*-introduced a classification scheme to determine the level of standard for radiation and turbulence sensors. Further discussion and recommendations regarding this classification scheme followed throughout the meeting. Classification of radiation sensors is based on time constant, offset, resolution, stability, and non-cosine, temperature and spectral response (Kasten 1985, Brock 2001). Likewise, turbulence sensors are classified into three categories (Foken and Oncley 1995),

Table 1. Proposed classification of sonic anemometers.

Classification	sensor
Fundamental	Kaijo-Denki typ-A CSAT3 NUWprobe (NCAR) Solent HS
General flux use	Kaijo-Denki typ-B Solent windmaster, R2, R3 METEK USA1 Young 81000
Normal use	2-D anemometers

Liebethal-*comparisons of radiation sensors during EBEX-2000 and VERTIKO measurement campaigns*-Classification of primary radiation sensors are based on their ability to internally correct for within dome heating, i.e. short-wave sensors Kipp-Zonen CM21 and Eppely PSP. Differences between longwave sensors were associated with solar heating effects. Net radiometers (Kipp-Zonen CNR1, Schultze, and REBS Q7.1) generally overestimated nighttime R_n by ~10-25 w m^{-2}, and underestimated daytime R_n by 1-80 w m^{-2}. Recommendations encouraged in-house calibration of sensors to a

primary standard that includes checking calibration coefficients and body temperature corrections over different conditions.

Vogt-*comparisons of radiation sensors*- The authors utilized a variety of upward- and downward facing radiations sensors for an intercomparison. Their findings include; that clouds can introduce 5-18 sec time constants in longwave radiation and data acquisition should accommodate this, longwave data should be excluded in early morning conditions when dew exists, differences in transmissivity exists between domes of same and dissimilar manufacturers, and leakage of shortwave radiation into longwave sensors exists and should be quantified.

Mauder-*comparison of sonic anemometers and humidity sensors during EBEX-2000 and EVA-GRIPS experiment*.- For the EBEX-2000 campaign, 5 sonic anemometers (3 fundamental, 2 general flux) were compared over irrigated cotton at a height of 4.7 m on different towers ~ 10-15 m apart. Planar fit rotation scheme (Wilczak *et al.* 2001) and path length correction (Moore, 1986) were used. Data was screened based on Foken and Wichura 1986. The intercomparison utilized a single reference instrument CSAT3 and used parameters $\bar{u}, \sigma_w^2, u^*, \overline{w'T'}$ to compare the other 3d anemometers. Intercepts did not differ from 0, and slopes were ± 3 % with $R^2 > 0.97$ for each of the parameters from (another) CSAT3, Solent HS and NUW(NCAR) anemometers. Regressions with the USA-1 probe had a slope of 1.05, 0.93, 1.02, 0.85 for $\bar{u}, \sigma_w^2, u^*, \overline{w'T'}$, respectively. The Young 81000 anemometer tended to overestimate σ_w^2 by ~ 6%, and only 88% of the variability in u* was accounted for.

For the EVA-GRIPS- campaign, 3 CSAT3 and 4 USA-1 anemometers were used for the intercomparison over 0.1 m grass canopy measured at 3.25 m ~ 10 m between towers. CSAT3 measured higher σ_w^2 by ca. 4-22 % than did USA-1. Similarly, CSAT3 probes tended to measure ~ 10-20% higher buoyancy flux ($\overline{w'T'}$). METEK anemometers account for flow distortion with an internal 'head correction' switched on. The calculation and effect of this correction is unknown, and should be open for discussion. The Solent R2 and R3 probes are considered omni-directional but limited evidence suggests flow distortion can occur around stanchions that support the head.

Recommendationd for humidity sensors include, Licor IRGAs have less inherent signal noise than kypton hygrometers, and the humidity sensor for standard calibrations should be a dewpoint chilled mirror able to run at 10 hrz.

Lebs-*comparisons of scintillometers and humidity sensors*-Kypton hygrometers have greater random noise than Licor IRGAs in measured water vapor. Moreover, variance among different kypton hygrometers (of the same manufacturer) can differ by ~ 10 %. Pathlength effects (Moore 1986) do not explain the apparent systematic bias seen between sensors. While Licor IRGA comparatively measures lower absolute concentrations in water vapor (~ 11%), fluxes are generally the same due to large non-correlated variance to w by the krypton hygrometers.

Anthoni-*open and close path comparison*- The authors compared the response of the Li-cor closed-path 6262 and open-path sensors over Pondersoa pine sites in Oregon.

Anthoni et al. applied the high frequency loss correction to the data collected from the closed-path sensor as outlined by Goulden et al. (1996), and applied the WPL corrections to the open-path data. The NOAA open path seemed to measure higher fluxes at night than the Licor 6262 closed path. Concentration measured by Licor 7500 and 6262 generally fall on a 1:1 line, but the amount of variability accounted for was not reported. NEE estimated by the closed path was ~ 20% **higher** than that measured by the open path at night. In contrast, NEE estimated by the closed-path was ~ 20% **lower** than that measured by the open path (7500) during the daytime. NEE estimates from the closed-path remained ~ 35% **lower** when integrating daily totals of NEE during summer periods with long daylengths. Moreover, nighttime estimates from the closed path were higher than the sum of integrated chamber measurements (from the Metolius site), suggesting the overestimation of R_e by the closed path system. Under near neutral conditions, open path sensors have difficulty in measuring low frequency contributions. Whereas, closed path sensors may miss high frequency components. The WPL corrections can be large, ~ 100 % under certain conditions, and there is no significant difference if applying this correction to 10 hz data or to the 30-min averages.

Liebethal-***Spectra and WPL correction***- an overview of the WPL approach, and defined as a 1d flux unit conversion however, the authors urge all sites to examine the entire control volume and to consider both vertical and horizontal advection. They also recommend that manufacturers report the frequency response and time constants of their instrumentation.

Mauder-***rotations, planar fit and u* correction*** –Authors question if the planar fit approach is appropriate for both night and day flow regimes? Or should separate datasets be used to calculate rotations to estimate flow during the day and night. Is planar fit appropriate for all wind directions? Some EUROFLUX sites still triple rotation assuming that $\overline{v} = 0, \overline{w} = 0, and\, \overline{w'v'} = 0$ the 30-min averaging time (Aubinet *et al.* 2000). During nighttime and low windspeed conditions in EBEX-2000 (over short canopy cotton, flat terrain), large rotation angles can occur using 2d rotation schemes. In contrast, planar fit method maintains correction angles close to zero shunting more turbulence into the w spectra. Hence, using the 2d rotation approach under low windspeed conditions, an artificial correlation can occur between horizontal and vertical wind components and can double u* when compared to estimates using the planar fit method. Changing the method of rotation may change the u* threshold. Sites converting over to the planar rotation should re-calculate their u* threshold values.

Beyrich–***transformation buoyancy flux to sensible heat flux***-as estimated by Kaimal and Gaynor 1991, if no crosswind corrections for temperature are included;

$$H = (M_a C_p / V)(\overline{w'T_s'} - (3.210^{-4} * T_k * \overline{w'q'})) \qquad \text{Eq. 1}$$

or with crosswind corrections

$$H = (M_a C_p / V)(\overline{w'T_s'} - (3.210^{-4} * T_k * \overline{w'q'}) + 2\hat{u}u'w' / 403) \qquad \text{Eq. 2}$$

or as estimated by Schotanus *et al.* 1983 accouning for crosswind effects

$$H = (M_a C_p / V)(\overline{w'T_s'} - (0.51 * T_k * \overline{w'q'})) + 2\frac{\overline{T}\overline{u}}{\overline{c}^2}\overline{w'u'} \qquad \text{Eq 3.}$$

The middle term in eqs. 1-3 is assumed to equal

$$0.51 * T_k * \overline{w'q'} \cong 0.51 \frac{C_p \overline{T}}{L\beta} \text{ where } \frac{1}{\beta} = \frac{\Delta q}{\Delta \theta} \qquad \text{Eq 4.}$$

This in turn, assumes equal transfer functions for heat and water vapor, i.e., $K_H = K_q$
For sonic anemometers that measure temperature along the vertical axis, Lui et al. 2001 suggests,

$$H = (M_a C_p / V)(\overline{w'T_s'} - (0.51 * T_k * \overline{w'q'})) + 2\frac{\overline{T}}{\overline{c^2}}(\overline{u}\,\overline{u'w'}A + \overline{v}\,\overline{v'w'}B) \qquad \text{Eq 5.}$$

And for sonic anemomenters that measure temperature along orthogonal axis (i.e., METEK USA1), A = B = 0.75, such that;

$$H = (M_a C_p / V)(\overline{w'T_s'} - (0.51 * T_k * \overline{w'q'})) + 1.5\frac{\overline{T}}{\overline{c^2}}\overline{u}u_*^2 \qquad \text{Eq 6.}$$

where, M_a is mol wt of dry air, C_p is the specific heat of dry air, V is the molar volume of air such that;
$V = (R*T_k)/P$, and R is the ideal gas constant, T_k is air temperature, and P is atmospheric pressure.
$T_k = T_s/(1 + 3.210^{-4}*q)$ Eq. 7
Crosswind effects increase curvilinearly with increases in u/u*, seem to have a greater effect with increases in surface roughness, and better fit the observed data. Overall the Schotanus transformation can account for ± 20 % of the flux. Other factors that may influence heat flux at high u/u* values include, vibrations in the sonic, vertical and horizontal flux divergences, and an oasis effect-stable stratification during daytime hours.

Letzel- ***LES study of the energy balance closure problem with eddy covariance technique***- LES model PALM (Raasch and Schröter 2001) was used to assess 1) the spatial representativeness of sensible and latent heat fluxes from a single point measurement (e.g. tower), and 2) the systematic underestimation of surface energy balance closure by eddy covariance. Model dimensions were 4 x 4 x 2 km with 250 x 250 x 250 m grid cells, where each intersection was a virtual tower resulting in 200 virtual towers. Comparisons were made between LES method using spatial Reynolds decomposition and the 'virtual tower' method using temporal Reynolds decomposition, such that;

$$F_s = w_s'T_s' + \underbrace{[w]}_{=0}[T] + w_s'[T] + \underbrace{[w]}_{=0}[T_s] = \overline{w_s'T_s'} + \underbrace{\overline{w_s'}}_{=0}[T] \text{ no large scale vertical motion}$$

$$F_t = w_t'T_{t_s}' + \overline{wT} + \underbrace{w_t'}_{=0}\overline{T} + \overline{w}\underbrace{T_t'}_{=0} = \overline{w_t'T_t'} + \overline{wT} = \text{EC flux and mean flow contribution}$$

Without modeling geostrophic winds, the distribution of the probability function was negatively skewed against the difference between these two methodologies (LES vs virtual tower) over a 1 h averaging period. The differences between these two methods were expressed as a ratio. Lengthening the averaging period to 3 h reduced the magnitude of the probability function and the skewness. Though the distribution remained slightly skewed. Modeling ambient surface winds from 1 to 4 m s^{-1} increased the probability function and reduced the skewness, i.e., deceases the imbalance closer to the canopy.

Letzel *et. al*. found that, i) 10-20 towers were needed to reduce the uncertainty to within 10%, ii) imbalance exists even for homogeneous CBL resulting in limitations for single point measurements, iii) longer averaging time slightly reduces the imbalance, iv) higher ambient winds strongly reduces the imbalance, v) the imbalance increases with height. Even though these approach is produce robust results and provides future directions from EC research, it lacks the use of actual turbulent times series and no high frequency turbulent characteristics.

Foken-*QA/QC for micromet and flux measurements*-an overall approach to assessing QA/QC in a dataset and links the assessment to a program that flags data dependent on the level of quality. The QA/QC assessment begins with defining the appropriate tests and criteria as outlined in Moncrieff *et al.* 1997, Aubinet *et al.* 2000, Foken *et al.* 1997, Müller *et al.* 1995. Criteria for wind statistics are found in DeGaetano 1997, Radiation in Gilgen *et al*. 1994, profile systems in Handorf 1996, Turbulent tests in Foken and Wichura 1996, and addition raw data, steady state and turbulence tests can be found in Mahrt 1991, Vickers and Mahrt 1997, Kaimal and Finnigan 1994, and Højstrup 1993. Limitations to quality control tools include the inability to identify exact causes for uncertainty. Further tests are needed to identify canopy coupling/decoupling, and interpretion of more complex QC analyses (wavelet, spectra etc..) needs advanced micromet experience and cannot be automated QC by programs.

Göckede-Linked the Foken QA/QC software package with source area models to determine which locations within the source area contribute to flagged data. Source weight function and roughness length were determined for 30-min averages to match EC data. 2-d land use classification and topography was determined from remote sensed data. Two source area models were used; FSAM analytical model (Schimd *et al.* 1997, Schmid 1994) and Forward Lagrangian Model (Rannik *et al.* 2000). Relative contributions to the source area derived from the Lagrangian model were of greater magnitude closer to the tower as those from FSAM, i.e smaller footprint. Both models preformed well, but need to be interpreted differently,

Table 2. Some assumptions and characteristics of the two source area models.

Schmid 1994	Rannik *et al.* 2000
Analytical model	Lagrangian stochastic model
Homogeneous turbulence	Inhomogeneous turbulence
No along-wind dispersion	Includes along-wind dispersion
No canopy	Considers canopy effects
Sources are at the ground	Vertical source distribution

Montagnani-Estimated advection with 3 profile towers measuring CO_2, windspeed and temperature from an open-canopy coniferous forest on a ~ 10° slope. Fetch to the south was large and homogeneous, fetch to the north was fragmented and patchy. Daytime horizontal flow was upslope from the south, nighttime flows were downslope from the north. During the daytime hours advection was negligible, using the approach outlined in Aubinet *et al*. 2000. Spatial heterogeneity of CO_2 concentrations play a key role in

determining horizontal advection. CO_2 concentrations generally increased downslope, and on average, horizontal advection flux exported carbon downslope. Vertical motions also advected carbon out of the system. The sum of vertical and horizontal advection indicates the potential of large amounts of carbon being exported from this system. Nighttime turbulent fluxes were often negligible compared to advection fluxes. Stable nights temperature inversions occur, density gradients develop and catabatic flows develop. Horizontal advection upslope was ~ 3.5 times greater than downslope components. Independent measures of respiration (scaled chamber measurements) were consistently higher than the combination of eddy corvariance, storage and advection fluxes.

Cessatti-results from the same site Montagnani reported from, Cessatti and colleagues estimated vertical advection using two approaches. If

$$V_adv = \int_0^{z_r} \overline{w} \frac{\partial \rho_c}{\partial z} \qquad \text{Eq. 8}$$

then, approach 1 is defined by,

$$V1_adv = \overline{w}_r \left(\overline{\rho}_r - \frac{1}{z_r} \int_0^{z_r} \overline{\rho}(z) \partial z \right) \qquad \text{Eq. 9}$$

and approach 2 defined by,

$$V2_adv = \overline{w}_r \overline{\rho}_r - \int_0^{z_r} \frac{\partial \overline{w}}{\partial z} \overline{\rho}(z) \partial z \qquad \text{Eq. 10}$$

Both approaches utilize planar fit rotation scheme. Approach 1 assumes a linear decrease in $\overline{w}$ with a decrease in height. In contrast, approach 2 makes no assumption in the shape of the vertical gradient of $\overline{w}$. Estimates using approach 2 where ~ 30 % less than those assuming a linear gradient in $\overline{w}$, i.e., approach 1.

Table 3. Preliminary results showing the advection effects on carbon balance from the Renon site, Italy. Units are in g C m^{-2} d^{-1}.

Flux components	**upslope**	**downslope**	**Total**
Eddy	-2.938	-2.938	**-2.938**
Storage	-0.045	-0.045	**-0.045**
H_adv	2.015	0.583	**1.299**
V2_adv	1.197	1.523	**1.302**
Total	**0.229**	**-0.877**	**-0.382**

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