A-posteriori analysis of surface energy budget closure to determine missed energy pathways

Chad W. Higgins[1]

Received 29 June 2012; revised 29 August 2012; accepted 31 August 2012; published 6 October 2012.

[1] The residual of the surface energy budget is represented as the linearized sum of energy losses due to storage, advection and flux underestimation. Individual contributions to the residual can be quantified through constrained multiple linear regression which identifies the site specific processes that are responsible for the lack of energy budget closure. This residual decomposition approach is applied to energy balance data from the Surface Layer Turbulence and Environmental Science Test (SLTEST) site at the Dugway Proving Grounds in the Utah Salt Flats. In this case, energy storage in the soil and underestimation of the soil heat flux accounted for 89% of the residual variance. Underestimation of the sensible and latent heat fluxes had no apparent contribution to the residual, and the contribution of advection to the residual was not statistically significant. **Citation:** Higgins, C. W. (2012), A-posteriori analysis of surface energy budget closure to determine missed energy pathways, *Geophys. Res. Lett.*, *39*, L19403, doi:10.1029/2012GL052918.

1. Introduction

[2] Measurements of the Earth's surface energy budget do not close at timescales less than several hours [*Wilson et al.*, 2002; *Oncley et al.*, 2007; *Foken*, 2008; *Foken et al.*, 2010; *Kidston et al.*, 2010; *Foken et al.*, 2011; *Leuning et al.*, 2012]. Several experiments have been carried out to determine the root cause of this imbalance by targeting specific processes: storage [*Oliphant et al.*, 2004; *Jacobs et al.*, 2008; *Moderow et al.*, 2009; *Lindroth et al.*, 2010], advection [*Aubinet et al.*, 2010; *Kochendorfer and Paw*, 2011]. Spatial variability [*Steinfeld et al.*, 2007; *Mauder et al.*, 2010], footprint issues [*Schmid*, 1997], flux measurement corrections [*Mauder and Foken*, 2006], and meteorological conditions [*Franssen et al.*, 2010]. In some cases, the authors do close the energy budget within reasonable limits [e.g., *Jacobs et al.*, 2008], however, these successes are rare.

[3] The apparent lack of closure impacts many techniques that estimate fluxes at the Earth's surface based on an assumed energy balance. In irrigation scheduling, FAO-56 Penman-Monteith, the recommended way to estimate evaporation by the Food and Agriculture Organization of the United Nations [*Trajkovic and Kolakovic*, 2009] and the American Society of Civil Engineers [*Allen*, 2000] relies on an assumption of energy balance [*Brutsaert*, 2005]. Satellite estimates of evapotranspiration routinely rely on energy budget assumptions [*Allen et al.*, 2007; *Compaore et al.*, 2008; *Long and Singh*, 2010]. Carbon flux measurements, important in determining the net ecosystem exchange of CO_2, are sometimes corrected by assuming energy budget closure [*Massman and Lee*, 2002; *Wilson et al.*, 2002].

[4] Despite the lack of closure, and the myriad of studies devoted to the investigation of the individual factors that lead to missed energy, a unified approach to diagnose the cause of insufficient energy budget closure *a-posteriori* does not exist. Each field site is different, and factors contributing to incomplete closure can be caused by site specific or measurement specific effects. Direct measurement of some energy pathways such as advection or energy storage can be expensive and data intensive. The salient question is: can we evaluate the energy budget closure mismatch in a diagnostic way such that the source(s) of the mismatch is identified for a particular field site? In this way experimentalists can diagnose the site specific closure problem and invest in the appropriate instrumentation needed to capture the missed energy pathway(s).

2. Methods

[5] The surface energy balance is written as:

$$R_n = H + LE + G + S + A + W + O_T \tag{1}$$

Where R_n is the net radiation, H is the sensible heat flux, LE, is the latent heat exchange due to evaporation, S is the energy storage in the air, soil and plant canopy, A is the advection, W is the total measurement error, and O_T are other terms not considered in this study (soil water transport, freeze/thaw in a snowpack, energy used for photosynthesis, entropy production, mismatched measurement footprints etc.). In the simplest case $S + A + W + O_T$ is assumed to be small and the energy balance is considered in the following way:

$$\eta = R_n - H - LE - G, \tag{2}$$

where η is the residual. The residual can also be written as:

$$\eta(t) = S(t) + A(t) + W(t) + O_T(t). \tag{3}$$

The time series of the residual has a functional form that is the linear combination of the time series behavior of the storage, advection, errors, and other terms. If the behavior of these terms could be mapped to specific, independent, measured quantities, it would be possible to attribute a

[1]Department of Biological and Ecological Engineering, Oregon State University, Corvallis, Oregon, USA.

Corresponding author: C. W. Higgins, Department of Biological and Ecological Engineering, Oregon State University, 116 Gilmore Hall, Corvallis, OR 97331, USA. (chad.higgins@oregonstate.edu)

0094-8276/12/2012GL052918

fraction of the residual to each physical process. Proceeding term by term in equation (3):

$$S(t) = \sum_{i=1:n} S_i(t) = S_{air}(t) + S_{soil}(t) + S_{canopy}(t)$$
$$S(t) \approx C_{S,air}\frac{\partial T_a}{\partial t} + C_{S,soil}\frac{\partial T_s}{\partial t} + C_{S,leaf}\frac{\partial T_l}{\partial t} + C_{S,bark}\frac{\partial T_b}{\partial t} + C_{S,core}\frac{\partial T_c}{\partial t}. \quad (4)$$

The storage is equal to the total storage in the air, soil, and the plant canopy. These storages are proportional to the time derivative of the air temperature T_a, the skin temperature T_s, the leaf temperature T_l, the bark temperature T_b, and the core trunk temperature T_c. $C_{S,air}$, $C_{S,soil}$, $C_{S,leaf}$, $C_{S,bark}$, and $C_{S,core}$ are related to the density and heat capacity each component respectively, and are assumed to be constant over the time interval of analysis.

[6] Following *Leuning et al.* [2012] the advection of a scalar, χ, can be estimated by

$$A_\chi = \bar{\rho}c\int_0^h \bar{u}\frac{\partial \chi}{\partial x}dz \approx \bar{\rho}ch\frac{\bar{u}}{2}\frac{\Delta\chi}{\Delta x} \quad (5)$$

To precede, an approximation of the stream-wise scalar gradient is required. The scalar transport equation for neutral atmospheric stability conditions,

$$\bar{u}\frac{\partial \chi}{\partial x} = \frac{\partial \overline{w'\chi'}}{\partial z}, \quad (6)$$

was solved for idealized surface conditions [*Sutton*, 1934], and for general surface conditions [*Polyanin*, 2002], thus the horizontal scalar gradient can be obtained under neutral conditions given a surface boundary condition. Coupled with the assumption of stationarity already invoked, it follows that each possible wind angle is associated with a unique, unknown surface condition which is in turn associated with a scalar gradient. In addition to wind direction, the advection likely has a strong dependence on atmospheric stability [*Aubinet et al.*, 2000] that was not considered in the above analysis. Modeling the stream wise scalar gradient as an unknown function of both wind direction and stability, and combining with equation (5) yields:

$$A(t) \approx c_A\bar{u}(t)f(\theta, z/L). \quad (7)$$

Where $f(\theta, z/L)$ is an unknown function of wind direction, θ, and atmospheric stability, z/L. Here, z is the measurement height and L is the Obukhov length. Since f is periodic in θ (the upwind topography associated with θ is the same upwind topography associated with θ + 360°) the natural course of action is to approximate f with a truncated Fourier series.

$$A(t) \approx a_0(z/L)\bar{u}(t) + a(z/L)_1\bar{u}(t)\sin(\theta(t)) + a_2(z/L)\bar{u}(t)\cos(\theta(t)) \quad (8)$$

Where $a_0(z/L)$, $a_1(z/L)$, and $a_2(z/L)$ are unknown Fourier coefficients that are functions of stability. Here only the first order terms of the series are used. Analysis of measurements taken above highly variable surfaces may require additional terms.

[7] Errors can be organized as systematic errors [*Moncrieff et al.*, 1996] caused by imperfect sensor alignment, flux underestimates caused by sensor separation [*Kristensen et al.*, 1997], sampling issues [*Lenschow et al.*, 1994; *Lee et al.*, 2004; *Kidston et al.*, 2010], and random error [*Salesky et al.*, 2012]. Sampling issues and sensor separation issues can be analyzed with a transfer function approach [*Lee et al.*, 2004] which allows the residual to be expressed as a fraction of the measured flux. Sensor alignment issues are expressed geometrically.

$$W(t) \approx \left(\frac{1}{\cos\phi} - 1 + C_{H,sample}\right)H(t) + \left(\frac{1}{\cos\lambda} - 1 + C_{LE,sample} + C_{separation}\right)LE(t) + \left(\frac{1}{\cos\varsigma} - 1\right)G(t) - \left(\frac{1}{\cos\psi} - 1\right)R_n(t) + W_{random} \quad (9)$$

Where ϕ, λ, ς, and ψ are the angles of imperfect alignment between the fluxes and the instrumentation. $C_{H,sample}$, $C_{LE,sample}$, and $C_{separation}$ are the positive constants that link sampling and sensor separation issues to underestimation of fluxes, and W_{random} is the expected random error in the flux measurements, characterized by *Salesky et al.* [2012] and is expected to be ~10%. Combining equations (3), (4), (8), and (9), allowing for a constant offset, aggregating constants and neglecting the contribution of random noise and canopy storage yields:

$$\eta(t) = C_{S,air}\frac{\partial T_a}{\partial t} + C_{S,soil}\frac{\partial T_s}{\partial t} + a_0(z/L)\bar{u}(t) + a_1(z/L)\bar{u}(t)\sin(\theta(t)) + a_2(z/L)\bar{u}(t)\cos(\theta(t)) + C_H H(t) + C_{LE}LE(t) + C_G G(t) - C_{Rn}R_n(t) + c_{offset}, \quad (10)$$

If a constant Bowen ratio is observed during the course of the experiment, $H(t)$ and $LE(t)$ are no longer linearly independent and $C_H H(t) + C_{LE}LE(t)$ should be replaced by $(C_H + C_{LE}/\beta_0)H(t) = C_\beta H(t)$. The data are conditionally sampled based on stability regime, and the unknown coefficients in equation (10) are determined with constrained multiple linear regression ('lsqlin' function in Matlab™). The resulting contribution of each physical process to the residual is estimated for stable, unstable and near neutral atmospheric stability. Any variance in the residual not explained by equation (10) that is greater than the expected random error of measurement is attributed to O_T. Note that the fundamental assumption in the above analysis is that the coefficients in equation (10) do not change over the analysis timescale. For this reason, analysis of long time series is discouraged. The shortest time series that yields converged statistics in the regression should be used.

[8] To facilitate the linear regression, realistic limits are set on the values of the unknown coefficients in equation (10). $C_{S,air}$ and $C_{S,soil}$ are positive as they are related to the physical properties: ρc_p where ρ is the density and c_p is the specific heat. Tilt errors, are constrained by setting a reasonable maximum sensor misalignment. Sampling errors are constrained by the methodology in *Lee et al.* [2004]. For advection, the methodology proposed in *Kochendorfer and*

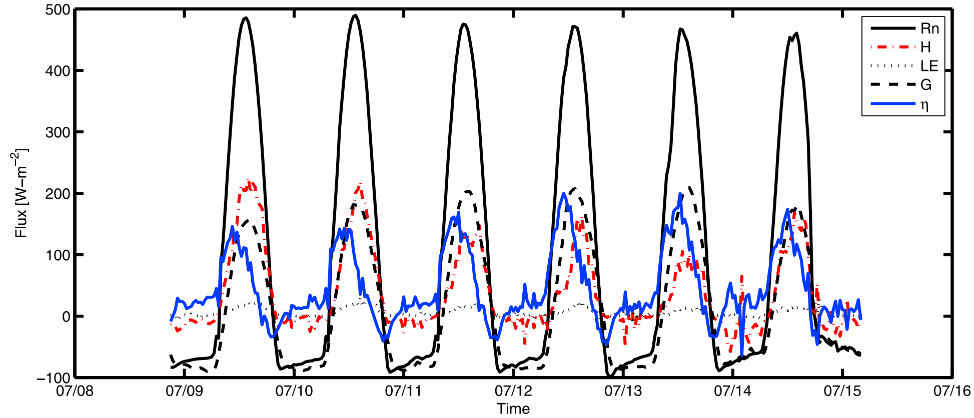

Figure 1. Time series of the surface energy budget terms measured at the SLTEST site in the Utah west desert. Sensible heat flux (dashed red line) and soil heat flux (dashed black line) account for the bulk of the measured energy fluxes. Latent heat flux (dotted black line) is small, as expected, in the desert environment. The residual, η, (blue line) is large, accounting for >25% of the net radiation.

Paw [2011] can be used. Care must be taken to ensure that spurious values of flux are not included in the regression as spurious values have a disproportionate effect on the results.

3. Experiment Description

[9] A complete energy budget station was installed in the Utah Salt Flats at the Surface Layer Turbulence and Environmental Science Test (SLTEST) facility at the Unites States Army Dugway Proving Ground in the summer of 2002. A full description of the experimental setup can be found in *Higgins et al.* [2007, 2009]. Net radiation was measured with a Q7.1 net radiometer from Radiation Energy Systems. The ground heat flux was measured with an array of 4 HukseFlux T3 REBS soil heat flux plates. Sensible and latent heat fluxes were measured with a Campbell Scientific CSAT3 sonic anemometer and a Krypton fast response hygrometer. The three component velocity vector, temperature, and water vapor concentration were sampled at 10 Hz; the velocity vectors were expressed into flow coordinates using the double rotation method; humidity data were corrected for O_2 concentrations, and all fluctuating quantities were linearly de-trended before covariance calculations to reduce unrealistic correlations caused by non-stationarity in the signals. After quality control, 300 segments of data representing 6 days were available to use in the analysis. A time series of the measured energy budget terms is shown in Figure 1. Stability Classifications of $z/L > 0.05$ for stable conditions, $z/L < -0.05$ for unstable conditions, and $|z/L| < 0.05$ for near neutral conditions were used. Due to the low amount of data points (∼10 segments) associated with near neutral conditions, the analysis was only performed on the stable and unstable segments. The bulk of the available energy is transported through the sensible heat flux and the soil heat flux. Note that even in this idealized situation, the energy budget is not closed with an average residual of ∼25%.

4. Results and Discussion

[10] The residual (shown in Figure 1) was decomposed into components corresponding to storage, advection, and

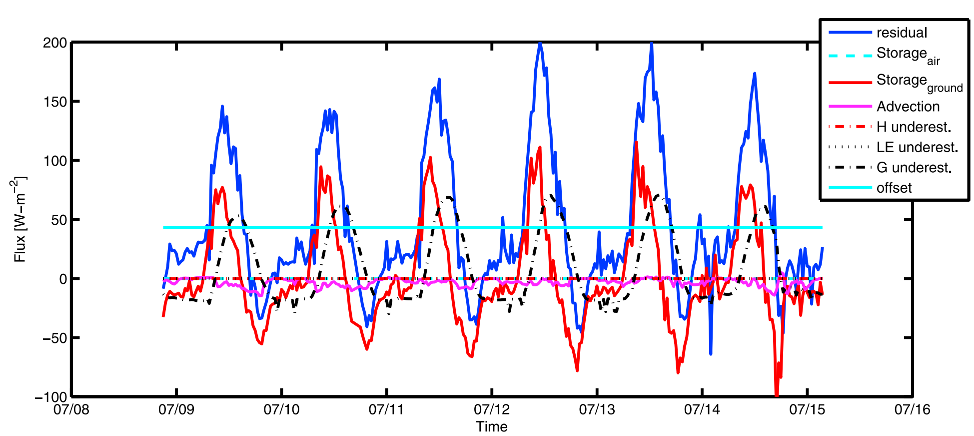

Figure 2. Results of the constrained linear regression to determine the missing energy pathways in the surface energy budget. Energy storage in the soil (red line) accounts for 59% of the variance of the residual. Underestimation of the soil heat flux (black dashed line) accounts for 30% of the variance on the residual. Advection (magenta line) accounts for 1% of the variance in the residual and is not statistically significant. Note that Storage in the air column, underestimation of the sensible heat flux and underestimation of the latent heat flux do not contribute to the residual.

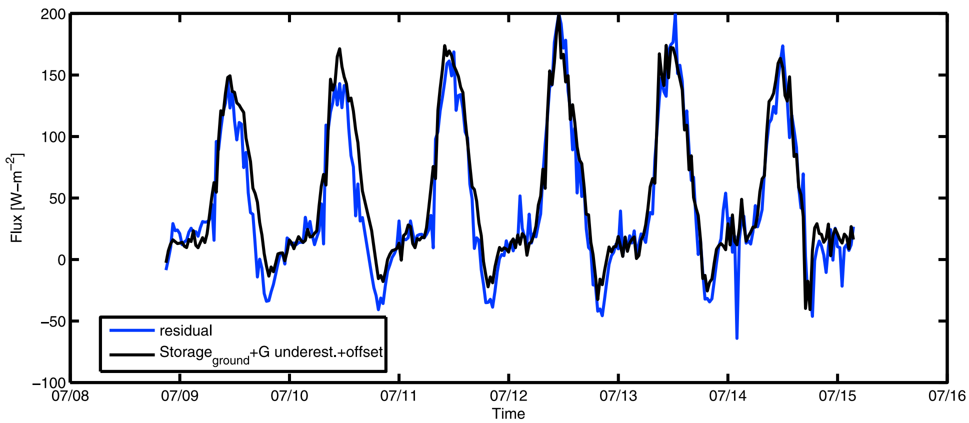

Figure 3. Comparison of the measured residual (blue line) to the sum of the energy storage in the ground the underestimation of the soil heat flux, and the offset determined from the residual decomposition (black line). The heat storage in the ground and the underestimation of the soil heat flux account for 89% of the variance in the residual. The RMS error between the measured residual and sum of the relevant terms from the residual decomposition is 19 W-m^{-2}.

flux underestimation using the *a-posteriori* analysis outlined above (results shown in Figure 2). After the analysis, each coefficient is analyzed for statistical significance at a 99% confidence. Fifty nine percent of the residual's variance can be attributed to energy storage in the soil layer, thirty percent is attributed to underestimates of the soil heat flux, and one percent is attributed to advection (not statistically significant).

[11] None of the residual is attributed to air column storage or underestimation of the sensible or latent heat flux measured by eddy covariance $C_{S,air} = C_{LE} = C_H = 0$. From this analysis we can conclude 1) the energy storage in the soil and underestimation of the soil heat flux are responsible for the lack of energy budget closure at the SLTEST experiment site, and 2) fluxes measured with the eddy covariance technique were not underestimated. Advection did have a strong dependence on atmospheric stability. The coefficients in equation (10) differed by more than a factor of 2 across atmospheric stability classifications. Finally, a constant offset of 50 W-m^{-2} was observed across the entire data set. The mechanism responsible for a constant offset is unclear, and could potentially be attributed to the outdated radiation measurements, but the contribution to the residual and ultimate closure of the surface energy budget is significant. A direct comparison between the measured residual and the sum of ground storage, ground heat flux underestimate and the offset is shown in Figure 3. The RMS error between the linear form and the measured residual is 19 W-m^{-2}, well within the combined error limits of the sum of the measurements.

[12] The purpose of an *a posteriori* energy budget analysis is to identify weaknesses in experimental design that can be corrected in future experiments. For the example presented, the experimental design should be adapted to resolve the soil heat flux and the energy storage in the soil layer above the soil heat flux plate with greater accuracy. The logical course of action is to implement a soil temperature profiling strategy to explicitly measure the heat storage term and to resolve the thermal gradients that give rise to the soil heat flux. Furthermore, the observed constant offset is indicative of a biased energy measurement, likely due to the outdated and inaccurate Q7.1 radiation sensor. Future experiments should include a more precise instrument for net radiation.

[13] The purpose of this technique is not to force a closure of the energy budget. To do so would be reckless. Rather, the analysis presented provides clues into the physical processes that should be monitored in more detail at a specific experimental location. Only 5–7 days of data are needed for the analysis; therefore the analysis can be performed during an experiment, and the setup modified in an iterative fashion until a satisfactory energy budget closure is attained.

5. Conclusions

[14] A new method to analyze Earth surface energy budgets *a-posteriori* has been presented. The method was applied to energy flux measurements taken at the SLTEST site in the Utah Salt Flats. At this field site, 59% of the residual variance can be attributed to energy storage in the soil, and 30% can be attributed to underestimates of the soil heat flux. Underestimation of the fluxes measured with eddy correlation did not contribute the residual. The proposed method provides a framework which can be used to reanalyze energy budget data, and provides a methodology to interpret lack of closure. It is clear that the advection term is the most difficult to characterize. In particular, its effect was expected to be minimal given the homogeneous topography of the SLTEST site. Future work to further characterize the expected functional behavior of the advection term should be performed over variable surfaces. Although the method should not be used to force the energy budget to close, it does provide valuable clues that point to the physical processes that lead to imbalance in the surface energy budget, and therefore has the potential to aid future studies by identifying site specific issues associated with surface energy budget closure.

[15] **Acknowledgments.** I gratefully acknowledge Richard Cuenca for his helpful comments, and the field support and cooperation from the US Army at the Dugway Proving Ground that made the field measurements possible.

[16] The Editor thanks the anonymous reviewers for assisting in the evaluation of this paper.

References

Allen, R. G. (2000), Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study, *J. Hydrol.*, *229*(1–2), 27–41, doi:10.1016/S0022-1694(99)00194-8.

Allen, R. G., et al. (2007), Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Model, *ASCE J. Irrig. Drain. Eng.*, *133*(4), 380–394, doi:10.1061/(ASCE)0733-9437(2007)133:4(380).

Aubinet, M., et al. (2000), Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology, *Adv. Ecol. Res*, *30*(30), 113–175.

Aubinet, M., et al. (2010), Direct advection measurements do not help to solve the night-time CO_2 closure problem: Evidence from three different forests, *Agric. For. Meteorol.*, *150*(5), 655–664, doi:10.1016/j.agrformet.2010.01.016.

Brutsaert, W. (2005), *Hydrology: An Introduction*, Cambridge Univ. Press, Cambridge, U. K., doi:10.1017/CBO9780511808470.

Compaore, H., et al. (2008), Evaporation mapping at two scales using optical imagery in the white Volta basin, upper east Ghana, *Phys. Chem. Earth*, *33*(1–2), 127–140, doi:10.1016/j.pce.2007.04.021.

Foken, T. (2008), The energy balance closure problem: An overview, *Ecol. Appl.*, *18*(6), 1351–1367, doi:10.1890/06-0922.1.

Foken, T., et al. (2010), Energy balance closure for the LITFASS-2003 experiment, *Theor. Appl. Climatol.*, *101*(1–2), 149–160, doi:10.1007/s00704-009-0216-8.

Foken, T., et al. (2011), Results of a panel discussion about the energy balance closure correction for trace gases, *Bull. Am. Meteorol. Soc.*, *92*(4), ES13–ES18, doi:10.1175/2011BAMS3130.1.

Franssen, H. J. H., et al. (2010), Energy balance closure of eddy-covariance data: A multisite analysis for European FLUXNET stations, *Agric. For. Meteorol.*, *150*(12), 1553–1567, doi:10.1016/j.agrformet.2010.08.005.

Higgins, C. W., et al. (2007), The effect of filter dimension on the subgrid-scale stress, heat flux, and tensor alignments in the atmospheric surface layer, *J. Atmos. Oceanic Technol.*, *24*(3), 360–375, doi:10.1175/JTECH1991.1.

Higgins, C. W., et al. (2009), Geometric alignments of the subgrid-scale force in the atmospheric boundary layer, *Boundary Layer Meteorol.*, *132*(1), 1–9, doi:10.1007/s10546-009-9385-3.

Jacobs, A. F. G., et al. (2008), Towards closing the surface energy budget of a mid-latitude grassland, *Boundary Layer Meteorol.*, *126*(1), 125–136, doi:10.1007/s10546-007-9209-2.

Kidston, J., et al. (2010), Energy balance closure using eddy covariance above two different land surfaces and implications for CO_2 flux measurements, *Boundary Layer Meteorol.*, *136*(2), 193–218, doi:10.1007/s10546-010-9507-y.

Kochendorfer, J., and U. K. T. Paw (2011), Field estimates of scalar advection across a canopy edge, *Agric. For. Meteorol.*, *151*(5), 585–594, doi:10.1016/j.agrformet.2011.01.003.

Kristensen, L., et al. (1997), How close is close enough when measuring scalar fluxes with displaced sensors?, *J. Atmos. Oceanic Technol.*, *14*(4), 814–821, doi:10.1175/1520-0426(1997)014<0814:HCICEW>2.0.CO;2.

Lee, X., et al. (2004), *Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis*, Kluwer Acad., Dordrecht, Netherlands.

Lenschow, D. H., et al. (1994), How long is long enough when measuring fluxes and other turbulence statistics, *J. Atmos. Oceanic Technol.*, *11*(3), 661–673, doi:10.1175/1520-0426(1994)011<0661:HLILEW>2.0.CO;2.

Leuning, R., et al. (2012), Reflections on the surface energy imbalance problem, *Agric. For. Meteorol.*, *156*, 65–74, doi:10.1016/j.agrformet.2011.12.002.

Lindroth, A., et al. (2010), Heat storage in forest biomass improves energy balance closure, *Biogeosciences*, *7*(1), 301–313, doi:10.5194/bg-7-301-2010.

Long, D., and V. P. Singh (2010), Integration of the GG model with SEBAL to produce time series of evapotranspiration of high spatial resolution at watershed scales, *J. Geophys. Res.*, *115*, D21128, doi:10.1029/2010JD014092.

Massman, W. J., and X. Lee (2002), Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges, *Agric. For. Meteorol.*, *113*(1–4), 121–144, doi:10.1016/S0168-1923(02)00105-3.

Mauder, M., and T. Foken (2006), Impact of post-field data processing on eddy covariance flux estimates and energy balance closure, *Meteorol. Z.*, *15*(6), 597–609, doi:10.1127/0941-2948/2006/0167.

Mauder, M., et al. (2010), An attempt to close the daytime surface energy balance using spatially-averaged flux measurements, *Boundary Layer Meteorol.*, *136*(2), 175–191, doi:10.1007/s10546-010-9497-9.

Moderow, U., et al. (2009), Available energy and energy balance closure at four coniferous forest sites across Europe, *Theor. Appl. Climatol.*, *98*(3–4), 397–412, doi:10.1007/s00704-009-0175-0.

Moncrieff, J. B., et al. (1996), The propagation of errors in long-term measurements of land-atmosphere fluxes of carbon and water, *Global Change Biol.*, *2*(3), 231–240, doi:10.1111/j.1365-2486.1996.tb00075.x.

Oliphant, A. J., et al. (2004), Heat storage and energy balance fluxes for a temperate deciduous forest, *Agric. For. Meteorol.*, *126*(3–4), 185–201, doi:10.1016/j.agrformet.2004.07.003.

Oncley, S. P., et al. (2007), The Energy Balance Experiment EBEX-2000. Part I: Overview and energy balance, *Boundary Layer Meteorol.*, *123*(1), 1–28, doi:10.1007/s10546-007-9161-1.

Polyanin, A. D. (2002), *Handbook of Linear Partial Differential Equations for Engineers and Scientists*, Chapman and Hall/CRC, Boca Raton, Fla., doi:10.1201/9781420035322.

Salesky, S. T., et al. (2012), Estimating random error in eddy covariance fluxes: The filtering method, *Boundary Layer Meteorol.*, *144*(1), 113–135, doi:10.1007/s10546-012-9710-0.

Schmid, H. P. (1997), Experimental design for flux measurements: Matching scales of observations and fluxes, *Agric. For. Meteorol.*, *87*(2–3), 179–200, doi:10.1016/S0168-1923(97)00011-7.

Steinfeld, G., et al. (2007), Spatial representativeness of single tower measurements and the imbalance problem with eddy-covariance fluxes: Results of a large-eddy simulation study, *Boundary Layer Meteorol.*, *123*(1), 77–98, doi:10.1007/s10546-006-9133-x.

Sutton, O. G. (1934), Wind structure and evaporation in a turbulent atmosphere, *Proc. R. Soc. A*, *146*(858), 701–722, doi:10.1098/rspa.1934.0183.

Trajkovic, S., and S. Kolakovic (2009), Estimating reference evapotranspiration using limited weather data, *ASCE J. Irrig. Drain. Eng.*, *135*(4), 443–449, doi:10.1061/(ASCE)IR.1943-4774.0000094.

Wilson, K., et al. (2002), Energy balance closure at FLUXNET sites, *Agric. For. Meteorol.*, *113*(1–4), 223–243, doi:10.1016/S0168-1923(02)00109-0.