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

Chad W. Higgins

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; Koehler and Pau, 2011], spatial variability [Steinfeld et al., 2007; Mauder et al., 2010], footprint issues [Schim, 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.


[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:

\[ R_n = H + LE + G + S + A + W + O_T \]  

(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:

\[ \eta = R_n - H - LE - G, \]  

(2)

where \( \eta \) is the residual. The residual can also be written as:

\[ \eta(t) = S(t) + A(t) + W(t) + O_T(t). \]  

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

\[ S(t) = \sum_{i=1}^{n} S_i(t) = S_{air}(t) + S_{soil}(t) + S_{canopy}(t) \]

\[ S(t) \approx C_{S,air} \frac{\partial T_a}{\partial t} + C_{S,soil} \frac{\partial T_b}{\partial t} + C_{S,leaf} \frac{\partial T_l}{\partial t} + C_{S,bark} \frac{\partial T_b}{\partial t} + C_{S,core} \frac{\partial T_c}{\partial t} \]

\[ (4) \]

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 \( T_b \), 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, \( \chi \), can be estimated by

\[ A_{\chi} = \rho C_v \int \frac{\partial \chi}{\partial x} \, dz \approx \rho C_v \Delta x \int \frac{\partial \chi}{\partial x} \, dt \]

\[ (5) \]

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

\[ \frac{\partial \chi}{\partial t} + u \frac{\partial \chi}{\partial x} - \frac{\partial \chi}{\partial z} \]

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:

\[ A(t) \approx c_r \bar{u}(t) f(\theta, z/L). \]

\[ (7) \]

Where \( f(\theta, z/L) \) is an unknown function of wind direction, \( \theta \), and atmospheric stability, \( z/L \). Here, \( z \) is the measurement height and \( L \) is the Obukhov length. Since \( f \) is periodic in \( \theta \) (the upwind topography associated with \( \theta \) is the same upwind topography associated with \( \theta + 360^0 \)) the natural course of action is to approximate \( f \) with a truncated Fourier series.

\[ A(t) \approx a_0(z/L)\bar{u}(t) + a_1(z/L)\bar{u}(t) \sin(\theta(t)) + a_2(z/L)\bar{u}(t) \cos(\theta(t)) \]

\[ (8) \]

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 over 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.

\[ W(t) \approx \left( \frac{1}{\cos \phi} - 1 + C_{E, sample} \right) H(t) + \left( \frac{1}{\cos \lambda} - 1 \right) G(t) \]

\[ + C_{separation} LE(t) + \left( \frac{1}{\cos} - 1 \right) R(t) + W_{random} \]

\[ (9) \]

Where \( \phi, \lambda, \varsigma, \) and \( \psi \) are the angles of imperfect alignment between the fluxes and the instrumentation. \( C_{E, sample}, C_{E, LE, sample}, \) and \( C_{separation} \) are the positive constants that link sampling and sensor separation issues to underestimation of fluxes, and \( W_{random} \) is the random expected error in the flux measurements, characterized by Salesky et al. [2012] and is expected to be \( \sim 0.10\% \). 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:

\[ \eta(t) = C_{S,air} \frac{\partial T_a}{\partial t} + C_{S,soil} \frac{\partial T_b}{\partial t} + a_0(z/L)\bar{u}(t) + a_1(z/L)\bar{u}(t) \sin(\theta(t)) + a_2(z/L)\bar{u}(t) \cos(\theta(t)) + C_H H(t) + C_{E, LE} LE(t) + C_{E, G} G(t) - C_{Re} R(t) + constant. \]

\[ (10) \]

If a constant Bowen ratio is observed during the course of the experiment, \( H(t) \) and \( LE(t) \) are no longer linearly independent and \( C_{H,LE} LE(t) \) should be replaced by \( C_{H} + C_{E, LE}/\beta_0 H(t) = C_{H,LE}(t). \) The data are conditionally sampled based on stability regime, and the unknown coefficients in equation (10) are determined with constrained multiple linear regression (‘lsqin’ function in Matlab). The resulting contribution of each physical process to the residual is estimated for stable, unstable and 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: \( \rho C_p \) where \( \rho \) 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
3. Experiment Description

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

The residual (shown in Figure 1) was decomposed into components corresponding to storage, advection, and...
5. Conclusions

[14] A new method to analyze Earth surface energy budgets \textit{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 covariance technique was 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 \textit{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.

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.

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,
Allen, R. G., et al. (2007), Satellite-based energy balance for mapping
evapotranspiration with internalized calibration (METRIC)—Model,
Aubinet, M., et al. (2000), Estimates of the annual net carbon and water
30(30), 113–175.
Aubinet, M., et al. (2010), Direct advection measurements do not help
to solve the atmospheric surface layer boundary layer, Boundary Layer Meteorol.,
Brutsaert, W. (2005), Hydrology: An Introduction, Cambridge Univ. Press,
Compore, H., et al. (2008), Evaporation mapping at two scales using optical
imagery in the white Volta basin, upper east Ghana, Phys. Chem. Earth,
Foken, T. (2008), The energy balance closure problem: An overview,
Foken, T., et al. (2010), Energy balance closure at the LITFASS-2003 experiment,
Foken, T., et al. (2011), Results of a panel discussion about the energy
data: A multisite analysis for European FLUXNET stations, Agric. For. Meteorol.,
Higgins, C. W., et al. (2007), The effect of filter dimension on the subgrid-
scale stress, heat flux, and tensor alignments in the atmospheric sur-
Higgins, C. W., et al. (2009), Geometric alignments of the subgrid-scale
force in the atmospheric boundary layer, Boundary Layer Meteorol.,
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,
Kidston, J. I., et al. (2010), Energy balance closure using eddy covariance
above two different land surfaces and implications for CO2 flux measure-
Kochendorfer, J., and U. K. T. Paw (2011), Field estimates of scalar advec-
tion across a canopy edge, Agric. For. Meteorol., 151(5), 585–594,
Kristensen, L., et al. (1997), How close is close enough when measuring
Lenschow, D. H., et al. (1994), How long is long enough when measuring
Leuning, R., et al. (2012), Reflections on the surface energy imbalance
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 reso-
2010JD014092.
Masson, W. J., and X. Lee (2002), Eddy covariance flux corrections and
uncertainties in long-term studies of carbon and energy exchanges,
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.,
Mauder, M., et al. (2010), An attempt to close the daytime surface energy
balance using spatially-averaged flux measurements, Boundary Layer Meteorol.,
Moderow, U., et al. (2009), Available energy and energy balance closure
at four coniferous forest sites across Europe, Theor. Appl. Climatol.,
Moncrieff, J. B., et al. (1996), The propagation of errors in long-term mea-
surements of land-atmosphere fluxes of carbon and water, Global
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,
Overview and energy balance, Boundary Layer Meteorol., 123(1),
Polyanin, A. D. (2002), Handbook of Linear Partial Differential Equations
for Engineers and Scientists, Chapman and Hall/CRC, Boca Raton, Fla.,
Saley, S. T., et al. (2012), Estimating random error in eddy covari-
ance fluxes: The filtering method, Boundary Layer Meteorol.,
Schmid, H. P. (1997), Experimental design for flux measurements: Match-
ing scales of observations and fluxes, Agric. For. Meteorol., 87(2–3),
Steinfeld, G., et al. (2007), Spatial representativeness of single tower mea-
surements and the imbalance problem with eddy-covariance fluxes:
Results of a large-eddy simulation study, Boundary Layer Meteorol.,
Sutton, O. G. (1934), Wind structure and evaporation in a turbulent
1934.0183.
Trjaptsin, S., and S. Kolakov (2009), Estimating reference evapotran-
spiration using limited weather data, ASCE J. Irrig. Drain. Eng., 135(4),
Wilson, K., et al. (2002), Energy balance closure at FLUXNET sites,
00109-0.