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Authors: Paul C. Stoy, Matthias Mauder, Thomas Foken, Barbara Marcolla, Eva Boegh, Andreas Ibrom, M. Altaf Arain, Almut Arneth, Mika Aurela, Christian Bernhofer, Alessandro Cescatti, Ebba Dellwik, Pierpaolo Duce, Damiano Gianelle, Eva van Gorsel, Gerard Kiely, Alexander Knohl, Hank Margolis, Harry McCaughey, Lutz Merbold, Leonardo Montagnani, Dario Papale, Markus Reichstein, Matthew Saunders, Penelope Serrano-Ortiz, Matteo Sottocornola, Donatella Spano, Francesco Vaccari, and Andrej Varlagin

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A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity

Paul C. Stoy^{a,*}, Matthias Mauder^b, Thomas Foken^c, Barbara Marcolla^d, Eva Boegh^e, Andreas Ibrom^f, M. Altaf Arain^g, Almut Arneth^{b,h}, Mika Aurelaⁱ, Christian Bernhofer^j, Alessandro Cescatti^k, Ebba Dellwik^l, Pierpaolo Duce^m, Damiano Gianelle^d, Eva van Gorselⁿ, Gerard Kiely^o, Alexander Knohl^p, Hank Margolis^q, Harry McCaughey^r, Lutz Merbold^s, Leonardo Montagnani^{t,u,v}, Dario Papale^w, Markus Reichstein^x, Matthew Saunders^y, Penelope Serrano-Ortiz^z, Matteo Sottocornola^d, Donatella Spano^A, Francesco Vaccari^m, Andrej Varlagin^B

^a Department of Land Resources and Environmental Science, Montana State University, Bozeman, MT, USA

^b Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research, Atmospheric Environmental Research, Kreuzeckbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany

^c University of Bayreuth, Department of Micrometeorology and member of Bayreuth Center of Ecology and Ecosystem Research (BayCEER), D-95440 Bayreuth, Germany

^d Fondazione Edmund Mach, IASMA Research and Innovation Centre, Sustainable Agro-ecosystems and Bioresources Department, via E. Mach, 1, I-38010 S. Michele all'Adige (Trento), Italy

^e Department of Environmental, Social and Spatial Change, Roskilde University, Universitetsvej 1, Postbox 260, 4000 Roskilde, Denmark

^f Department of Chemical and Biochemical Engineering, Center of Ecosystems and Environmental Sustainability, Technical University of Denmark (DTU), Frederiksborgvej 399, DK-4000 Roskilde, Denmark

^g School of Geography and Earth Sciences, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4K1, Canada

^h Department of Physical Geography and Ecosystems Analysis, Lund University, Sölvegatan 12, 223 62 Lund, Sweden

ⁱ Finnish Meteorological Institute, Climate Change Research, P.O. Box 503, FIN-00101, Helsinki, Finland

^j Technische Universität Dresden, Faculty of Environmental Sciences, Institute of Hydrology and Meteorology, 01062 Dresden, Germany

^k European Commission – DG Joint Research Centre, Institute for Environment and Sustainability, Climate Change Unit, TP290, Via E. Fermi, 2749, I-21027 Ispra (VA), Italy

^l DTU Wind Energy, Department of Wind Energy, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark

^m IBIMET-CNR, Institute of Biometeorology, National Research Council, Via G. Caproni 8, 50144 Florence – Traversa La Crucca 3, 07100 Sassari, Italy

ⁿ CSIRO Marine and Atmospheric Research, Pye Laboratory, GPO Box 3023, Canberra ACT 2601, Australia

^o Hydromet Group, Civil and Environmental Engineering Department, University College Cork, Ireland

^p Georg-August University Göttingen, Büsgenweg 2, 37077 Göttingen, Germany

^q Faculté de foresterie et de géomatique, Université Laval, Sainte-Foy, Quebec G1K 7P4, Canada

^r Department of Geography, Queen's University, Kingston, Ontario, Canada K7L3N6

^s Department of Environmental Systems Science, Institute of Agricultural Sciences, ETH Zurich, Universitätsstr. 2, 8092 Zurich, Switzerland

^t Forest Services of Autonomous Province of Bolzano, Bolzano, Italy

^u Laboratory of Chemical Physics, Agency for the Environment of Autonomous Province of Bolzano, Bolzano, Italy

^v Faculty of Science and Technology, Free University of Bolzano, Piazza Università 1, 39100, Bolzano, Italy

^w Department for Innovation in Biological, Agro-food and Forest Systems (DIBAF), University of Tuscia, 01100 Viterbo, Italy

^x Max Planck Institute for Biogeochemistry, P.O. Box 10 01 64, 07701 Jena, Germany

^y School of Biology & Environmental Science, University College Dublin Science Centre, Belfield Dublin 4, Ireland

^z Departamento de Desertificación y Geocología, Estación Experimental de Zonas Áridas, CSIC, Ctra. De Sacramento s/n, Almería, Spain

^A Department of Economics and Woody Plants (DESA), University of Sassari, Via de Nicola 9, 07100 Sassari, Italy

^B A.N. Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, Leninsky pr., 33, Moscow 119071, Russia

ABSTRACT

The energy balance at most surface-atmosphere flux research sites remains unclosed. The mechanisms underlying the discrepancy between measured energy inputs and outputs across the global FLUXNET tower network are still under debate. Recent reviews have identified exchange processes and turbulent motions at large spatial and temporal scales in heterogeneous landscapes as the primary cause of the lack of energy balance closure at some intensively-researched sites, while unmeasured storage terms cannot be ruled out as a dominant contributor to the lack of energy balance closure at many other sites. We analyzed energy balance closure across 173 ecosystems in the FLUXNET database and explored the relationship between energy balance closure and landscape heterogeneity using MODIS products and GLOBEstat elevation data. Energy balance closure per research site ($C_{EB,s}$) averaged 0.84 ± 0.20 , with best

average closures in evergreen broadleaf forests and savannas (0.91–0.94) and worst average closures in crops, deciduous broadleaf forests, mixed forests and wetlands (0.70–0.78). Half-hourly or hourly energy balance closure on a percent basis increased with friction velocity (u_*) and was highest on average under near-neutral atmospheric conditions. $C_{EB,s}$ was significantly related to mean precipitation, gross primary productivity and landscape-level enhanced vegetation index (EVI) from MODIS, and the variability in elevation, MODIS plant functional type, and MODIS EVI. A linear model including landscape-level variability in both EVI and elevation, mean precipitation, and an interaction term between EVI variability and precipitation had the lowest Akaike's information criterion value. $C_{EB,s}$ in landscapes with uniform plant functional type approached 0.9 and $C_{EB,s}$ in landscapes with uniform EVI approached 1. These results suggest that landscape-level heterogeneity in vegetation and topography cannot be ignored as a contributor to incomplete energy balance closure at the flux network level, although net radiation measurements, biological energy assimilation, unmeasured storage terms, and the importance of good practice including site selection when making flux measurements should not be discounted. Our results suggest that future research should focus on the quantitative mechanistic relationships between energy balance closure and landscape-scale heterogeneity, and the consequences of mesoscale circulations for surface-atmosphere exchange measurements.

1. Introduction

The surface-atmosphere exchanges of energy, momentum, water and trace gases are central components of the Earth system. Our understanding of these processes at the ecosystem level increasingly relies on observations from single or multiple eddy covariance flux measurement towers, regional flux measurement networks (e.g. Aubinet et al., 2000; Li et al., 2005), and the global FLUXNET database (Baldocchi et al., 2001; Papale et al., 2006). Most FLUXNET studies seek to understand processes controlling the biosphere-atmosphere flux of CO_2 (e.g. Baldocchi, 2008; Jung et al., 2009; Law et al., 2002; Stoy et al., 2009). Fewer studies to date have investigated global and regional water and energy fluxes apart from their relationship to CO_2 flux, with notable exceptions (e.g. Falge et al., 2001; Law et al., 2002; Hollinger et al., 2009; Jung et al., 2011). The relative paucity of eddy covariance energy and water flux studies is disproportional to the importance of these fluxes to the climate system.

Water, carbon and energy flux studies that rely on eddy covariance data are challenged by incomplete energy balance closure at most research sites (Aubinet et al., 2000; Leuning et al., 2012; Wilson et al., 2002). To date, multi-site syntheses have found an average eddy covariance energy balance closure (C_{EB}) ranging between 0.75 and 0.87 (Barr et al., 2006; Falge et al., 2001; Hendricks Franssen et al., 2010; Li et al., 2005; Wilson et al., 2002). Near-to-full C_{EB} has been reported at some sites (e.g. Haverd et al., 2007; Heusinkveld et al., 2004; Lindroth et al., 2009; Moderow et al., 2009; Vourlitis and Oechel, 1999), but these studies are in the minority. C_{EB} can be increased by measuring energy storage terms that are often excluded from conventional observations (Heusinkveld et al., 2004; Lindroth et al., 2009; Meyers and Hollinger, 2004), but additional measurements, including advective transport, often prove ineffective for closing the energy balance completely (Aubinet et al., 2010; Etzold et al., 2010; Moderow et al., 2011), in part because of the critical role of sensor accuracy for advection measurements (Dellwik et al., 2010a,b; Leuning et al., 2008). Large surface flux field campaigns have yet to report full energy balance closure (Beyrich et al., 2002; Foken, 1998; Foken et al., 1997; Kanemasu et al., 1992; Koitzsch et al., 1988; Mauder et al., 2006; Panin et al., 1998; Tsvang et al., 1991) (see Table 2 in Foken, 2008), suggesting that a fundamental aspect of surface-atmosphere exchange has yet to be ascertained.

Foken (2008) and Panin and Bernhofer (2008) concluded that buoyancy-driven turbulent circulations resulting from landscape heterogeneity are likely responsible for energy imbalance at the tower measurement level. These studies follow work by Panin et al. (1998) and Mauder et al. (2007b), who identified a relationship

between energy balance closure and landscape patterns on a spatial scale on the order of tens of kilometres. In essence, this 'mesoscale hypothesis' suggests that relatively cool and dry air layers aloft are exchanged with relatively warm and moist air layers near the surface, and both the downward motion of cooler air and upward motion of warmer air result in a positive wT' that contributes to a lack of energy balance closure if this flux is unmeasured by the eddy covariance instrumentation (Fig. 1). More experimental evidence of the interaction between surface heterogeneity and mesoscale circulations were obtained from aircraft measurements (Mauder et al., 2007a) and a multi-tower experiment (Mauder et al., 2010), but potential impacts of landscape-level heterogeneity on energy balance closure has not been tested across flux networks to date.

Other results highlight the importance of correctly measuring and interpreting energy storage terms to achieve energy balance closure. A recent study by Leuning et al. (2012) found that 45% of FLUXNET sites approached energy balance closure using daily averages after correctly accounting for lags in heat flux into soils, biomass, and the canopy air space (Gao et al., 2010; Haverd et al., 2007). Accounting for all energy storage terms results in a closed energy balance at select sites (Lindroth et al., 2009).

From these studies, it is clear that a closed energy balance can occur at certain sites, yet the energy balance at hundreds of flux sites worldwide remain unclosed. We adopt a data-driven approach (Gray, 2009; Hunt et al., 2009) and combine eddy covariance and remote sensing databases to test if millions of observations are consistent with the expectations of the mesoscale hypothesis that landscape-level heterogeneity is negatively related to energy balance closure. Our objectives are twofold. First, we characterize C_{EB} at 173 sites in the FLUXNET database as it relates to micrometeorological drivers, considering both half-hourly (or hourly) observations ($C_{EB,i}$) and site-level means ($C_{EB,s}$). We then test the hypothesis that energy balance closure is related to landscape-level heterogeneity using data products from the Moderate-Resolution

Fig. 1. Conceptual description of mesoscale circulations, driven in part by landscape-level heterogeneity, suggested by Foken et al. (2011), Mauder et al. (2010) and others to contribute to lack of energy balance closure at single-tower sites. The anisotropic nature of the mesoscale circulations is on the order of tens of kilometres in the horizontal direction.

Imaging Spectroradiometer (MODIS) and the GLOBESat elevation data set. We hypothesize that C_{EB} is related to landscape-level heterogeneity following the conclusions of Foken et al. (2011).

2. Methods

2.1. FLUXNET: instantaneous energy balance closure

Flux and meteorological data from the LaThuile FLUXNET database [www.fluxdata.org, accessed May 31, 2008] and processed according to FLUXNET protocols (Papale et al., 2006; Reichstein et al., 2005) were used here. Energy balance closure on the half-hourly or hourly basis is denoted for the purposes of this analysis as ‘instantaneous’ ($C_{EB,i}$), and was calculated as:

$$C_{EB,i} = \frac{\lambda E + H}{R_n - G - J} \quad (1)$$

i.e. the fraction of available energy defined as the net radiation (R_n) minus soil heat flux (G) that is realized as surface-atmosphere turbulent fluxes of latent heat (λE) and sensible heat (H). Minor storage and metabolic terms (J) were set to zero here as they are neither included in the database nor measured at most FLUXNET sites, but their inclusion is important for C_{EB} at many sites (Haverd et al., 2007; Lindroth et al., 2009). $C_{EB,i}$ data for which all measured terms in equation 1 pass the FLUXNET quality control criteria (Papale et al., 2006), and for which friction velocity (u_*) measurements were available, are examined here; no gapfilled data products were used.

During periods when energy fluxes are small, $C_{EB,i}$ may degrade although the absolute energy balance residual is only a few $W m^{-2}$, which is of minor concern. For a comprehensive interpretation of the results, we also explore the absolute energy balance residual, which can be defined as:

$$R_{EB,i} = R_n - G - \lambda E - H - J \quad (2)$$

with J again set to zero.

2.2. FLUXNET: energy balance closure per site

For the analysis of energy balance closure per site, we explored the 173 (of 253) sites, where observations of R_n , λE , H , and G were available (Table A1). Two sites with energy balance closure greater than 2 were excluded for quality control concerns. Energy balance closure for each site, $C_{EB,s}$, was defined as:

$$C_{EB,i} = \frac{\sum(\lambda E + H)}{\sum(R_n - G - J)} \quad (3)$$

again assuming that J is negligible. This approach is sometimes called the ‘bulk method’ (Hendricks Franssen et al., 2010), the energy balance ratio (Wilson et al., 2002), or the relative energy balance closure (Aubinet et al., 2000). Half-hourly data for which R_n , λE , H , and G were measured and passed quality-control criteria, including sufficient u_* to assure turbulent transport for the turbulent flux terms (Reichstein et al., 2005), were converted from $W m^{-2}$ to $J m^{-2}$ per half hour (or hour) and summed for the calculation of $C_{EB,s}$. We note that the apparent lack of energy balance closure need not constitute evidence for erroneous turbulent flux measurements (Aubinet et al., 2000).

Both $C_{EB,s}$ and mean $C_{EB,i}$ may be expected to be somewhat less than unity if energy storage in the aboveground vegetation, in the canopy air space, above the soil heat flux plates, and owing to metabolism (i.e. the terms that contribute to J) are not considered. We note that energy storage terms average out on an annual basis under steady-state conditions. Choosing only individual years with excellent data acceptability (>90%) to further minimize the role of canopy and soil heat storage variability does not change mean $C_{EB,s}$

(data not shown). Regardless, one may assume that metabolism and unmeasured storage terms contribute to C_{EB} . We test surrogates for metabolism using gross primary productivity (GPP) and we use precipitation (P) as a surrogate for soil moisture, a primary control over soil heat storage, which is seldom reported in the FLUXNET database. For the statistical analyses, we treat each FLUXNET site, not site-year, as independent.

2.3. Environmental variables

Energy balance closure can be expected to be a function of u_* and atmospheric stability (Aubinet et al., 2000), both of which vary diurnally in most instances. We explore relationships between $C_{EB,i}$ and u_* , the solar zenith angle, and the Obukhov length (L) as a primary determinant of atmospheric stability using:

$$L = \frac{-\rho C_p u_*^3 T}{kgH} \quad (4)$$

where ρ is the density of air, C_p is the specific heat capacity of dry air, k is von Kármán’s constant, g is gravitational acceleration and T is air temperature in Kelvin.

Daytime periods are defined as those during which the solar zenith angle is less than 90° . To differentiate between morning and afternoon we define ‘zenith 2’ as the solar zenith angle with periods before solar noon denoted as negative.

2.4. Kernel density estimation

Visualizing relationships amongst millions of observations is a formidable challenge. We used two-dimensional kernel density estimates to present the relationships amongst $C_{EB,i}$ and environmental variables. Kernel density estimation is a non-parametric approach for estimating probability density functions from a given dataset. Histograms are the simplest non-parametric density estimator, but suffer from the arbitrary choice of bin size. Kernel density estimators place a smooth kernel (usually a Gaussian window, also chosen here) with a given bandwidth about measured data points, and combine these to create an estimate of the probability distribution of all observations. We used a linear diffusion algorithm following Botev et al. (2010) to choose optimal kernel bandwidths and avoid over- or under-smoothing. Kernel density estimation is used here to improve visual display rather than for the statistical interpretation of the data, and like a probability distribution or density function the sum of all kernel density values equals one.

2.5. MODIS: land cover classifications

Following the suggestions of Foken (2008), the landscape characteristics of the 20×20 km area surrounding the 173 flux towers were analyzed in relation to $C_{EB,s}$. The 20 km length scale was suggested to be representative of anisotropic atmospheric motions that exhibit statistical stationarity (Mauder et al., 2007a). The MODIS MCD12Q1 PFT (plant functional type) land cover classification product was downloaded for the 20×20 km areas surrounding all 173 towers for 2006. As these data are categorical, an appropriate metric for their variability is their information entropy after Shannon (1948):

$$I(X) = -\sum_{i=1}^N p(x_i) \ln p(x_i) \quad (5)$$

where N is the number of bins that a pixel can take for each attribute and $p(x_i)$ is the fraction of pixels in each bin i representing each different MODIS PFT classification. The PFT product has 12 classes

Fig. 2. The instantaneous energy balance closure, $C_{EB,i}$ as a function of the friction velocity (u^* , m s^{-1}) for all observations (A) and daytime periods (B) for which the solar zenith angle was less than 90° plotted as a distribution using a two-dimensional kernel density estimate. The colorbar denotes probabilities. Subplot C is the median $C_{EB,i}$ per u^* bin.

(water = 0, evergreen needle leaf forest = 1, evergreen broadleaf forest = 2, etc.), therefore $N = 12$ and the Shannon entropy of a uniform landscape with a single plant functional type is zero. Unfilled and unknown MODIS pixels were excluded from the entropy calculations.

2.6. MODIS: enhanced vegetation index (EVI)

We chose the MODIS product with the highest spatial resolution, 250 m in the MOD13Q1 product, for the calculation of EVI in the 20×20 km area surrounding the 173 flux towers analyzed here. EVI was chosen over the normalized difference vegetation index (NDVI) because of the saturating NDVI–leaf area index (LAI) relationship in forest canopies (Huete et al., 2002). EVI was chosen over LAI to avoid uncertainties in the MODIS LAI algorithm.

The 16-day resolution of the MOD13Q1 EVI product creates a challenge for quantifying a simple metric of landscape-level variability. A full spatiotemporal analysis of EVI across 173 sites is complicated by quality control issues including the presence of clouds and/or snow. To simplify the comparison between $C_{EB,s}$ and EVI, we obtained 20×20 km EVI data for each site for 2005–2007, and chose the scene with the greatest amount of reliable data that had the highest mean EVI. This approach calculated landscape-level variability with high data quality during growing season periods when incident solar radiation was greatest, on average, and when most energy on an absolute basis tends to go missing (see Fig. 4C). The total variance of the EVI observations across the 20×20 km region, $\sigma^2(\text{EVI})$, was used as the metric of landscape-level heterogeneity in subsequent analyses. We also investigated the mean EVI, $\mu(\text{EVI})$, at the tower location to explore the effects of canopy density (as a surrogate for heat storage in the canopy) in determining $C_{EB,s}$. Per the recommendations of the MODIS land surface project team, the average of the nine MODIS pixels surrounding and including the flux tower was taken to represent $\mu(\text{EVI})$.

3. Results

3.1. Instantaneous energy balance closure

The FLUXNET quality control criteria (Papale et al., 2006) were met by nearly 7.7×10^6 half-hourly (or hourly) data points. $C_{EB,i}$ as a function of u^* is shown in Fig. 2. The peak of the 2D kernel density estimate between u^* and $C_{EB,i}$ lies near the origin (Fig. 2A), but

Fig. 3. The instantaneous energy balance closure, $C_{EB,i}$ as a function of (A) solar zenith angle and (B) adjusted zenith angle ('Zenith 2') in which all times between midnight and solar noon (i.e. morning) are denoted as negative. The colorbar denotes probabilities following Fig. 2. Subplot C is the median $C_{EB,i}$ per solar zenith angle bin.

shifts to a space between $ca. 0.2$ and 0.5 m s^{-1} when only daytime data are considered (Fig. 2B). The median $C_{EB,i}$ per u^* bin increases quickly until a u^* value of about 0.2 m s^{-1} is reached, and continues to increase albeit with a smaller slope at higher u^* values (Fig. 2C) and does not reach unity.

$C_{EB,i}$ is consistently low during nighttime periods with solar zenith angles $> 90^\circ$, especially during the day/night and night/day transitions (Fig. 3A). $C_{EB,i}$ increases more slowly during the morning than the corresponding decrease in the afternoon (Fig. 3B). Median $C_{EB,i}$ approaches 0.8 under near-neutral conditions and decreases as the atmosphere becomes more stable or unstable (Fig. 4A and B). The energy balance residual ($R_{EB,i}$) is also higher during near-neutral periods when both $C_{EB,i}$ and u^* are highest (Fig. 4C and D). u^* and H enter into the calculation of L and are shown with respect to L in Fig. 4 for reference.

Of the 173 sites explored here, 73 sites show significantly lower $C_{EB,i}$ as a function of time from the beginning to the end of the measurement record, 69 sites have significantly higher $C_{EB,i}$ over time, and 31 sites were unchanged. In other words, energy balance closure declined over the measurement period at over 40% of the sites studied here.

3.2. Site-level energy balance closure

The mean (standard deviation) of the energy balance closure, $C_{EB,s}$, for the 173 sites listed in Table A1 is 0.84 ± 0.20 (Table 1). $C_{EB,s}$ ranges from 0.28 to 1.67 after excluding severe outliers that were not analyzed on account of quality control concerns. The slope and intercept of the relationship between $\Sigma(R_n - G)$ and $\Sigma(\lambda E + H)$ for all sites (with 95% confidence intervals in parentheses) are $0.82 (\pm 0.035)$ and $57 (\pm 261) \text{ MJ m}^{-2}$ (Fig. 5). The intercept is not statistically different from zero.

Table 1

The mean and standard deviation of the energy balance closure (C_{EB}) in the FLUXNET database for different plant functional type groupings.

	n	C_{EB}
All	173	0.84 ± 0.20
Forest	88	0.83 ± 0.22
Non-forest	57	0.83 ± 0.19
Other ^a	28	0.87 ± 0.15

^a Savannas, shrublands and wetlands that may or may not be dominated by woody vegetation.

Fig. 4. The median instantaneous energy balance closure ($C_{EB,i}$, subplots A and B), friction velocity (u_*) and absolute energy balance residual ($R_{EB,i}$, subplots C and D) including sensible heat (H) and latent heat flux (λE) as a function of the inverse of the Obukhov length L (m). Plots for all data observations are on the left (subplots A and C) and plots for daytime only periods (with solar zenith angle $< 90^\circ$) are on the right (subplots B and D).

Mean $C_{EB,s}$ for different vegetation types are listed in Table 2. Evergreen broadleaf forests and savannas tend to have the highest values of $C_{EB,s}$, and deciduous broadleaf forests, mixed forests, crops and wetlands the lowest. The $C_{EB,s}$ of forests (0.83 ± 0.22) short-statured vegetation (0.83 ± 0.18), and other vegetation (grouped as savannas and wetlands, 0.87 ± 0.19) do not differ as determined by a two-sided t -test ($p > 0.05$) and a two-sample Kolmogorov-Smirnov test at the 0.05 probability level. $C_{EB,i}$ is not related to the Bowen ratio (data not shown), but site-level C_{EB} ($C_{EB,s}$) is negatively related to the site-level Bowen ratio ($\Sigma H / \Sigma \lambda E$; $r = -0.16$; $p = 0.04$).

3.3. Energy balance closure in relationship to landscape variability

MODIS PFT and EVI for the 20×20 km area surrounding the tower in Hainich Forest, Germany are shown as examples in Fig. 6. There is a significant negative relationship ($r = -0.17$; $p = 0.011$) between $C_{EB,s}$ and $I(\text{PFT})$ with an intercept at 0.89, suggesting

that energy balance closure approaches *ca.* 0.9 in landscapes with uniform vegetation type. $C_{EB,s}$ is significantly related to both $\mu(\text{EVI})$ in the nine pixels surrounding the tower ($r = -0.20$; $p = 0.008$) and $\sigma^2(\text{EVI})$ for the 20×20 km area surrounding the tower (Fig. 7, $r = -0.21$; $p = 0.004$) even after excluding obvious outliers [$\sigma^2(\text{EVI}) > 0.04$] that may have spuriously influenced this relationship ($r = -0.24$; $p = 0.001$). The intercept is not statistically different than unity.

3.4. Models for energy balance closure

$C_{EB,s}$ is significantly related to MODIS PFT and EVI, but also to mean precipitation, GPP, the site-level Bowen ratio, and landscape-level variability in elevation derived from the GLOBESat elevation dataset ($p < 0.05$ in all cases). We created linear models of the variables that contribute to $C_{EB,s}$, and subjected these to information criterion analyses to identify a minimal model for $C_{EB,s}$. The minimal model identified by the Akaike information criterion

Table 2

The mean and standard deviation of energy balance closure (C_{EB}), the mean EVI of the pixels surrounding flux towers [$\mu(\text{EVI})$], and the variance of EVI in 20×20 km regions surrounding flux towers [$\sigma^2(\text{EVI})$] for different ecosystem types for the 173 sites in the FLUXNET database with measurements of available energy that sum to greater than zero. Three sites had no available ecosystem type information and are excluded from this table but are included in the analysis.

Vegetation type	Abbrev.	n	C_{EB}	$\mu(\text{EVI})$	$\sigma^2(\text{EVI})$
Crops	CRO	25	0.78 ± 0.16	0.45 ± 0.13	$0.014 \pm 6.9 \times 10^{-3}$
Shrubs ^a	SHR	9	0.87 ± 0.15	0.32 ± 0.16	$0.010 \pm 8.4 \times 10^{-3}$
Deciduous Broadleaf Forest	DBF	20	0.70 ± 0.19	0.47 ± 0.12	$0.014 \pm 7.6 \times 10^{-3}$
Evergreen Broadleaf Forest	EBF	10	0.94 ± 0.16	0.39 ± 0.12	$0.008 \pm 5.9 \times 10^{-3}$
Evergreen Needleleaf Forest	ENF	47	0.88 ± 0.23	0.43 ± 0.11	$0.013 \pm 1.2 \times 10^{-2}$
Grasslands	GRA	32	0.86 ± 0.20	0.42 ± 0.12	$0.010 \pm 5.5 \times 10^{-3}$
Mixed Forest	MF	10	0.79 ± 0.18	0.47 ± 0.13	$0.011 \pm 4.4 \times 10^{-3}$
Savanna ^b	SAV	10	0.91 ± 0.14	0.36 ± 0.11	$0.007 \pm 4.6 \times 10^{-3}$
Wetlands	WET	7	0.76 ± 0.13	0.39 ± 0.13	$0.007 \pm 4.5 \times 10^{-3}$

^a Open and closed shrublands.

^b Savannas and woody savannas.

Fig. 5. The relationship between the cumulative sum of available energy (net radiation, R_n minus soil heat flux, G) and the cumulative sum of surface fluxes of latent heat (λE) and sensible heat (H) for each of the 173 research sites in the FLUXNET database for which all four variables are measured and sum to a positive value. The slope of the best-fit linear relationship, in black, is $0.82 (\pm 0.035)$ and the intercept is $57 (\pm 261) \text{ MJ m}^{-2}$ for the measurement record of each site. The 1:1 relationship is shown as a black dashed line.

included $\sigma^2(EVI)$, mean precipitation, landscape-level variability in elevation, and an interaction term between $\sigma^2(EVI)$ and mean precipitation. A model with only $\sigma^2(EVI)$ and mean precipitation had the lowest value of the Bayesian information criterion.

4. Discussion

4.1. Instantaneous energy balance closure

More energy (i.e. $R_{EB,i}$) goes missing during periods with better relative energy balance closure, which tend to occur during daytime (Fig. 4, Hendricks Franssen et al., 2010; Wilson et al., 2002). Research on energy balance closure and surface atmosphere exchange should continue to focus on the challenges presented by both daytime and nighttime conditions. However, as more energy goes missing during daytime periods (when more energy is available), breakthroughs in understanding the energy balance closure problem will likely come with a focus on daytime periods. We also note that mornings tend to have slightly worse $C_{EB,i}$ (Fig. 3) and higher $R_{EB,i}$ (data not shown) when G and the storage terms that contribute to J tend to be positive rather than later in the afternoon when G and J have peaked or are decreasing (Hendricks Franssen et al., 2010; Leuning et al., 2012), demonstrating the importance of accounting for storage terms in the energy balance. Median $C_{EB,i}$ is only ca. 0.8 during near-neutral conditions and decreases to nearly 0.7 during highly unstable conditions (Fig. 4; Aubinet et al., 2000; Hendricks Franssen et al., 2010). In other words, periods dominated by the convective production of turbulent kinetic energy, often characterized by larger eddies, have lower energy balance closure on average.

4.2. Energy balance closure per FLUXNET site

Mean $C_{EB,s}$ of the 173 FLUXNET sites investigated here (0.84) is of a similar magnitude to many previous multi-site synthesis (0.79, ranging from 0.53 to 0.99 (Wilson et al., 2002); 0.84, ranging from 0.58 to 1 (Li et al., 2005; Yu et al., 2006)) if not slightly worse than other syntheses (0.85–0.89, Barr et al., 2006). G may be

Fig. 6. The MODIS MCD12Q1 plant functional type (PFT) for the $20 \times 20 \text{ km}$ area surrounding the Hainich deciduous broadleaf forest, Germany for 2006 (A) and the MODIS MOD13Q1 enhanced vegetation index (EVI) for the same area, measured on DOY 177, 2005 (B). The eddy covariance tower site is at the center point of both scenes. The legend for subpanel A follows the MODIS PFT convention. The entropy of plant functional type, $I(\text{PFT})$, for Fig. 5A is 0.90 and the variance of EVI, $\sigma^2(EVI)$, of Fig. 5B is 8.6×10^{-3} .

Fig. 7. Energy balance closure for FLUXNET eddy covariance research sites ($C_{EB,s}$) as a function of the variance of the MODIS enhanced vegetation index (EVI) for the $20 \times 20 \text{ km}$ region surrounding each eddy covariance tower and averaged per ecosystem type. The solid line is the best-fit relationship after removing wetland ecosystem types and is defined as $C_{EB,s} = -14.76\mu(\sigma^2_{EVI}) + 0.99$. Excluding wetland sites (circled) results in a squared correlation coefficient of 0.54.

underestimated in many instances (Hsieh et al., 2009), suggesting that any system-wide underestimation in energy balance closure would likely occur in ecosystems with more incident radiation upon the soil surface. However, $C_{EB,s}$ tends to be higher in sites with lower $\mu(EVI)$ and there is no difference in $C_{EB,s}$ among forested and non-forested ecosystems. Combined with the observation that $C_{EB,i}$ is slightly lower on average during morning periods when G tends to increase, these results demonstrate that the correct measurement of G is a critical component of energy balance analyses, but by itself will not close the energy balance across many FLUXNET sites (Leuning et al., 2012).

The question remains, why is the energy balance not closed at most tower sites? One might expect forests to have lower or at least significantly different $C_{EB,s}$ than short-statured vegetation, because the role of heat storage in the larger canopy, lower average G , and possible advection and/or decoupling of above and below canopy flows in the larger canopy air space (Cava et al., 2008; Lindroth et al., 2009; Meyers and Hollinger, 2004; Moderow et al., 2009; Staebler and Fitzjarrald, 2004). Although these impacts may be important at many individual forest sites, the mean $C_{EB,s}$ in our analysis did not differ among forest and non-forest sites, suggesting that other mechanisms are also at play. The finding that $C_{EB,i}$ is lower during unstable conditions (Fig. 4; Aubinet et al., 2000) hints that mechanisms that drive convection may contribute to the lack of energy balance closure.

4.3. Landscape heterogeneity and energy balance closure

The large number of sites in this analysis permits us to perform a cautious interpretation of $C_{EB,s}$ for different vegetation types. If forest and non-forest ecosystems do not differ with respect to $C_{EB,s}$, why should $C_{EB,s}$ for grasslands average 0.86 but $C_{EB,s}$ for crops average 0.78 (Table 2, Fig. 7)? Likewise, why should evergreen broadleaf forests have nearly complete closure on average (0.94) when mean $C_{EB,s}$ for deciduous broadleaf forests is only 0.70? Our dataset shows that there are systematic relationships between vegetation types and landscape heterogeneity, e.g., savanna sites are found in more homogeneous landscapes than deciduous forest sites (Fig. 7). This might either be specific for the biome or an effect of the flux tower site selection. Differences in vegetation types (i.e. short vs. tall vegetation) cannot explain $C_{EB,s}$, but $C_{EB,s}$ varies systematically with landscape-level heterogeneity (Fig. 7). We argue therefore that landscape-level variability plays an important role that is often overlooked in single tower investigations by the flux measurement community.

In contrast, many studies of boundary-layer meteorology and turbulence place emphasis on the role of landscape-level heterogeneity on determining boundary layer dynamics (e.g. Shen and Leclerc, 1995). Some of these findings link strongly to the present analysis. For example, Baidya Roy et al. (2003) compared Regional Atmospheric Modeling System (RAMS) output across domains with different characteristic length scales in the central U.S. (longer than 25 km) and the Amazon (3–5 km). Heterogeneity in H occurred at across a wide range of length scales during boundary layer development, but eddies within the 10–20 km scale range intensified and organized into coherent structures by early afternoon in both cases, which dominated the dynamics of turbulence. Future work should further investigate the role of such organized coherent structures on the measured energy balance closure near the surface.

Foken (2008) reviewed the results of multiple large surface flux campaigns and argued that the problem of eddy covariance energy balance closure is fundamentally a problem of scale: lower frequency motions (Foken et al., 2006; Mauder et al., 2007a; Panin et al., 1998), possibly resulting from surface heterogeneity at the landscape scale (Mauder et al., 2010), explain in part the lack of

energy balance closure. Our results agree with these conclusions; landscape-level heterogeneity, here quantified by the $J(PFT)$ and $\sigma^2(EVI)$ (Fig. 7) is significantly related to $C_{EB,s}$. Both the Akaike and Bayesian information criteria suggested that $\sigma^2(EVI)$ should not be excluded from models for $C_{EB,s}$. These empirical relationships become more clear with the graphical representation of Table 2 in Fig. 7; grasslands and evergreen broadleaf forests in the FLUXNET database tend to lie in homogeneous areas with low $\sigma^2(EVI)$, and crops and deciduous broadleaf forests tend to lie in heterogeneous areas with high $\sigma^2(EVI)$. Excluding wetlands, $\sigma^2(EVI)$ explains 54% of the variance in $C_{EB,i}$ when averaged by plant functional type.

Leuning et al. (2012) point out that mesoscale circulations are unlikely to fully close the energy balance at many sites if mean vertical wind velocities on the order of 20–40 mm s⁻¹ are required for advective flux divergence errors on the order of 50–100 W m⁻² for vertical temperature differences of 2 K. Mauder et al. (2010) demonstrated that such mean vertical wind velocities are possible in a heterogeneous agricultural landscape. Characteristic values of mean vertical wind velocity across global eddy covariance sites remain uncertain, as do their temporal variability, and the contribution of mesoscale circulations to lack of energy balance closure at different sites remains unclear.

Our analysis does not suggest that landscape-level variability is the only contributing factor to $C_{EB,s}$, in fact many variables investigated here are significantly related to $C_{EB,s}$. The role of water (approximated by P), with its large heat capacity, also plays an important role in $C_{EB,s}$ noting the low $C_{EB,s}$ of wetlands (Fig. 7) and the relationship between $C_{EB,s}$ and P in the linear models. This result agrees with Leuning et al. (2012) and others that demonstrate that energy storage terms cannot be excluded as a principal contributor to the lack of energy balance closure. Landscape-level variability in topography is an important factor contributing to lack of closure, as one might anticipate given the challenges of measuring surface-atmosphere flux in topographically diverse terrain. Relationships with latitude and seasonality should also be explored further. The information criteria analyses suggest that landscape-level variability in vegetation and topography and indices of ecosystem water content should not be excluded when interpreting the surface-atmosphere energy balance at the network level. Consistent measurements of soil moisture across the tower network will likely add clarity to the role of energy storage and hydrological advection on energy balance closure. Our findings place observations from FLUXNET in agreement with the major results from large surface-atmosphere exchange observation campaigns (Foken, 2008; Foken et al., 2006; Mauder et al., 2007a; Panin et al., 1998). It is important to note that invoking landscape-level arguments undoubtedly does not take the place of proper practice when measuring surface-atmosphere exchange at a point.

The surface heterogeneity relationships, whereas significant, have substantial scatter as may be expected given the multiple factors that contribute to the lack of closure (Fig. 7). These include sensor separation and high frequency losses (Clement et al., 2009) (especially for latent heat flux measurements with closed-path sensors (Ibrom et al., 2007)), footprint variability in space and time (Oren et al., 2006), unmeasured energy fluxes (i.e. ‘minor terms’; Oncley et al., 2007) including canopy heat storage (Lindroth et al., 2009; Moderow et al., 2009) and metabolic terms (Meyers and Hollinger, 2004), instrument biases in radiation measurements (Brotzke and Duchon, 2000), advection (Aubinet et al., 2010; Moderow et al., 2011), the length of the averaging period (Malhi et al., 1998; Sanchez et al., 2010; Voronovich and Kiely, 2007), sonic angle of attack (Cava et al., 2008; Nakai et al., 2006), G measurement accuracy (Hsieh et al., 2009) and open versus closed path methodologies (Burba et al., 2008; Teklemariam et al., 2009). Different explanations for lack of energy balance closure are likely to

dominate at different sites (Kidston et al., 2010; Moncrieff et al., 1996).

The mechanisms relating surface heterogeneity to $C_{EB,s}$ can only be inferred with the available data. If, in fact, surface heterogeneity contributes to buoyancy-driven turbulent circulations (Foken, 2008), the best strategy for including the flux information contained in these larger atmospheric motions remains to be discovered. Longer averaging periods are frequently cited (Cava et al., 2008; Finnigan et al., 2003; Malhi et al., 1998; Mauder and Foken, 2006), but this comes at the expense of capturing the diurnal variability in flux and may violate the steady state criterion underlying EC measurements. Accounting for turbulent organized structures (Badiya Roy and Avissar, 2002; Kanda et al., 2004; Steinfeld et al., 2007) may improve energy balance closure if simple parameterizations can be found. If larger atmospheric motions dominate $C_{EB,s}$, CO_2 , water and energy flux estimates should not be simply adjusted for lack of closure (Baldocchi, 2008) because such a correction relies on similarity assumptions that are not supported by low frequency spectra (Foken et al., 2011; Kidston et al., 2010; Mauder et al., 2007a; Ruppert et al., 2006), although we note that many watershed-level analyses demonstrate improved water budget closure when correcting λE for lack of energy balance closure (Barr et al., 2012; Jung et al., 2011; Twine et al., 2000). Our analysis cannot preclude effects due to fetch or forest canopy edges (Detto et al., 2008; Sogachev et al., 2008), which are difficult to ascertain using 250 m or 1 km MODIS products. The connection between the flux footprint and energy balance closure is discussed in Appendix B.

4.4. Conclusions

The flux community has made substantial advances in understanding the mechanisms underlying the energy balance closure problem (Foken et al., 2011; Leuning et al., 2012), but additional work needs to be done (Mahrt, 2010). However, assuming conservatively that the terms excluded from equation 1 comprise a couple to a few percentage points apiece, on average, then C_{EB} is on the order of 0.95 or greater for many sites and vegetation types (namely grasslands, evergreen broadleaf forests and savannas) in version 2 of the FLUXNET database. These assumptions lend confidence to eddy covariance-based surface energy balance studies on long-term flux sums although further investigations into the energy balance closure problem are needed.

No surface flux campaign project (e.g. LITFASS-2003) has reported full energy balance closure to date (see Table 2 in Foken, 2008), suggesting that the same will hold for individual towers. The leading hypothesis from comprehensive surface flux investigations is that larger atmospheric motions, potentially driven by surface heterogeneity, are the principal explanation for lack of closure. The present study agrees that landscape-level heterogeneity is an important contributor to lack of energy balance closure from a data-driven perspective (Gray, 2009); $C_{EB,s}$ in globally-distributed flux towers is significantly related to landscape-level heterogeneity in land cover (via PFT) and characteristics (via EVI, Fig. 7). Models for $C_{EB,s}$ across the FLUXNET database cannot exclude $\sigma^2(\text{EVI})$, landscape-level topographic variability, or P . The placement of future flux towers should be cognizant of the larger region beyond the immediate flux footprint.

The physical explanations behind the relationship between energy balance closure and landscape heterogeneity should be investigated mechanistically, for example using large eddy simulation or regional atmospheric modeling approaches (Badiya Roy and Avissar, 2002; Kanda et al., 2004; Steinfeld et al., 2007). A greater mechanistic understanding of flux transporting mechanisms and heat storage terms will add value to the water and energy flux

observations in the FLUXNET database and, finally, bring closure to the energy balance closure problem.

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Appendix A.

Table A1 details the FLUXNET sites used in this analysis.

Appendix B. The relationship between flux footprints and energy balance closure

It must be assumed that both the area surrounding a flux station (classified for example with satellite data) and the footprint climatology of a station have a significant influence on energy balance closure. Unfortunately, footprint information is only available for a few stations, although recent analyses have extended footprint analyses to entire flux networks (e.g. Chen et al., 2011, 2012). Göckede et al. (2008) performed a footprint classification for the European FLUXNET sites (i.e. the CarboEurope-IP sites) to quantify the contribution of the target area to the measured flux according to the footprint climatology. Site evaluations were performed by calculating the percentage of half-hourly measurements exceeding the threshold of 80% flux contribution from the target land cover type. No statistical relationship was found between relative energy balance closure and the percentage of half hourly measurements exceeding the threshold of 80% flux contribution from the target land area for three sites, using both the entire data set and data with a zenith angle $< 50^\circ$ to incorporate only daytime values that may feature secondary circulations (data not shown). Only for four of twenty sites (DK-Sor, BE-Bra, DE-Tha and IT-Ren) were significant differences between the entire observational data set and data with a solar zenith angle $< 50^\circ$ found.

The satellite pictures of the stations DK-Sor, BE-Bra, DE-Tha and IT-Ren (Fig. A1) demonstrate that each tower is in a nearly homogeneous area related to the turbulent eddy covariance flux footprint, but the larger landscape exhibits considerable

Table A1

Ecosystem type and geographic information for the 173 FLUXNET sites with available soil heat flux measurements investigated here. Abbreviations follow Table 2. NA means that ecosystem type information was not available; these sites are excluded from the analyses in Table 1 and Fig. 3. References follow information in fluxdata.org when possible.

Site	Veg.	Latitude	Longitude	Reference
ATNeu	GRA	47.11667	11.3175	Wohlfahrt et al. (2008)
AUFog	WET	-12.5425	131.307	Guerschman et al. (2009)
AUHow	SAV	-12.4943	131.152	Hutley et al. (2000)
AUTum	EBF	-35.6557	148.152	Finnigan and Leuning (2000)
AUWac	EBF	-37.429	145.187	Beringer et al. (2006)
BEBra	MF	51.3092	4.52056	de Pury and Ceulemans (1997)
BEJal	MF	50.5639	6.07333	-
BELon	CRO	50.5522	4.74494	Moureaux et al. (2006)
BEVie	MF	50.3055	5.99683	Aubinet et al. (2001)
BRBan	EBF	-9.82442	-50.1591	Borma et al. (2009)
BRMa2	EBF	-2.6091	-60.2093	-
BRSa3	EBF	-3.01803	-54.9714	Saleska et al. (2003)
BRSp1	SAV	-21.6195	-47.6499	Baker et al. (2004)
BWMa1	SAV	-19.9155	23.5605	Veenendaal et al. (2004)
CACa1	ENF	49.8672	-125.334	Morgenstern et al. (2004)
CACa2	ENF	49.8705	-125.291	Humphreys et al. (2006)
CACa3	ENF	49.5346	-124.9	Jassal et al. (2008)
CAGro	MF	48.2167	-82.1556	Pejam et al. (2006)
CAMer	WET	45.4094	-75.5186	Lafleur et al. (2003)
CAOas	DBF	53.6289	-106.198	Black et al. (1996)
CAObs	ENF	53.9872	-105.118	Jarvis et al. (1997)
CAOjp	ENF	53.9163	-104.692	Baldocchi et al. (1997)
CAQcu	ENF	49.2671	-74.0365	Giasson et al. (2006)
CAQfo	ENF	49.6925	-74.3421	Bergeron et al. (2007)
CATP1	ENF	42.6609	-80.5595	Peichl and Arain (2007)
CATP2	ENF	42.7744	-80.4588	Peichl and Arain (2007)
CATP3	ENF	42.7068	-80.3483	Peichl and Arain (2007)
CATP4	ENF	42.7098	-80.3574	Arain and Restrepo-Coupe (2005)
CHOe1	GRA	47.2856	7.73214	Ammann et al. (2007)
CHOe2	CRO	47.2863	7.73433	Kutsch et al. (2010)
CNBed	EBF	39.5306	116.252	Liu et al. (2009)
CNCha	MF	42.4025	128.096	Guan et al. (2006)
CNDo1	WET	31.5167	121.961	Yan et al. (2008)
CNDo2	WET	31.5847	121.903	Yan et al. (2008)
CNDo3	WET	31.5169	121.972	Yan et al. (2008)
CNDu1	CRO	42.0456	116.671	Zhang et al. (2007)
CNDu2	GRA	42.0467	116.284	Zhang et al. (2007)
CNHaM	GRA	37.37	101.18	Fu et al. (2006)
CNKu1	EBF	40.5383	108.694	Wilske et al. (2009)
CNKu2	SHR	40.3808	108.549	Wilske et al. (2009)
CNXfs	NA	44.13417	116.3286	Miao et al. (2009)
CNXi1	GRA	43.54583	116.6778	Chen et al. (2009)
CNXi2	GRA	43.5544	116.671	Wang et al. (2008)
DEBay	ENF	50.1419	11.8669	Valentini et al. (2000)
DEGeb	CRO	51.1001	10.9143	Anthoni et al. (2004a)
DEGri	GRA	50.9495	13.5125	Owen et al. (2007)
DEHai	DBF	51.0793	10.452	Knohl et al. (2003)
DEHar	ENF	47.9344	7.601	Bernhofer et al. (1996)
DEKli	CRO	50.8929	13.5225	Owen et al. (2007)
DEMeh	GRA	51.2753	10.6555	Don et al. (2009)
DETha	ENF	50.9636	13.5669	Bernhofer et al. (2003)
DEWet	ENF	50.4535	11.4575	Anthoni et al. (2004b)
DKFou	CRO	56.4842	9.58722	Soegaard et al. (2003)
DKLva	GRA	55.6833	12.0833	Soussana et al. (2007)
DKSor	DBF	55.4869	11.6458	Pilegaard et al. (2001)
ESES1	ENF	39.346	-0.31881	Sanz et al. (2004)
ESES2	CRO	39.2755	-0.31522	-
ESLJu	SHR	36.9282	-2.75047	Serrano-Ortiz et al. (2007)
ESLMa	SAV	39.9415	-5.77336	-
ESVDA	GRA	42.1522	1.4485	Gilmanov et al. (2007)
FIHyy	ENF	61.8474	24.2948	Suni et al. (2003)
FIKaa	WET	69.1407	27.295	Aurela et al. (2002)
FISod	ENF	67.3619	26.6378	Thum et al. (2007)
FRAur	CRO	43.5494	1.10778	Beziat et al. (2009)
FRGri	CRO	48.844	1.95243	Laville et al. (1999)
FRHes	DBF	48.6742	7.06462	Granier et al. (2000)
FRLam	CRO	43.4933	1.23722	Beziat et al. (2009)
FRLBr	ENF	44.7171	-0.7693	Berbigier et al. (2001)
FRPue	EBF	43.7414	3.59583	Rambal et al. (2004)
HUBug	GRA	46.6911	19.6013	Nagy et al. (2005)
HUMat	GRA	47.8469	19.726	Nagy et al. (2005)
IECa1	CRO	52.8588	-6.91814	Black et al. (2006)
IEDri	GRA	51.9867	-8.75181	Peichl et al. (2011)
ILYat	ENF	31.345	35.0515	Grunzweig et al. (2003)

Table A1 (Continued)

Site	Veg.	Latitude	Longitude	Reference
ISGun	DBF	63.8333	-20.2167	Falge et al. (2002)
ITAmP	GRA	41.9041	13.6052	Wohlfahrt et al. (2008)
ITBCi	CRO	40.5238	14.9574	Reichstein et al. (2003)
ITCas	CRO	45.06285	8.668539	Skiba et al. (2009)
ITCol	DBF	41.8494	13.5881	Valentini et al. (1996)
ITCpz	EBF	41.7052	12.3761	Tirone et al. (2003)
ITLav	ENF	45.9553	11.2812	Cescatti and Marcolla (2004)
ITLec	EBF	43.3046	11.2706	Maselli et al. (2009)
ITLMa	GRA	45.5813	7.15463	Maselli et al. (2006)
ITMal	GRA	46.1167	11.7028	Flechard et al. (2007)
ITMBo	GRA	46.0156	11.0467	Marcolla et al. (2011)
ITNoe	SHR	40.606	8.151	Reichstein et al. (2002)
ITNon	DBF	44.6898	11.0887	Nardino et al. (2002)
ITPT1	DBF	45.2009	9.06104	Migliavacca et al. (2009)
ITRen	ENF	46.5878	11.4347	Marcolla et al. (2005)
ITRo1	DBF	42.4081	11.93	Rey et al. (2002)
ITRo2	DBF	42.3903	11.9209	Tedeschi et al. (2006)
ITSRo	ENF	43.72786	10.28444	Chiesi et al. (2005)
JPMas	CRO	36.05397	140.0269	Saito et al. (2005)
JPTom	MF	42.7395	141.5149	Hirano et al. (2003)
KRHm	NA	34.55	126.57	Lee et al. (2003)
KRKw1	MF	37.7486	127.163	Kim et al. (2006)
NLCa1	GRA	51.971	4.927	Jacobs et al. (2007)
NLLan	CRO	51.9536	4.9029	Moors et al. (2010)
NLLoo	ENF	52.1679	5.74396	Dolman et al. (2002)
NLLut	CRO	53.3989	6.356	Moors et al. (2010)
PLWet	WET	52.7622	16.3094	Chojnicki et al. (2007)
PTMi2	GRA	38.4765	-8.02455	Pereira et al. (2007)
RUChe	WET	68.6147	161.339	Corradi et al. (2005)
RUFyo	ENF	56.46167	32.92389	Kurbatova et al. (2008)
RUZot	ENF	60.8008	89.3508	Kurbatova et al. (2002)
SEAbi	DBF	68.36239	18.79475	Christensen et al. (2007)
SEFaj	WET	56.2655	13.5535	Lund et al. (2007)
SEFla	ENF	64.1128	19.4569	Valentini et al. (2000)
SENor	ENF	60.0865	17.4795	Lagergren et al. (2008)
SESk1	ENF	60.125	17.9181	Gioli et al. (2004)
SKTat	ENF	49.1208	20.1635	Matese et al. (2008)
UKAMo	WET	55.7917	-3.23889	Hargreaves et al. (2003)
UKEBu	GRA	55.866	-3.20578	Famulari et al. (2004)
UKESa	CRO	55.90694	-2.85861	Hendricks Franssen et al. (2010)
UKGri	ENF	56.60722	-3.79806	Medlyn et al. (2005)
UKHam	DBF	51.15353	-0.8583	Wilkinson et al. (2012)
UKHer	CRO	51.7838	-0.47608	-
USARb	GRA	35.5497	-98.0402	Fischer et al. (2007)
USARc	GRA	35.54649	-98.04	Fischer et al. (2007)
USARM	CRO	36.6058	-97.4888	Fischer et al. (2007)
USAtq	WET	70.4696	-157.409	-
USAud	GRA	31.5907	-110.51	-
USBkg	GRA	44.3453	-96.8362	Gilmanov et al. (2005)
USBlo	ENF	38.8952	-120.6328	Goldstein et al. (2000)
USBn1	ENF	63.9198	-145.378	Liu et al. (2005)
USBn2	DBF	63.9198	-145.378	Liu et al. (2005)
USBn3	SHR	63.9227	-145.744	Liu et al. (2005)
USBo1	CRO	40.0062	-88.2904	Meyers and Hollinger (2004)
USBo2	CRO	40.009	-88.29	Meyers and Hollinger (2004)
USBrw	WET	71.3225	-156.6259	Vourlitis and Oechel (1999)
USCaV	GRA	39.0633	-79.4208	Owen et al. (2007)
USFmf	ENF	35.1426	-111.7273	Dore et al. (2008)
USFPe	GRA	48.3077	-105.1019	Gilmanov et al. (2005)
USFR2	SAV	29.9495	-97.9962	Heinsch et al. (2004)
USFuf	ENF	35.089	-111.762	Dore et al. (2008)
USFwf	GRA	35.4454	-111.7718	Dore et al. (2008)
USGoo	GRA	34.2547	-89.8735	Wilson and Meyers (2007)
USHo1	ENF	45.2041	-68.7402	Hollinger et al. (1999)
USIB1	CRO	41.8593	-88.2227	Allison et al. (2005)
USIB2	GRA	41.8406	-88.241	Allison et al. (2005)
USlvo	WET	68.4865	-155.75	Epstein et al. (2004)
USKS2	SHR	28.6086	-80.6715	Powell et al. (2006)
USLos	DBF	46.0827	-89.9792	Desai et al. (2008)
USMe1	ENF	44.5794	-121.5	Law et al. (2001)
USMe2	ENF	44.4523	-121.5574	Campbell et al. (2004)
USMe3	ENF	44.3154	-121.6078	Vickers et al. (2009)
USMe4	ENF	44.4992	-121.6224	Irvine et al. (2004)
USMMS	DBF	39.3231	-86.4131	Schmid et al. (2000)
USMOz	DBF	38.7441	-92.2	Gu et al. (2006)
USNC1	SHR	35.8115	-76.7115	Noormets et al. (2010)
USNC2	ENF	35.8031	-76.6679	Domec et al. (2009)

Table A1 (Continued)

Site	Veg.	Latitude	Longitude	Reference
USNe1	CRO	41.1651	−96.4766	Verma et al. (2005)
USNe2	CRO	41.1649	−96.4701	Verma et al. (2005)
USNe3	CRO	41.1797	−96.4397	Verma et al. (2005)
USNR1	ENF	40.0329	−105.546	Monson et al. (2002)
USOho	DBF	41.5545	−83.8438	DeForest et al. (2006)
USSO2	SHR	33.3739	−116.6229	Lipson et al. (2005)
USSO3	SHR	33.3772	−116.6227	Lipson et al. (2005)
USSO4	SHR	33.3844	−116.6403	Lipson et al. (2005)
USSP1	ENF	29.7381	−82.2188	Clark et al. (1999)
USSP2	ENF	29.7648	−82.2448	Clark et al. (1999)
USSP3	ENF	29.7548	−82.1633	Clark et al. (1999)
USSRM	SAV	31.8214	−110.866	Scott et al. (2009)
USSyv	MF	46.242	−89.3477	Desai et al. (2005)
USTon	SAV	38.4316	−120.966	Ma et al. (2007)
USVar	GRA	38.4133	−120.9507	Ma et al. (2007)
USWBW	DBF	35.9588	−84.2874	Verma et al. (1986)
USWCr	DBF	45.8059	−90.0799	Cook et al. (2004)
USWi1	DBF	46.7305	−91.2329	Noormets et al. (2007)
USWi2	ENF	46.6869	−91.1528	Noormets et al. (2007)
USWi8	DBF	46.7223	−91.2524	Noormets et al. (2007)
USWkg	GRA	31.7365	−109.942	Scott et al. (2010)
USWrc	ENF	45.8205	−121.952	Chen et al. (2002)

Fig. A1. Satellite photographs taken from ca. 13,400 m over a small forest in an agricultural landscape (DK-Sor, A), an alpine region (IT-Ren, B), a forest in a suburban area (BE-Bra, C) and a managed forest surrounded mainly by agriculture (DE-Tha). The eddy covariance tower is located in the middle of all images, which are approximately 20 km along the east-west axis.

variability. The surface energy balance is likely affected on a scale of ca. 20 km × 20 km, possibly as a result of secondary circulations, during daytime periods. On the other hand, for the station DK-Sor, the energy balance closure is better for daytime data, when the small forest area tends to lie within the flux footprint.

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