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On the use of field measurements of energy fluxes to evaluate land surface models

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ABSTRACT

Eddy covariance (EC) is the generally preferred technique today for measuring energy and mass fluxes of vegetated surfaces, with many experimental sites now established in the global Fluxnet network. A fundamental problem with EC, violating the principle of energy conservation, is that energy balances determined using EC are generally “unclosed”, with combined sensible and latent heat fluxes commonly underestimating available energy by 20% or more. Despite this lack of energy closure, however, recently published evaluations of land surface models (LSM) indicate that modelers generally use available EC measurements for model validation. It is, however, almost impossible to conduct consistent analyses of LSM performance when the models, which assume energy budget closure, are evaluated against measurements that do not close the energy budget. Our study suggests that measurements of energy fluxes must satisfy the energy budget closure prior to their use in LSM evaluations. Using long-term measurements collected at four sites in North America, we show that the closure issue of the measured energy fluxes must be resolved, before it is possible to test adequately LSM simulations of seasonal and interannual variability in energy and water exchanges. The ever-increasing application of LSM to a wide range of problems makes it imperative to recognize that model validation must be carried-out using appropriate data.

1. Introduction

The establishment of the Fluxnet network, since the mid-1990s, resulted in long-term high quality observations of heat and mass exchanges between land surface and the atmosphere, for a wide range of ecosystems (http://www.fluxnet.ornl.gov/fluxnet/index.cfm). These observations have the potential to improve our understanding of terrestrial ecosystem functioning and their responses to meteorological and climatic forcing, and therefore, to enhance our ability to represent important aspects of the interactions between the continental biosphere and the atmosphere within land surface models (LSM). The latter objective was indeed a major justification for the establishment of the Fluxnet network (Baldocchi et al., 1996).

Methods to measure land surface–atmosphere exchanges of heat and mass are numerous and have been synthesized in a number of publications (e.g., Moncrief et al., 1996; Twine et al., 2000; Baldocchi, 2003; Finnigan, 2004). Eddy covariance (EC) is the most widely used technique at currently operational flux-tower sites worldwide (http://www.fluxnet.ornl.gov/fluxnet/index.cfm). Nonetheless, an analysis by Wilson et al. (2002), of surface flux measurements at 27 EC sites distributed across North Amer-

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ica and Western Europe, showed that energy budget closure was lacking at all the investigated sites. Aubinet et al. (2000) reported a similar finding based on analyses of EC data collected at European sites. Typically, the lack in annual energy closure ranges between 5% and 30%. Naturally, field analyses of how surface energy and mass fluxes are partitioned using data that do not close the energy budget become questionable (e.g., McCaughey et al., 1997; Liu et al., 2006), especially when the energy imbalance is a large fraction of measured available energy (e.g., 20% or more). The problem of energy closure in measured data also leads to inconsistent evaluations of models of land surface processes (referred to here as land surface models, LSM), because it becomes difficult to understand whether discrepancies between model output and measured data are attributable to model shortcomings or to problems of energy closure in the measured data. Consequently, the performance of models that have been evaluated and calibrated against unclosed measurements of surface energy budget becomes uncertain, and constrains their use to help understand effects of climate variability and climatic change on natural and managed ecosystems.

The current inability of EC to close the energy budget is a well-known issue, which has led several authors to emphasis the necessity to find a way to handle it (e.g., Moncrief et al., 1996; Mahrt, 1998; Twine et al., 2000; Wilson et al., 2002; Massman and Lee, 2002; Baldocchi, 2003; Liu et al., 2006). Some modelers have also pointed out the difficulty to evaluate ecosystem models using flux measurements that exhibit a lack of energy closure (e.g., El Maayar and Kucharik, 2003; Kucharik et al., 2006), and the imperative need for resolving observed energy budget imbalances in measured data prior to their use to test LSM (Kustas et al., 1999). Despite all these caveats and recommendations, modelers are still testing the performance of LSM, in which the energy budget is assumed to close, using EC data that do not generally satisfy the energy budget closure requirement (e.g., Delire and Foley, 1999; Amthor et al., 2001; El Maayar et al., 2002; Hanson et al., 2004; Kothavala et al., 2005; Zhang et al., 2005; Grant et al., 2005, 2006; Ju et al., 2006; Kucharik et al., 2006). Our objective here is to investigate and discuss the effects of using unclosed energy budget measurements of sensible and latent heat fluxes at the land surface on analyses of LSM simulations. To fulfill this objective, we compared simulations of a widely used LSM with two EC datasets at four sites distributed across North America (Canada and the continental USA). The first dataset, termed hereafter “uncorrected data”, comprises EC data as they were measured in the field and distributed through Fluxnet networks; i.e., data that exhibit an energy imbalance and that are commonly used in model evaluation efforts (e.g., Hanson et al., 2004; Ju et al., 2006). The second dataset, termed hereafter “corrected data”, includes the first dataset to which we applied a procedure to close the energy budget. Firstly, we investigated the effects of using uncorrected data instead of corrected data on analyses of simulated average monthly and annual sensible heat flux (*H*) and evapotranspiration (ET). Secondly, we explored the inconsistency that is associated with the use of uncorrected data to evaluate simulations of seasonal and interannual variability of *H* and ET. Our comparisons were made using the integrated biosphere simulator (IBIS), but the analyses were expanded

Table 1 – Key ecological, climatic, and soil conditions at the experimental sites that were selected for this study

Site name and location	Campbell River (BC, Canada)	BOREAS-SSA (SK, Canada)	Walker Branch Watershed (TN, USA)	Little Washita watershed (OK, USA)
Symbol	CR	SOA	WBW	LW
Dominant vegetation type	Temperate coniferous (mature Douglas-*fir* forest)	Boreal broadleaf deciduous forest (old aspen)	Temperate broadleaf deciduous forest (mature oak)	Warm (C4) tall grasses
Geographical coordinates (latitude/longitude)	49.87N/125.34W	53.63N/106.20W	35.96N/84.29W	34.96N/96.68W
Elevation (m)	300	601	365	500
Annual mean temperature (°C)	9.4	−0.4	13.9	16.1
Annual precipitation (mm)	1369	368	1355	805
Dominant soil texture	Sandy	Silty loam	Silty loam	Clay loam
Maximum LAI	6.7	4.5	6	3
Canopy height (m)	33	21	25	0.5

Shown values of temperature and precipitation are 1961–1990 normals.

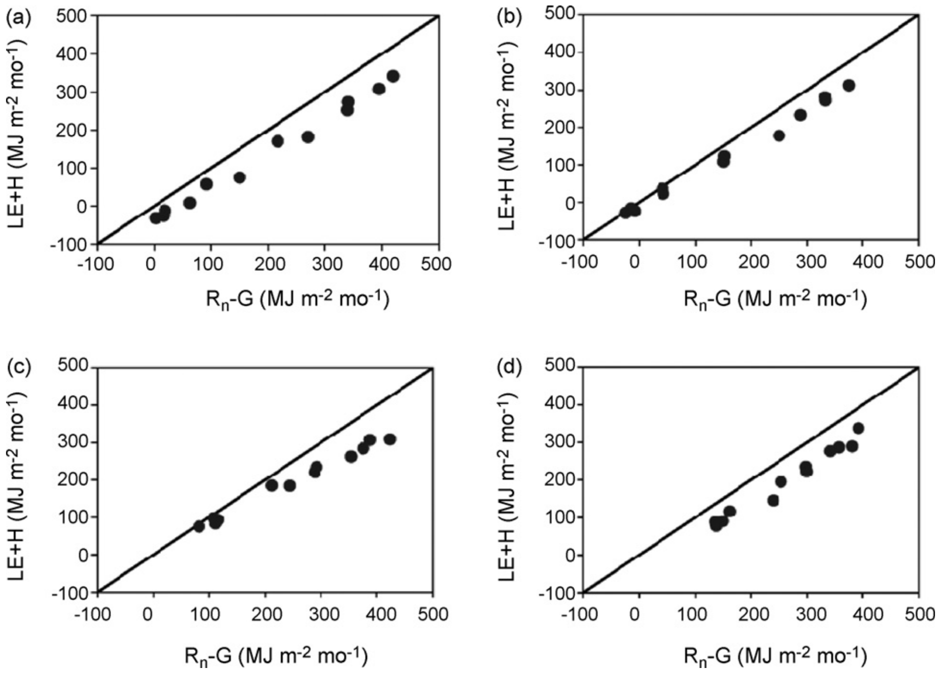

Fig. 1 – Illustration of the average lack of energy closure in measured data at the selected sites: (a) CR-Douglas-fir forest; (b) SOA-old aspen forest; (c) WBW-oak forest; (d) LW-warm grasses. Shown are average monthly data. The solid line indicates the 1:1 line.

to include other recent LSM simulations reported in the literature.

2. Model, sites and data descriptions

2.1. Model description

A key feature of IBIS is that it simulates ecosystem processes that operate at different time scales (ranging from minutes to years) within a single framework. These processes include soil and canopy physics, canopy physiology, vegetation phenology, soil biogeochemistry, and long-term vegetation dynamics (competition, mortality, large-scale disturbances). Complete descriptions of the model can be found in Foley et al. (1996) and Kucharik et al. (2000). In this study, we used a version of IBIS in which the original root water uptake scheme was replaced by a new scheme (Li et al., 2005).

2.2. Site information

Comparisons of IBIS simulations with uncorrected and corrected data were analyzed for a humid temperate coniferous forest located on the west coast of Canada (mature Douglas-fir), a mature boreal broadleaf deciduous forest located in the Canadian boreal region of central Saskatchewan (BOREAS southern old aspen site), a mature temperate broadleaf deciduous forest located in the south-eastern USA (mature oak), and a warm grassland located in the south mid-western USA. A summary of soil and key climatic and ecological conditions of the selected sites is given in Table 1.

2.3. Meteorological and flux data

Meteorological and EC flux data were collected at each site at a half-hourly time step, following Ameriflux research protocols (http://www.fluxnet.ornl.gov/fluxnet/). Instrumentation and data collection procedures are fully described in several publications, including Humphreys et al. (2003) for the temperate coniferous forest site (CR), Black et al. (1996) and Amiro et al. (2006) for the boreal deciduous forest site (SOA), Hanson et al. (2004) for the temperate deciduous forest site (WBW), and Meyers (2001) for the warm grassland site (LW). Meteorological input variables are incident shortwave and longwave radiation, mean air

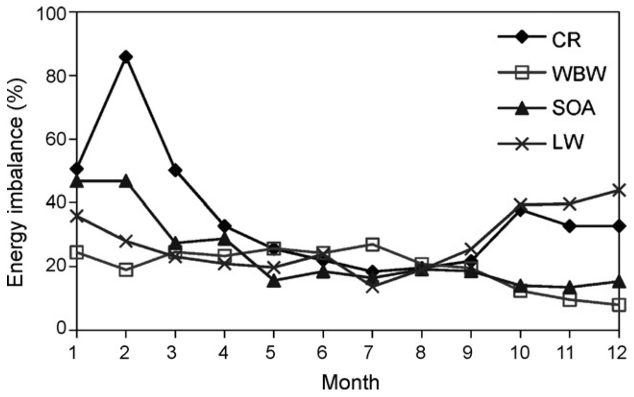

Fig. 2 – Average monthly relative energy imbalance in measured data at the selected sites.

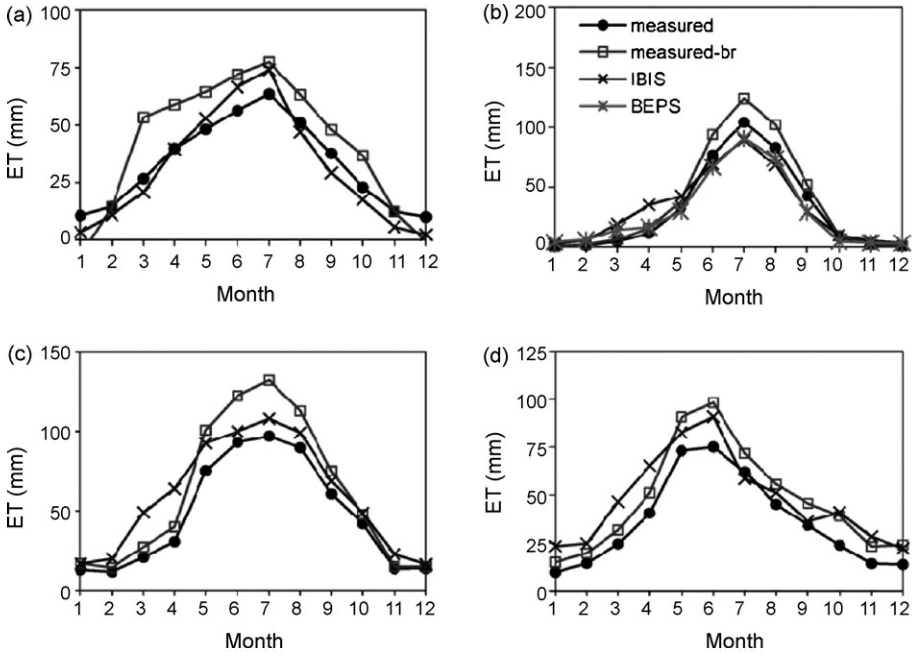

Fig. 3 – Simulated and measured variations of average monthly evapotranspiration (ET) at: (a) CR-Douglas-*fir* forest; (b) SOA-oak forest; (c) WBW-old aspen forest; (d) LW-warm grasses. Measured-br in the legend panel refers to corrected measurements using the Bowen ratio method.

temperature, precipitation, relative humidity, wind speed, and barometric pressure. Downward longwave radiation, whenever unavailable, was estimated using the formulae of Brutsaert (1982).

In this study, measured data cover the periods 1998–2004, 1997–2002, 1995–1998 and 1997–1998 for the CR, SOA, WBW and LW sites, respectively.

3. Energy closure at the four sites and correction of measured sensible and latent heat fluxes

Neglecting the amount of available energy at the land surface that is used for photosynthesis (typically less than 1% of net

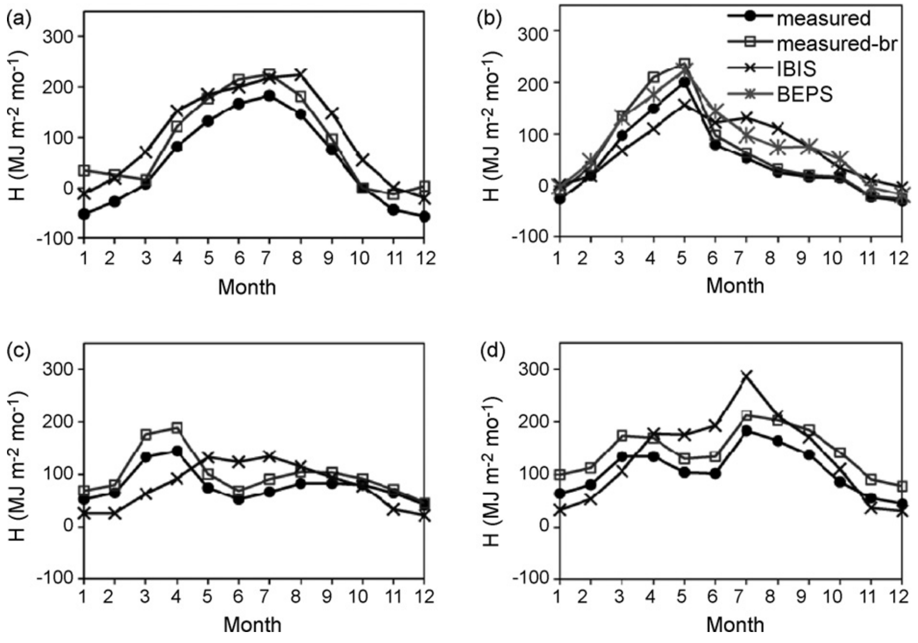

Fig. 4 – Simulated and measured variations of average monthly sensible heat flux (*H*) at: (a) CR-Douglas-*fir* forest; (b) SOA-oak forest; (c) WBW-old aspen forest; (d) LW-warm grasses. Measured-br in the legend panel refers to corrected measurements using the Bowen ratio method.

radiation), the surface energy budget can be expressed at daily or longer time scales as

$$R_n = H + \lambda E + G \tag{1}$$

where R_n, λE and G are net radiation, latent heat flux and soil heat flux, respectively. $R_n - G$ is commonly termed the *available energy* at the land surface. In forest ecosystems, G usually represents less than 5% of R_n, but in ecosystems with little or no vegetation, it may reach much greater proportions (Brutsaert, 1982). R_n is obtained from the sum of the net shortwave and longwave radiation streams, each computed from the difference between measured incoming and outgoing fluxes. Surface heat storage at daily or longer time scales is negligible.

The EC method, applied at all four sites selected for this study, allows for estimates of H and λE from direct measurements of fluctuations in the vertical wind velocity and the scalar concentration. Full details on this technique can be found in several publications (e.g., Arya, 1988; Campbell and Norman, 1998). In contrast with the Bowen ratio (BR) method (another well-established approach to measuring surface energy fluxes, e.g., Dabberdt et al., 1993; Peacock and Hess, 2004), EC does not force the energy budget to close though it offers the advantage of providing separate estimates of H and λE. Mahrt (1998) and Finnigan (2004), among many others, have discussed in detail the source of problems that cause the lack of closure in EC measurements of surface energy budget.

The lack of closure of the energy budget is commonly quantified by the relative difference between $R_n - G$ and $H + \lambda E$, expressed as a percentage: $100 \times [((R_n - G)/(H + \lambda E)) - 1]$. Fig. 1a–d shows average monthly data of $H + \lambda E$ plotted against $R_n - G$, while Fig. 2 shows average variation of the monthly observed energy imbalance at our selected sites. Assuming that R_n and G measurements are rather accurate (Twine et al., 2000; Wilson et al., 2002), Fig. 1a–d shows that $H + \lambda E$ is underestimated at all sites. This may arise from an underestimation of H or λE, or both. Fig. 1a–d shows also that the absolute energy imbalance is more important in summer (where $R_n - G$ is largest), while Fig. 2 shows that the energy imbalance is often proportionately larger in winter than in summer. At WBW and LW sites, the seasonal variations of energy imbalance are relatively small, which may be due to moderate variations in weather conditions at these sites compared to the Canadian sites. The annual averages of energy imbalances are 30%, 22%, 26%, and 30% at CR, SOA, WBW and LW, respectively. Such large energy imbalances seriously bring into question the use of measured data for LSM evaluations, and highlight the need to resolve this problem.

We argue that before using measurements of the surface energy budget (made using EC or any other method) to assess the performance of an LSM, the data must satisfy the fundamental principle of energy conservation. The problem of course is how best to close the energy budget for the EC method. Currently, as reported in Twine et al. (2000), there exist two approaches. The first assumes that measurements of H are accurate so that λE can be calculated merely by subtracting G and H from R_n (Eq. (1)). This approach is known in the literature as the residual method. However, because no compelling evidence exists to confirm that the EC method underestimates only λE (Katul et al., 1999; Twine et al., 2000), a second approach uses the Bowen ratio to close the energy budget. The BR approach assumes that for relatively homogenous vegetated surfaces (which we implicitly assume to be the case for Fluxnet sites), measurements of $R_n - G$ can be considered reliable and representative of the EC flux footprint. That is, any errors in measurement of $R_n - G$ are necessarily of much smaller magnitude than the energy imbalance determined from the simultaneous EC measurements. The BR approach then assumes that the EC technique provides correct estimates of the Bowen ratio ($\beta = H/\lambda E$) even though it underestimates H and λE, as some studies tend to confirm (Barr et al., 1994; Blanken et al., 1997). Thus, rearrangement of Eq. (1) yields:

$$\lambda E = \frac{R_n - G}{1 + \beta} \tag{2}$$

Then correct estimates of λE are assumed to be given by Eq. (2), after which H can also be inferred from:

$$H = R_n - \lambda E - G \tag{3}$$

Eqs. (2) and (3) effectively redistribute the imbalance to H and λE according to their measured relative proportions.

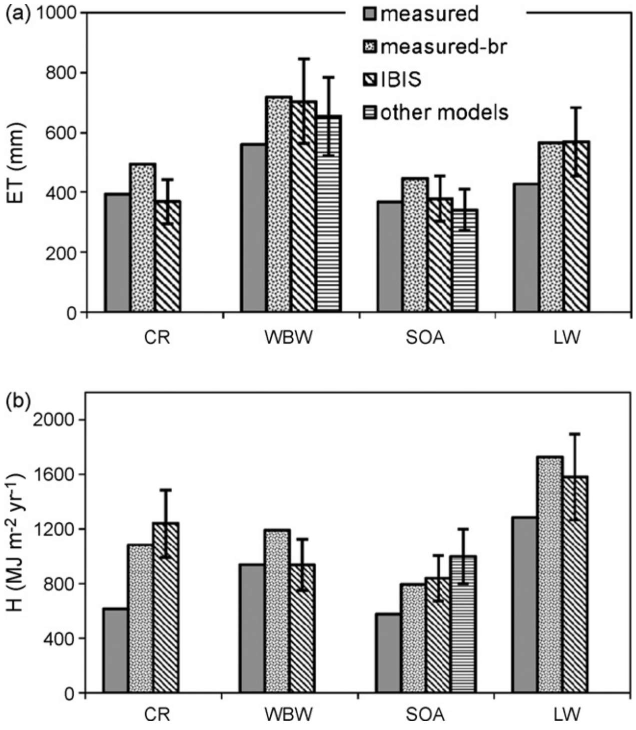

Fig. 5 – Simulated and measured average total annual: (a) evapotranspiration (ET); (b) sensible heat flux (*H*). The other models striped bar refers to BEPS estimates for the SOA site (Ju et al., 2006), and to average estimates (1995–1998) by twelve land surface models for the WBW site (Table 10 in Hanson et al., 2004). Measured-br refers to corrected measurements using the Bowen ratio method. The range bars are intended to illustrate a 20% variation around the simulated values (see text for details).

In the remaining text, corrected latent and sensible heat fluxes refer to λE and H as calculated from measured data using Eqs. (2) and (3).

4. Results

4.1. *Average monthly and yearly ET and H*

Our simulations were made using prescribed vegetation conditions. In particular, seasonal variations of leaf area index (LAI) at the WBW and SOA deciduous forest sites were taken from observations described in Baldocchi et al. (2001) and Barr et al. (2004), respectively. Evapotranspiration (ET) was derived by dividing λE by latent heat of vaporization, λ (~2.51 MJ/kg). Given that our objective is to investigate the general reliability of analyses of LSM performances inferred from comparisons with measurements of energy fluxes that do not satisfy the energy closure principle, the following analysis was not aimed at improving the performance of IBIS. Testing and validation of IBIS has been the focus of several previous studies, where uncorrected EC data were used to evaluate its simulations of heat and water exchanges between land surface and the atmosphere under varying environmental conditions (e.g., Delire and Foley, 1999; El Maayar et al., 2001, 2002; Kucharik et al., 2006).

Average monthly data show that after forcing the measured energy budget data to close, the discrepancy between

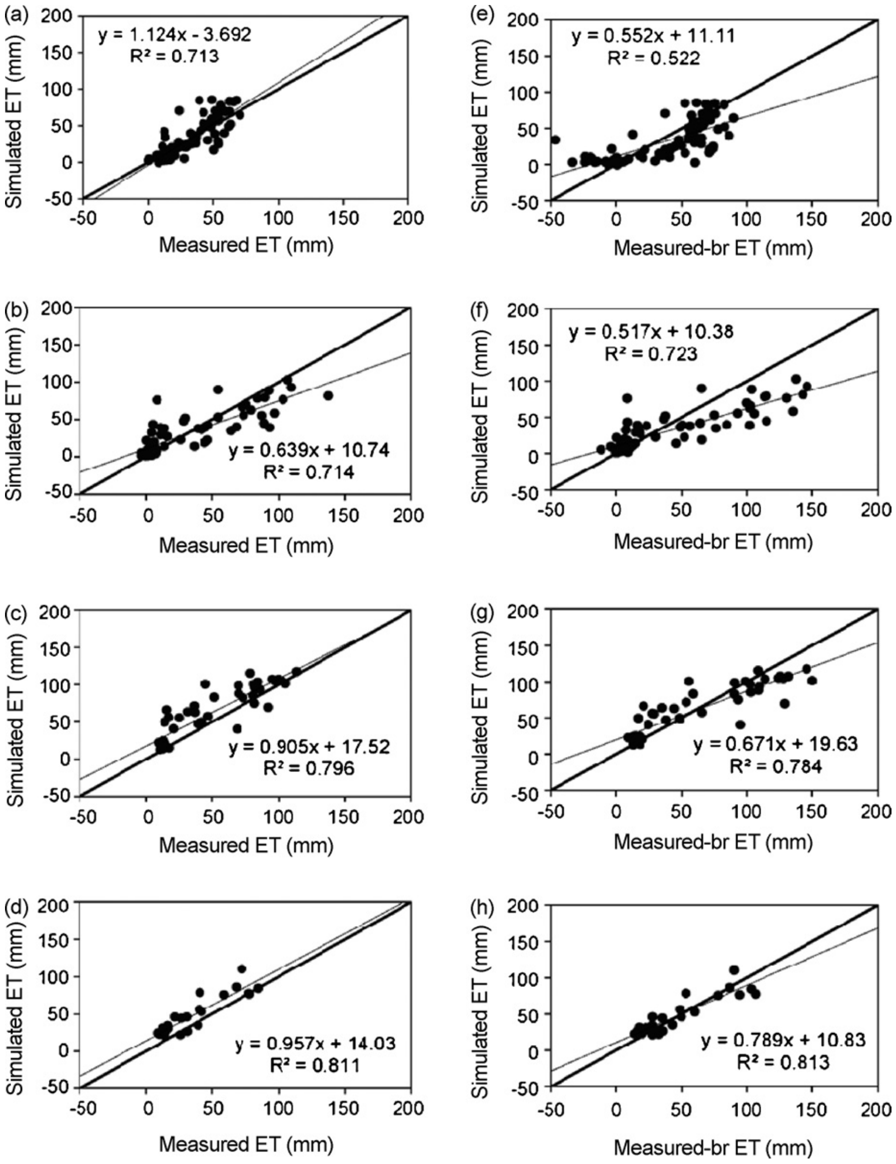

Fig. 6 – Simulated against measured monthly total evapotranspiration (ET) at: (a and e) CR-Douglas-*fir* forest (1998–2004, 7 years); (b and f) SOA-old aspen forest (1997–2002, 6 years); (c and g) WBW-oak forest (1995–1998, 4 years); (d and h) LW-tall warm grasses (1997–1998, 2 years). Simulated *versus* uncorrected measurements are shown in the left panels (a–d), while simulated *versus* corrected measurements are shown in the right panels (e–h). In all figures, the thick solid line indicates the 1:1 line.

simulated and measured monthly values of ET tend to be exacerbated at CR and SOA, but tends to be moderated at WBW and LW (Fig. 3a–d). This indicates that IBIS performs in reality both less and more accurately than what we might have concluded if it had been evaluated using uncorrected data. For sensible heat flux (Fig. 4a–d), results for CR, SOA and LW sites show that IBIS likely performs more accurately than we might have deduced if it had been evaluated using uncorrected EC data, though results for WBW alone would suggest the reverse.

It is commonly recognized within the modeling community that acceptable simulated rates of turbulent fluxes should not deviate from measured rates by more than 20%. On a yearly basis, simulated ET at WBW and LW fell within 20% of the corrected data but were more than 20% different from the uncorrected values, although the converse relationship occurred at CR (Fig. 5a). Hence, the use of uncorrected data to evaluate annual simulations of ET, would suggest the model behaved reasonably well at the CR site but not at WBW and LW, whereas using corrected data would indicate the opposite. Thus, accounting for the importance of energy conservation in the surface energy budget (i.e., closing the energy budget), shed light on the fact that the model likely works better at WBW and LW, but worse at CR. Similarly, comparison to cor-

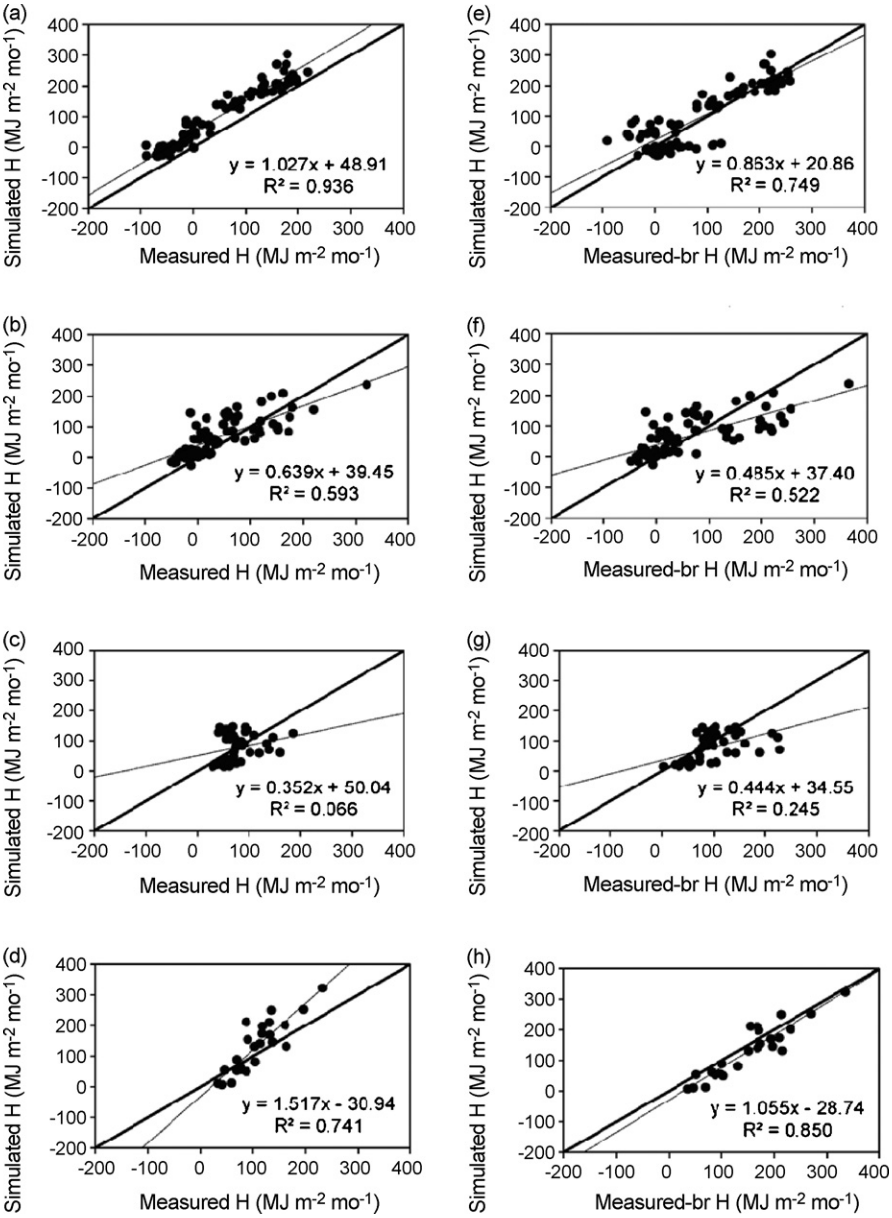

Fig. 7 – Simulated against measured monthly total sensible heat flux (*H*) at: (a and e) CR-Douglas-fir forest (1998–2004, 7 years); (b and f) SOA-old aspen forest (1997–2002, 6 years); (c and g) WBW-oak forest (1995–1998, 4 years); (d and h) LW-tall warm grasses (1997–1998, 2 years). Simulated *versus* uncorrected measurements are shown in the left panels (a–d), while simulated *versus* corrected measurements are shown in the right panels (e–h). In all figures, the thick solid line indicates the 1:1 line.

rected annual *H* values indicates the model behaves better at CR, SOA, and LW (but worse at WBW) than would be expected from uncorrected data (Fig. 5b). These results of suggest the use of uncorrected measurements to evaluate IBIS simulations leads to general underestimation of the model's performance in simulating heat and water exchanges between land surface and the atmosphere.

Interestingly, Fig. 3b indicates that at the SOA deciduous boreal forest site, monthly variation in ET estimated by IBIS was generally very similar to results obtained by Ju et al. (2006) using the boreal ecosystem productivity simulator (BEPS), which is another widely used ecosystem model (Liu et al., 1997; Chen et al., 1999). There was a significant deviation from this agreement for April, however, which corresponds approximately to the period of snow melt and soil thawing. In the first half of the year (up to May), BEPS' estimates of monthly *H* generally agreed better with the corrected measurement data (Fig. 4b). Conversely, IBIS' estimates of annual ET and *H* tended to agree better with corrected data than BEPS estimates (Fig. 5b). At WBW, furthermore, annual ET estimated by IBIS compared very well to average annual ET as estimated by twelve ecosystem models for the 1995–1998 period (Hanson et al., 2004).

4.2. *Seasonal and interannual variability of ET and H*

Seasonal and interannual variability in the partitioning of available energy ($R_n - G$) between sensible and latent heat fluxes at the land surface are key features that LSM should be able to reproduce correctly if they are to be used to investigate interactions between vegetation and the atmosphere, and how these may respond or contribute to climatic variability.

The overall agreement between IBIS simulations of monthly ET and *H* with both uncorrected and corrected measurement data is shown in Figs. 6 and 7, respectively. The results suggest that our perception of the ability of LSM to reproduce seasonal variability of ET and *H* might be very biased when simulations of these LSM are evaluated using uncorrected data. For instance, the ability of the model to reproduce the seasonal variability of ET at CR and WBW is in reality weaker than might be inferred from a comparison between simulated and uncorrected data (Fig. 6a, c, e and g). Conversely, the model reproduces the seasonal variability of *H* at LW much better than appears from using uncorrected data (Fig. 7d and h). After grouping simulated and uncorrected monthly data obtained at all sites, it seems that the model performs well in terms of seasonal variability of both ET and *H* over a range of ecosystems (Fig. 8a and b). In reality, the model actually performs less well than expected (Fig. 8c and d), though the overall performance remains fairly good.

Comparison of simulated data with the corrected measurements suggests that the model can capture the interannual variability of both ET and *H* much more successfully than what we might have concluded initially from comparison with the uncorrected data (Figs. 9a–c and 10a–c). In particular, Figs. 9c and 10c show that if we had relied on the uncorrected measurements for comparison, we would probably have concluded erroneously that the model failed to produce acceptable estimates of ET and *H* at the WBW and CR sites, respectively.

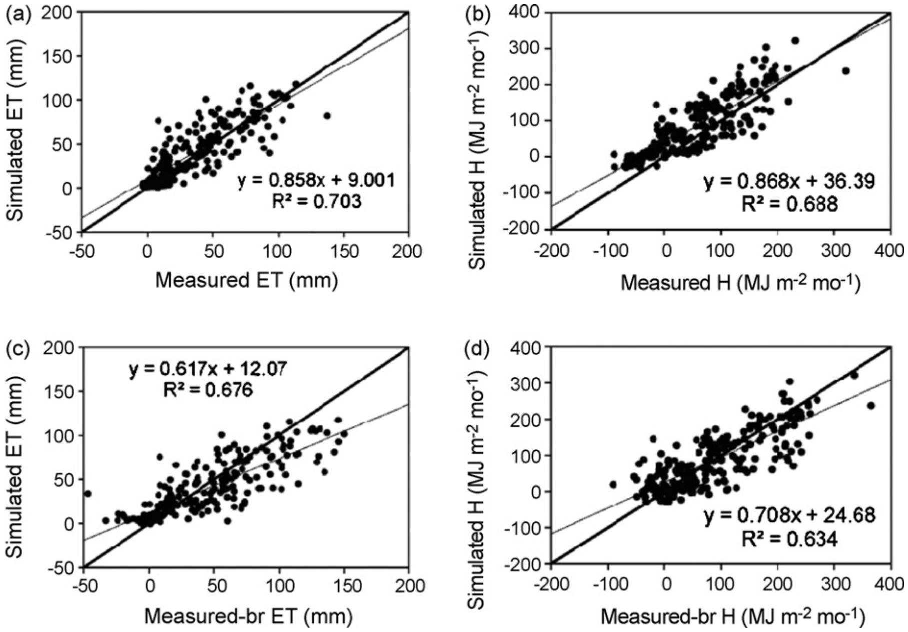

Fig. 8 – Simulated *versus* measured monthly fluxes: (a and c) total evapotranspiration (ET); and (b and d) total sensible heat flux (*H*). Panels (a) and (b) show simulated *versus* uncorrected measurements, while panels (c) and (d) show simulated *versus* corrected measurements. Each figure groups all simulated and measured monthly fluxes at the four sites (i.e., all monthly fluxes that were simulated and measured during the periods 1998–2004, 1997–2002, 1995–1998, and 1997–1998 at CR, SOA, WBW and LW sites, respectively. This yields a total of 19 × 12 months). In all figures, the thick solid line indicates the 1:1 line.

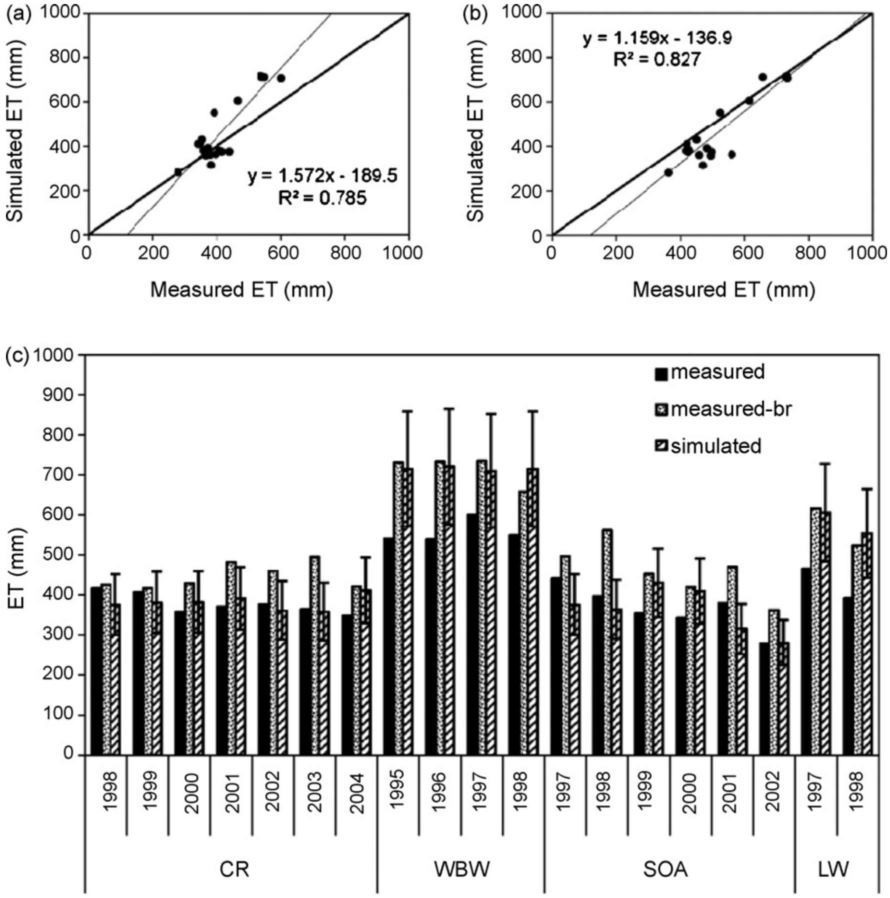

Fig. 9 – Simulated *versus* measured total annual evapotranspiration (*ET*) at all sites. (a) Simulated *versus* uncorrected measurements, while (b) shows simulated *versus* corrected measurements using the Bowen ratio method (BR; see text for details). Measured-br in (c) refers to measured *ET* corrected using the BR method. Panels (a) and (b) group all simulated and measured annual fluxes at the four sites (i.e., all annual fluxes that were simulated and measured during the periods 1998–2004, 1997–2002, 1995–1998, and 1997–1998 at CR, SOA, WBW and LW sites, respectively. This yields a total of 19 years). The range bars in (c) illustrate a 20% variation around the simulated values, while the thick solid line in (a) and (b) indicates the 1:1 line.

5. Concluding remarks

Understanding of global climate processes and their effects on the biosphere requires good knowledge of the partitioning of available energy between sensible and latent heat at the land surface. Such knowledge is needed to develop reliable tools for the study of both short-term and long-term ecosystem processes, and how these processes feedback and affect the climate system. As a group, LSM are among the tools needed for these purposes. Validating these LSM against measurements of the surface fluxes is a critically important step in their development and application. Such validation requires the best possible measurement data, and justifies further effort to resolve the problem of closing measured energy budgets using defensible procedures that respect the principle of energy conservation. Only then can we properly assess the performance of a particular model and determine how best to improve it.

A major outcome of the current Fluxnet program is the supply of long-term measurements of heat and mass exchanges between land surface and the atmosphere, for a wide range of terrestrial ecosystems. Such measurements are essential to evaluate the ability of ecosystem process models to reproduce seasonal and interannual variability of heat and mass flows, and ultimately to improve them. Our survey of recent LSM evaluations shows that many modelers commonly use available measurements without paying much attention to the issue of energy budget closure. This is a major concern as it becomes extremely difficult to accurately evaluate heat and mass outputs of LSM, in which the energy is forced to close, with measurements that do not satisfy the fundamental principles of energy conservation. We have found that LSM evaluations based on measurements not corrected for energy balance closure will likely yield inappropriate calibrations and parameterizations, and hence cause the models to provide results that are less accurate than they could be.

Our study demonstrates that a good agreement between LSM simulations and uncorrected surface flux measurements does not guarantee the success of these LSM, while a weak agreement does not necessarily imply their failure. We recognize that our analyses were based mainly on simulations of a

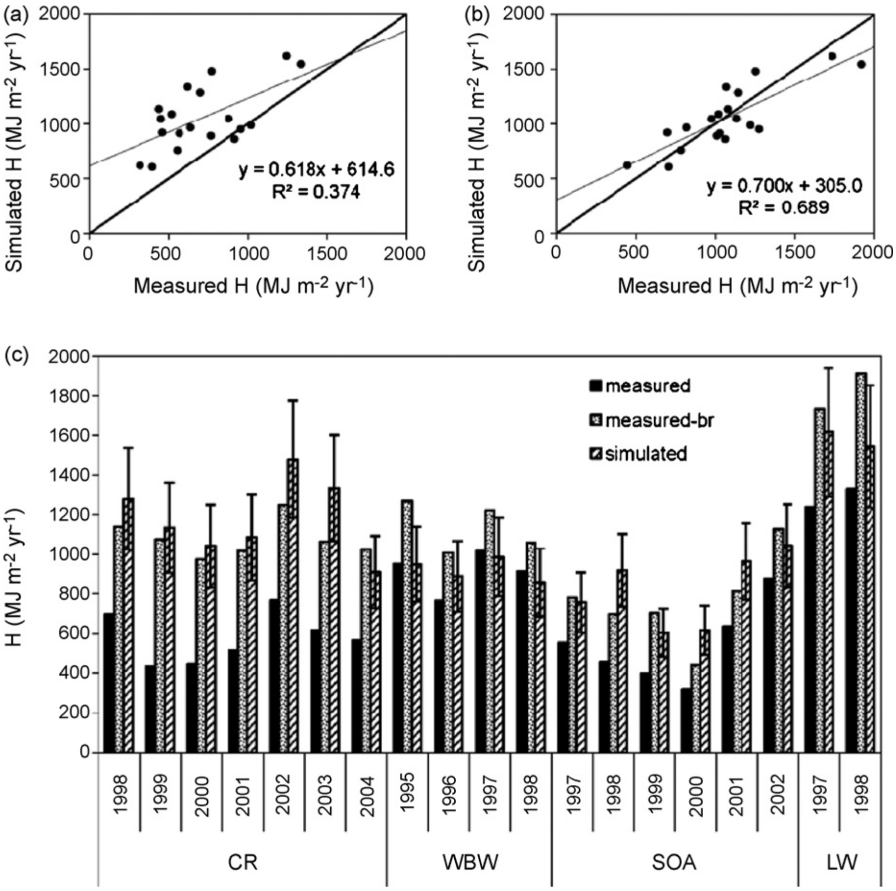

Fig. 10 – Simulated *versus* measured total annual sensible heat flux (*H*) at all sites. (a) Simulated *versus* uncorrected measurements, while (b) shows simulated *versus* corrected measurements using the Bowen ratio method (BR; see text for details). Measured-br in (c) refers to measured *H* corrected using the BR method. Panels (a) and (b) group all simulated and measured annual fluxes at the four sites (i.e., all annual fluxes that were simulated and measured during the periods 1998–2004, 1997–2002, 1995–1998, and 1997–1998 at CR, SOA, WBW and LW sites, respectively. This yields a total of 19 years). The range bars in (c) illustrate a 20% variation around the simulated values, while the thick solid line in (a) and (b) indicates the 1:1 line.

single LSM (IBIS). However, recent simulations by other state-of-the-art ecosystem models were also considered, which strengthen our conclusion concerning the importance of correcting measurements of energy fluxes, to close the energy budget, prior to their use for model evaluations. The use of the Bowen ratio method to correct the measured data for energy closure was recommended by Twine et al. (2000). However, according to our current knowledge of ecosystem processes (e.g., Ball et al., 1987; Leuning et al., 1995), a more appropriate approach might be a one that considers the coupling between carbon and energy flows.

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