Agricultural and Forest Meteorology 182–183 (2013) 145–155

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Inter-annual variability of carbon and water fluxes in Amazonian forest, Cerrado and pasture sites, as simulated by terrestrial biosphere models

Celso von Randow[a,*], Marcelo Zeri[a], Natalia Restrepo-Coupe[b], Michel N. Muza[c], Luis Gustavo G. de Gonçalves[d], Marcos H. Costa[e], Alessandro C. Araujo[f], Antonio O. Manzi[g], Humberto R. da Rocha[h], Scott R. Saleska[i], M. Alaf Arain[j], Ian T. Baker[k], Bruno P. Cestaro[h], Bradley Christoffersen[i], Philippe Ciais[l], Joshua B. Fisher[m], David Galbraith[n], Xiaodan Guan[o], Bart van den Hurk[p], Kazuhito Ichii[q], Hewlley Imbuzeiro[e], Atul Jain[r], Naomi Levine[s], Gonzalo Miguez-Macho[t], Ben Poulter[l], Debora R. Roberti[u], Alok Sahoo[v], Kevin Schaefer[w], Mingjie Shi[o], Hanqin Tian[x], Hans Verbeeck[y], Zong-Liang Yang[o]

[a] Centro de Ciência do Sistema Terrestre, Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, SP, Brazil
[b] Plant Functional Biology and Climate Change Cluster, University of Technology, Sydney, Australia
[c] Instituto Federal de Santa Catarina, Florianópolis, SC, Brazil
[d] Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, SP, Brazil
[e] Dep. Agricultural Engineering, Federal University of Viçosa, Viçosa, MG, Brazil
[f] Embrapa Amazônia Oriental, Belém, PA, Brazil
[g] Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, AM, Brazil
[h] Departamento de Ciências Atmosfericas, IAG, Universidade de São Paulo, São Paulo, Brazil
[i] Department of Ecology and Evolutionary Biology, University of Arizona, Tucson, AZ, USA
[j] School of Geography and Earth Sciences, McMaster University, Hamilton, ON, Canada
[k] Atmospheric Science Department, Colorado State University, Fort Collins, CO, USA
[l] Laboratoire des Sciences du Climat et de l'Environnement, CEA Orme des Merisiers, Gif sur Yvette, France
[m] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[n] School of Geography, University of Leeds, Leeds, UK
[o] Center for Integrated Earth System Science, Department of Geological Sciences, The University of Texas at Austin, Austin, TX, USA
[p] Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
[q] Faculty of Symbiotic Systems Science, Fukushima University, Japan
[r] Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[s] Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA, USA
[t] Condensed Matter Physics Department, University of Santiago de Compostela, Santiago de Compostela, Spain
[u] Dept of Physics, Federal University of Santa Maria, Santa Maria, RS, Brazil
[v] Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA
[w] National Snow and Ice Data Center, University of Colorado at Boulder, Boulder, CO, USA
[x] School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL, USA
[y] Laboratory of Plant Ecology, Ghent University, Ghent, Belgium

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 12 May 2013
Accepted 16 May 2013

Keywords:
Land-surface modeling
Surface fluxes
Amazonia
Inter-annual variability

ABSTRACT

This study analyzes the inter-annual variability (IAV) of simulations of 21 different land surface model formulations, driven by meteorological conditions measured at 8 flux towers, located in rain forest, forest-savanna ecotone and pasture sites in Amazonia, and one in savanna site in Southeastern Brazil. Annual totals of net ecosystem exchange (NEE) of carbon and evapotranspiration (ET), measured and simulated by each model for each site-year, were compared in terms of year-to-year variability and possible relation to climate drivers. Results have shown that most of models simulations for annual totals of NEE and ET, and IAV of these fluxes, are frequently different from measurements. The average of the model simulations of annual fluxes tend to respond to climatic drivers similarly to the observations, but with noticeable discrepancies. Annual measurements of NEE are negatively correlated to annual rainfall in the forest sites group. Although the ensemble of all models yields a similar result, only three model

* Corresponding author. Tel.: +55 12 31869321; fax: +55 12 31012825.
E-mail addresses: celso.vonrandow@inpe.br, cvrandow@gmail.com (C. von Randow)

.

http://dx.doi.org/10.1016/j.agrformet.2013.05.015

formulations reproduce a significant negative correlation of simulated NEE with rainfall. For the IAV of ET, tower measurements are controlled by annual variations of radiation and this feature is captured by the ensemble of the models, both at individual sites and when all forest sites are grouped. However, simulated ET values are also significantly correlated to the amount of precipitation in many models and in the model ensemble, while there is no significant correlation in the observations. In general, the surface models are able to reproduce the responses of fluxes to climatic drivers, but improvements are still needed to better capture their inter-annual variability.

1. Introduction

The Earth's atmosphere is in permanent interaction with the terrestrial biosphere, forming a coupled system. This interaction plays a fundamental role in the climate system and in biogeochemical and hydrological cycles through the exchange of energy and mass (for example, water and carbon), between the vegetation and the atmospheric boundary layer. With the objective of understanding and predicting these exchanges and their influence in the climate system, the main focus of many studies of surface–atmosphere interaction is to quantify the fluxes over terrestrial biomes, either by direct measurements in flux towers or by parameterization using land-surface models. This has been one key objective of the Large Scale Biosphere-Atmosphere Program in Amazonia (LBA), which initiated the scientific infrastructure for long-term flux measurements in Brazilian Amazonia (Keller et al., 2004).

It is known that Amazonia plays a key role in the regional and global climate system, by largely contributing to global surface evapotranspiration (and therefore constituting a large source of latent heat) and substantially acting in the global carbon cycle. However the Amazon forest is currently facing risks due to deforestation pressure and climate change (Davidson et al., 2012; Malhi et al., 2007). On the one hand, evidence from observational and modeling studies (e.g. Betts et al., 1997; Nobre et al., 1991; Sampaio et al., 2007; von Randow et al., 2004; Zhao et al., 2001) show that changes on surface cover may lead to a significant impact on regional and global climate. On the other hand, changes in rainfall regimes, especially in the dry season, may induce important alterations of the terrestrial ecosystem.

Carbon and water fluxes in the Amazonian ecosystem are expected to be coupled to regional climate conditions, but the dynamic mechanisms associated with their inter-annual variability (IAV) remain not fully understood (Nobre et al., 2009). Historical records of the Amazonian rivers show that IAV of precipitation in Amazonia is significant and dynamically linked with consistent anomalies in the surface water and energy balances over the basin and associated with the El Niño – Southern Oscillation phenomenon or oscillations in the Atlantic sea surface temperature, SST (Fu et al., 2001; Marengo, 1992; Marengo et al., 1998; Poveda et al., 2006; Richey et al., 1989). However, it must be emphasized that the combined tropical Pacific and Atlantic SST variability explains little more than 50% of inter-annual precipitation variance over Amazonia and not much is known about other mechanisms, internal or external to the region, responsible for the remaining unexplained IAV (Nobre et al., 2009).

One of the achievements of the LBA program was the establishment of a network of eddy covariance flux towers across Brazilian Amazonia, which are providing important knowledge about the characteristics of energy, water and carbon fluxes across the region (Araújo et al., 2002; Borma et al., 2009; Miller et al., 2004; Rocha et al., 2002, 2004, 2009; Sakai et al., 2004; Saleska et al., 2003; von Randow et al., 2004; Zeri and Sá, 2010). While land surface models have historically represented ecosystems of Amazonia as water-limited, predicting dry season declines in evapotranspiration and photosynthesis (e. g. Costa and Foley, 1997; Nobre et al., 1991), measurements at the sites in Central Amazonia appear to have little decline in evapotranspiration. Also, forest photosynthesis appear unaffected by the dry season, even showing some enhancement related to higher available solar energy (Restrepo-Coupe et al., 2013; Rocha et al., 2009), as many of these forests tend to have sufficient dry season water supply in most years because of the relatively high water holding capacity of the soils and the ability of deep root systems to access water down to 10+ m deep (Bruno et al., 2006; Lola da Costa et al., 2010; Markewitz et al., 2010; Negrón-Juárez et al., 2007). However, the sites in Southern Amazonia, with semi-deciduous forests or transitional forests to Cerrado vegetation (Brazilian savanna) and deforested areas have shown declines in dry season fluxes and clear indications of seasonal water stress, also related to more intense dry season climate at these sites (Rocha et al., 2009; von Randow et al., 2004).

By combining information from flux tower observations and terrestrial process-based models, we can improve our knowledge about the functioning of the ecosystems, interaction with the climate system and possibly identify missing mechanisms that could improve model simulations (Keenan et al., 2012). Terrestrial ecosystem models are important tools to aid studies of biosphere-atmosphere interaction and responses of ecosystem processes to hypothetical climate conditions. Processes are represented in models of different complexities, ranging from a simple representation of the transfer of mass and energy in the soil–plant–atmosphere interface, to complex versions that simulate changes in composition, structure and function of vegetation and soil biogeochemistry.

The proportions of IAV directly related to variability in climate drivers remain as an open question and a detailed assessment of the relative roles of climate and functional change on the interannual variability of CO_2 flux across a wide range of sites and climate zones is still needed. The IAV of carbon exchange has been found to correlate climatic drivers poorly (Richardson et al., 2007; Polley et al., 2010) or strongly (Yuan et al., 2009; Desai, 2010). The study of the relations of climatic variables and fluxes over the Amazon region may provide important new knowledge and reduce the uncertainty about the responses of the vegetation to natural climate variations and possible future extreme conditions.

The LBA-DMIP project was designed to synthesize and compare a suite of simulations of land surface and terrestrial ecosystem models in 8 flux towers of the LBA program, covering tropical rainforest, Cerrado and pasture sites (Gonçalves et al., 2013). In this work we analyze the inter-annual variability of the fluxes observed and simulated by the suite of participating models of the LBA-DMIP project, at forest, Cerrado and pasture sites in Amazonia, with the objective of giving insight into the following questions: how do carbon and water exchange vary from year to year and how do the models simulate this IAV in Amazonian sites? Are differences between simulations and observations related to specific sites or vegetation cover? The IAV of observed and simulated fluxes is mainly related to which climatic drivers?

2. Methods

Modeled and observed values at the 8 sites listed in Table 1 were obtained through the LBA-DMIP project

Table 1
List of eddy covariance tower sites[a] used in the LBA-MIP project.

Site short code	Site name	Longitude [°]	Latitude [°]	Elev. [m]	Biome type	Data availability
K34	Manaus Km34	−60.21	−0261	130	Tropical rainforest	2002–2005
K67	Santarém Km67	−5496	−0285	130	Tropical rainforest	2002–2004
K83	Santarém Km83	−5497	−0302	130	Tropical rainforest	2001–2003
RJA	Reserva Jarú	−6193	−10.08	191	Tropical rainforest	2000–2002
BAN	Javaes River – Bananal Island	−50.16	−0982	120	Forest-Savanna ecotone	2004–2006
K77	Santarém Km77	−5489	−0302	130	Pasture/Agriculture	2001–2005
FNS	Fazenda Nossa Senhora	−6236	−10.76	306	Pasture	1999–2001
PDG	Reserva Pe-de-Gigante	−4765	−2162	690	Savanna	2001–2003

[a] Principle Investigators and data references for these tower sites are as follows:
K34: Manzi, A., Nobre, A. (INPA, Brazil) (Araújo et al., 2002), K67: Wofsy, S. (Harvard University, USA), Saleska, S. (UofA, USA), Camargo, A. CENA/USP, Brazil) (Hutyra et al., 2007; Saleska et al., 2003), K83: Goulden M. (UC Irvine, USA), Miller, S. (SUNY, Albany, USA), da Rocha, H. (USP, Brazil). (Goulden et al., 2004; Miller et al., 2004; Rocha et al., 2004), K77: Fitzjarrald, D. (SUNY, Albany, USA) (Sakai et al., 2004), RJA: Manzi, A. (INPA, Brasil), Aguiar, R. (UNIR, Brazil.) (Kruijt et al., 2004; von Randow et al., 2004), FNS: Waterloo, M.(Vrije Universiteit Amsterdam, The Netherlands), Manzi, A. (INPA, Brazil) (von Randow et al., 2004), BAN: da Rocha, H. (USP, Brazil) (Borma et al., 2009), PDG: da Rocha, H. (USP, Brazil) (Rocha et al., 2002).

(http://www.climatemodeling.org/lba-mip/). On the scope of the LBA-DMIP project, data collected at 8 flux towers were consistently checked and gap-filled to drive and validate a suite of land-surface and terrestrial biosphere models. Here we provide a brief description of the methods used, while details of the site locations, data processing and characteristics of all the participating models are presented by Gonçalves et al. (2013).

The sites include evergreen forests (K34, K67 and K83), a semi-deciduous broadleaf forest (RJA), a deciduous broadleaf forest (forest-savanna ecotone, BAN), a savanna biome (PDG), and two pasture sites (FNS and K77). Seven of eight sites are in the Brazilian Amazon, while a savanna site in the state of São Paulo was also included. The meteorological forcing data collected at these sites were gap-filled according to a common protocol, providing continuous dataset for driving models. Also, carbon and latent heat fluxes collected using the eddy-covariance method were accumulated into annual totals of net ecosystem exchange (NEE) of carbon and evapotranspiration (ET) and used to infer the magnitude of inter-annual variability of carbon and water exchange.

The suite of model formulations includes 9 dynamic vegetation models and 8 land surface models (that do not simulate dynamic vegetation but simulate carbon and water exchange at time scales varying from hourly to monthly) that were driven by the standardized meteorological forcing data from the flux towers (Gonçalves et al., 2013). Additionally, variant versions of some models were run (such as, for example, 5 different models derived using the Simple Biosphere Model, SiB (Sellers et al., 1986) as their basis), resulting in a total of 21 different model formulations reported in this intercomparison (Table 2). Table 2 includes model numbers used in Figs. 1 and 2, presented in Section 3.

All simulations were performed using standard versions of the models, using the gap-filled meteorological forcing data at each site and locally observed values of soil texture and vegetation characteristics, where needed, according to the standard protocol described in Appendix 1 of Gonçalves et al. (2013). No parameter optimization or model calibration was performed prior to the intercomparison runs.

Due to lack of measurements of CO_2 storage within the canopy in some locations, slightly different approaches were used to infer NEE from the turbulent carbon fluxes measured (F_c) at the sites. Whenever available, the canopy storage flux (S_c) was added to F_c to infer the biotic NEE. During instrument malfunctions, S_c was modeled at RJA and K34, following Iwata et al. (2005). For sites with lower biomass and where the full instrumentation was not available (FNS, BAN and PDG), we assumed that annual NEE is equivalent to annual totals of F_c.

The correction of nighttime NEE values for periods of low turbulent mixing is also a complex issue and is probably the biggest cause of uncertainties in the accounting of carbon exchange using the eddy covariance technique in Amazonian sites (Araújo et al., 2002; Kruijt et al., 2004; Miller et al., 2004). In this paper, we maintain the different approaches for nighttime treatment at each site as reported in their reference papers (Table 1).

Also, evapotranspiration data (estimated from latent heat flux measurements) is likely partially underestimated in some sites, either due to physical limitations of the instrumentation (Massman

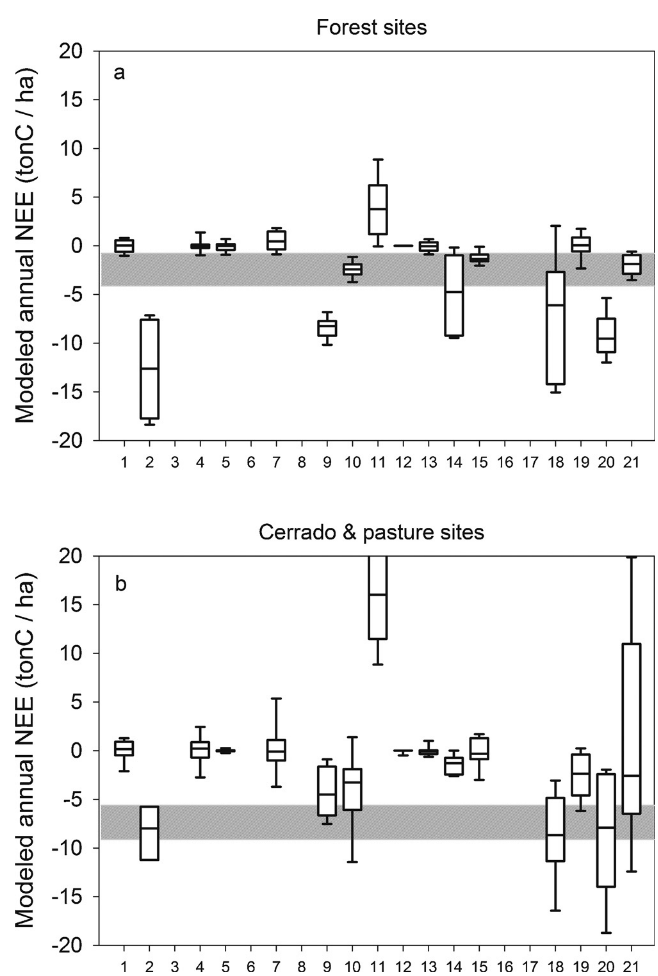

Fig. 1. Boxplots of annual Net Ecosystem Exchange (NEE) simulated at the sites listed in Table 1 with the suite of terrestrial biosphere models listed in Table 2 Each boxplot is a distribution of the annual site-year totals simulated by one particular model, for (a) forest sites (K34, K67, K83 and RJA); and (b) cerrado or pasture sites (BAN, FNS, K77, PDG). Shaded areas show the inter-quartile range of observations at the sites.

Table 2
Summary of models and its variants used.

Model #	Model Acronym	Simulates energy and water fluxes	Simulates carbon fluxes	Simulates dynamic vegetation	Reference
1	Biome-BGC	X	X		Thornton et al. (2002)
2	CLM35-DGVM	X	X	X	Levis et al. (2004)
3	CLM35	X	X		Oleson et al. (2008)
4	CLM4CN	X	X		Thornton et al. (2007)
5	DLEM	X	X	X	Tian et al. (2010)
6	ISAM	X	X		Yang et al. (2009)
7	JULES	X	X	X	Clark et al. (2011)
8	LEAF2-HYDRO	X			Miguez-Macho et al. (2007)
9	Noah-MP	X	X	X	Niu et al. (2011)
10	ORCHIDEE	X	X	X	Krinner et al. (2005)
11	SSiB2	X	X		Zhan et al. (2003)
12	SiB3	X	X		Baker et al. (2008)
13	SiBCASA	X	X		Schaefer et al. (2008)
14	CN-CLASS	X	X	X	Arain et al. (2006)
15	ED2	X	X	X	Medvigy et al. (2009)
16	PT-JPL	X			Fisher et al. (2008)
17	H-TESSEL	X			Balsamo et al. (2009)
18	IBIS	X	X	X	Kucharik et al. (2000)
19	LPJ	X	X	X	Sitch et al. (2003)
20	SiB2	X	X		Sellers et al. (1996)
21	SiB2(modified)	X	X		Rocha et al. (in preparation)

and Lee, 2002) or losses on scales of the order of more than 30 min. Studies have shown that the atmospheric boundary layer in Amazonia (von Randow et al., 2002, 2008) frequently presents slowly moving large eddies caused by strong convective motions and/or local circulations induced by surface heterogeneity, and turbulence is organized into "turbulent organized structures" (Foken, 2008; Kanda et al., 2004) which do not move with the wind fast enough to be adequately sampled in the time scales usually used in eddy covariance.

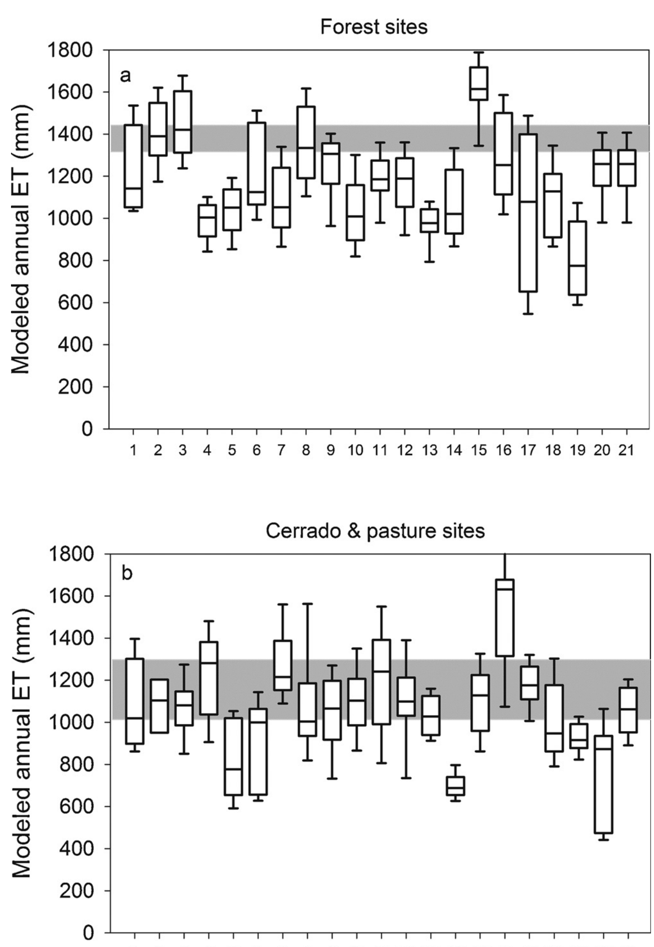

Fig. 2. Same as Fig. 1, but for annual Evapotranspiration (ET) simulated at the sites listed in Table 1 with the suite of terrestrial biosphere models listed in Table 2.

When necessary, the evapotranspiration fluxes were corrected to achieve energy balance closure maintaining the Bowen ratio as measured by the eddy flux (von Randow et al., 2004). This approach is preferred when it is likely that the underestimation of the fluxes is caused not by the instrument limitations but because of a failure to capture low-frequency transport or advection or from a mismatch between footprints of the flux measurements compared to that of the radiation measurements. From the previous studies in Amazonia (von Randow et al., 2004; Finnigan et al., 2003), we concluded that this approach is appropriate.

To evaluate the IAV of observed and modeled fluxes, sites were separated in two groups: rainforest sites (K34, K67, K83 and RJA) and Cerrado/pasture sites (BAN, K77, FNS and PDG), resulting in a total of 13 site-years available in the rainforest group and 14 site-years in the Cerrado/pasture group. Although grouping of the sites into broad categories may augment the spurious variability in each group, this classification is necessary because the dataset is limited for a more detailed analysis. Still, figures in the next section are presented showing each site in different colors. Model 'biases' were then calculated as the difference between annual simulated flux and annual measured flux at each site-year.

Finally, to analyze possible drivers of IAV at the sites, we investigate possible relations between the fluxes (as measured or modeled at each site-year) and climate variables R_n, P and annual values of Budyko's dryness index (D) given by

$$D = \frac{R_n}{\lambda P} \quad (1)$$

where R_n is the annual net radiation in MJ/m^2, P is the annual precipitation in mm, and λ (=245 MJ/kg) is the latent heat of vaporization.

3. Results

3.1. Inter-annual variability and comparison to observations

After computing the annual totals of NEE (t C/ha) and ET (mm) as measured and simulated by each model in each site-year, we separated the results into categories "Forest sites" and "Cerrado and pasture sites", and built boxplots for each model formulation, which are display in Fig. 1

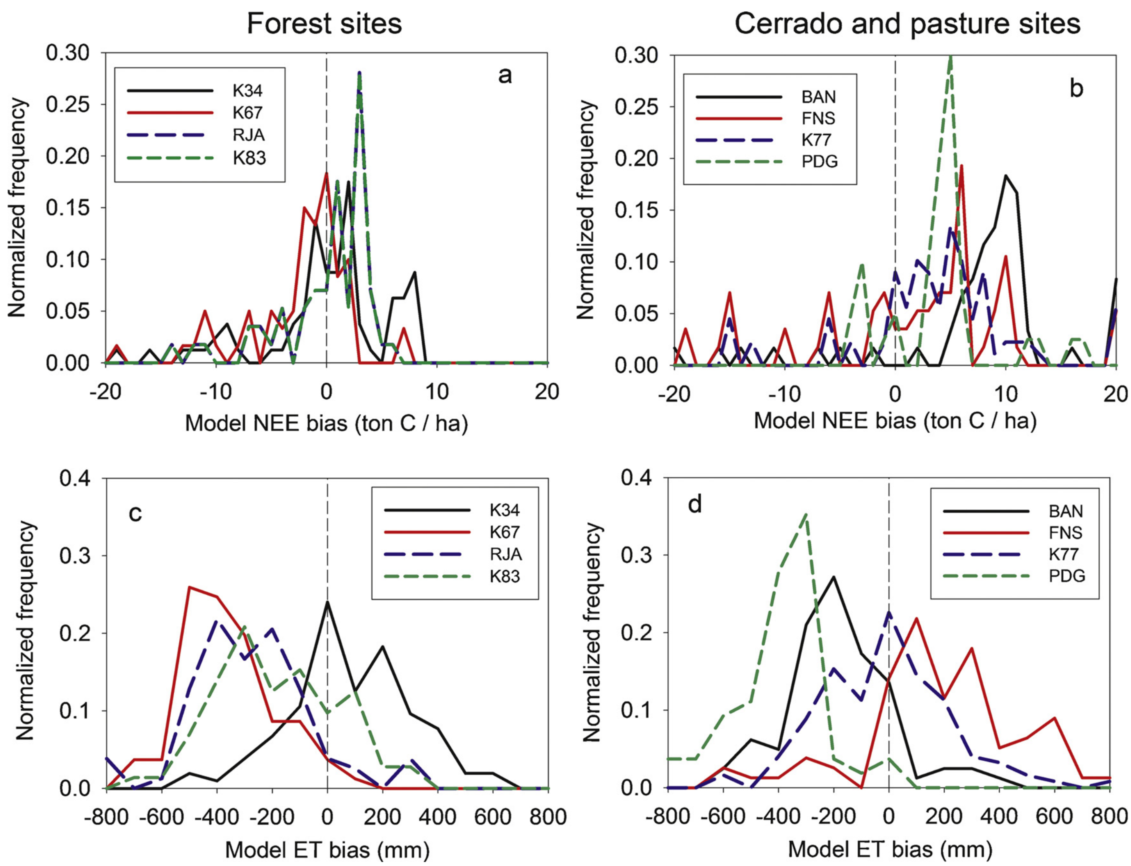

Fig. 3. Frequency distribution of model bias (modeled − measured) over all years at the LBA-DMIP sites, for (a) NEE at forest sites; (b) NEE at Cerrado and pasture sites; (c) Evapotranspiration at forest sites and (d) evapotranspiration at Cerrado and pasture sites.

The shaded areas in Fig. 1 show the inter-quartile range of observations at the forest sites (Fig. 1a) and at the Cerrado and pasture sites (Fig. 1b), which, for the forest category, span annual NEE values from −25 t C/ha (negative values represent net sink of carbon by ecosystem) in the first quartile, to nearly null (no net sink or source at some site-years) in the third quartile. For the Cerrado and pasture sites, the observed inter-quartile range is from −9 to −5 t C/ha.

Distributions of annual modeled NEE show that most models have lower IAV than observed (Fig. 1). Also, some models have large bias compared to the range of observations, especially at Cerrado and pasture sites. It should be noted, however, that these biases may be partly due to the tendency of models generally being held to conserve energy, moisture and carbon balance, and eddy covariance flux measurements being largely prone to uncertainties in those balances (Araújo et al., 2010; Miller et al., 2004).

The observed and modeled IAV of evapotranspiration is presented in Fig. 2 For ET in forest sites (Fig. 2a), some models appear to present similar ranges of IAV as measured in the flux towers, but the majority of the models underestimate the annual ET measured. For the Cerrado and pasture sites (Fig. 2b), the performance is slightly better: most models simulate IAV similar to the range observed, and, although some are also underestimating the fluxes, they agree better with the observed fluxes for this category than for the forests sites.

To identify with better clarity the differences between model simulations and flux measurements, we present in Fig. 3 the distribution of model bias for each site. Model bias, in this context, is calculated as the difference between annual fluxes simulated by each model and measured at the towers. Note that, in previous figures, distributions were aggregating data for all "forest" or "Cerrado/pasture" sites, and showing the variability of how each model simulated the fluxes in these categories. In Fig. 3, the distributions aggregate all model simulations in one site.

Results in Fig. 3a show that, for the forest sites, the model bias is in general normally distributed from negative to positive values, although slightly skewed to positive values. Fig. 3b shows, for the Cerrado and pasture sites, that the models generally simulate higher NEE than observed, or, rather, due to most towers measuring high carbon uptake (therefore strongly negative annual NEE), the difference between model and observations is frequently positive. Fig. 3c and d shows that, for evapotranspiration, the model biases distributions are wider and more variable, with considerable positive values at some sites and negative values at others. As noted from Fig. 2, there is a tendency of underestimation of annual ET in the forest sites, and we can see that this is also the case for the Cerrado sites.

3.2. Relations with climate drivers

Studies of responses of carbon and water fluxes to climate drivers are fundamentally important to understand the interaction between the terrestrial biosphere and the atmosphere, and possible climate-carbon cycle feedback. Recent studies in Amazonia have addressed aspects of seasonal variations of carbon and water fluxes and controls of radiation or precipitation (Costa et al., 2010; Restrepo-Coupe et al., 2013; Rocha et al., 2009), but there is still little information available about variability on longer time scales.

In Figs. 4–7 general relations between the annual values of carbon and water exchange with climate variables are presented, as measured at each tower and as an ensemble mean of all model simulations at each site-year. In these plots, we again aggregate all site-years of two categories ("forest sites" and "Cerrado and pasture

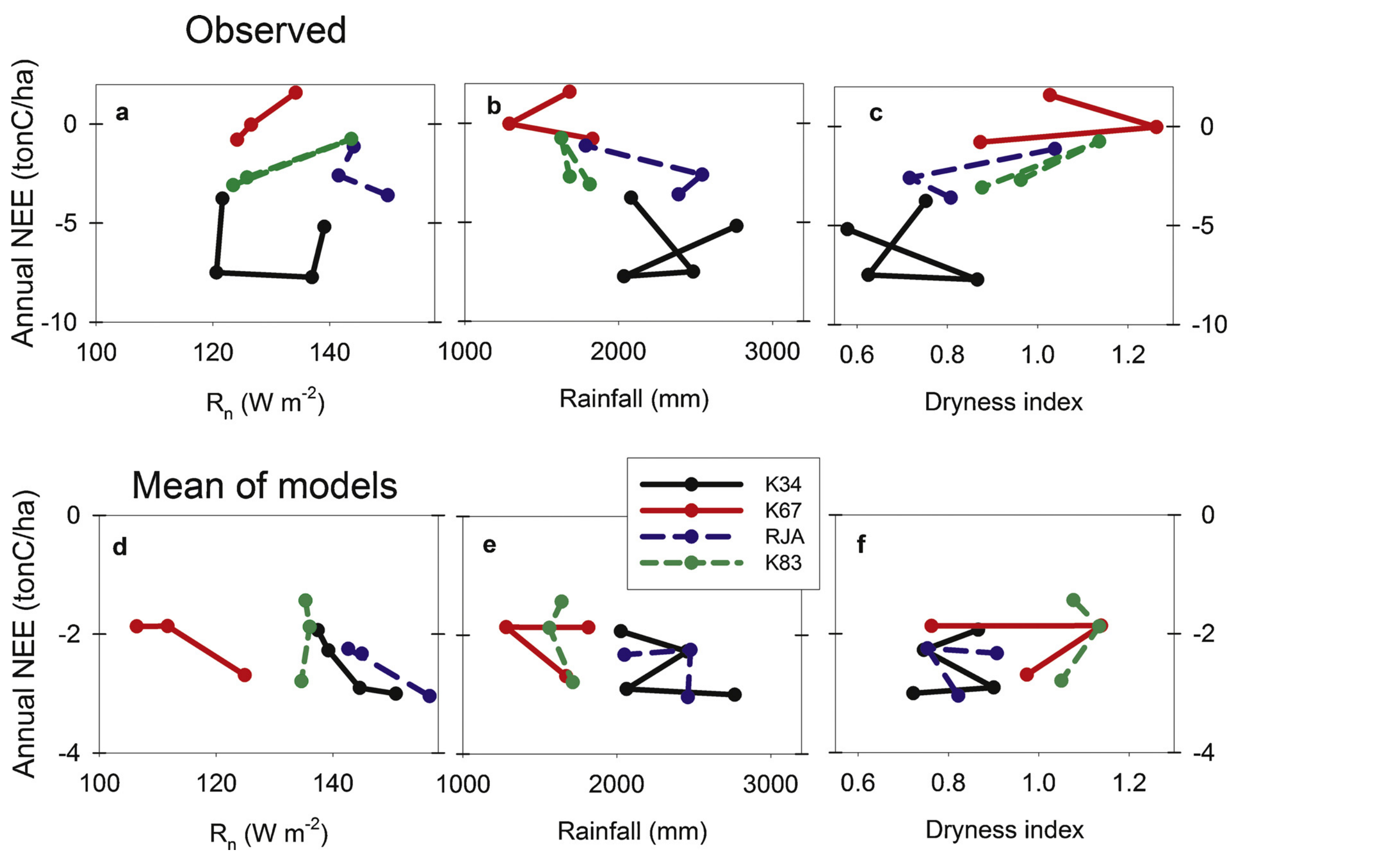

Fig. 4. Annual Net Ecosystem Exchange versus annual averages (or sums, in case of annual rainfall) of climate drivers as observed (top panels) or averaged over the suite of LBA-DMIP participating models (bottom panels), at the forest sites K34, K67, K83 and RJA.

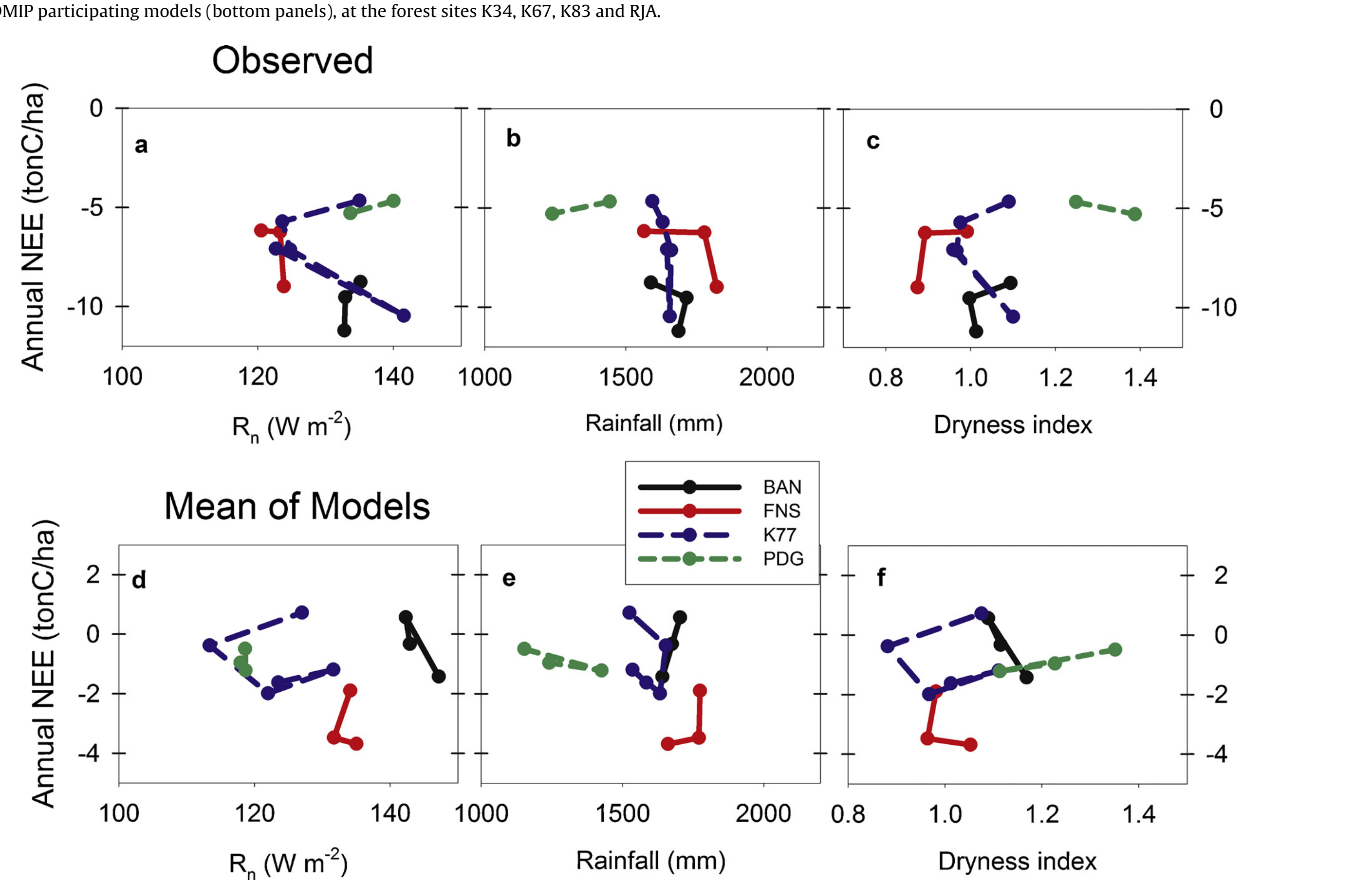

Fig. 5. Same as in Fig. 4, but for the Cerrado sites BAN and PDG, and for the pasture sites FNS and K77.

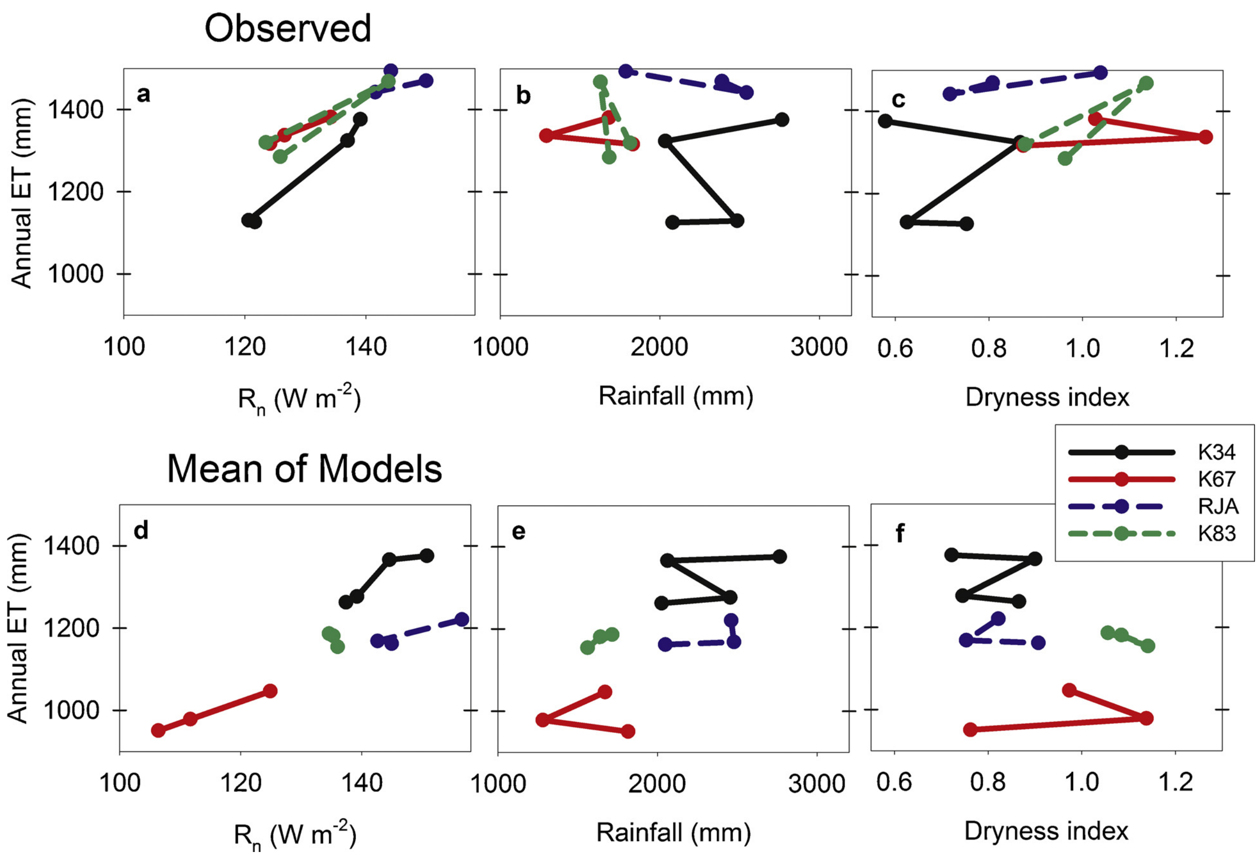

Fig. 6. Annual Evapotranspiration versus annual averages (or sums, in case of annual rainfall) of climate drivers as observed (top panels) or averaged over the suite of LBA-DMIP participating models (bottom panels), at the forest sites K34, K67, K83 and RJA.

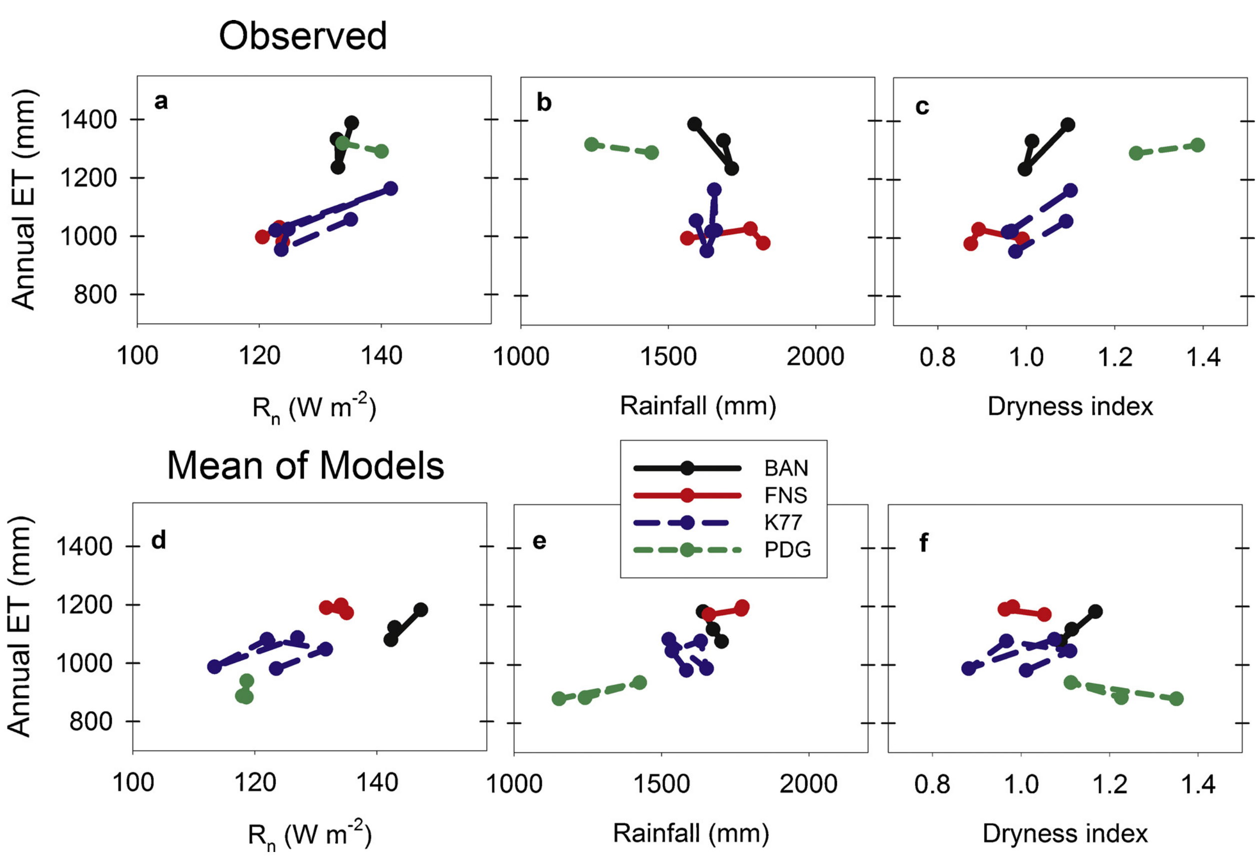

Fig. 7. Same as in Fig. 6, but for the Cerrado sites BAN and PDG, and for the pasture sites FNS and K77.

sites") in one plot, attempting to enlighten general main drivers of variability of annual fluxes.

Fig. 4a–f shows the NEE against annual average net radiation (R_n), total precipitation (P) and the Dryness index (D) for the forest sites. There are similarities in the general responses of the model simulations to the climate variables as to what is observed in the towers, but also some differences appear. The magnitude of variability among the sites is bigger than the variability of model simulations (note the scale of the y-axis in the top panels is bigger than in the bottom panels). Also, there appears to be little relation of the observed fluxes with R_n (Fig. 4a), but the models are clearly radiation-controlled (Fig. 4d). On the other hand, it is possible to see that the sites subject to lesser annual rainfall have lower uptake (and some site-years, in fact, resulted in a source of carbon to the atmosphere) than others. This results in a pattern of higher net uptake in site-years with higher annual rainfall or lesser D (Fig. 4b and c), which is captured by the models (Fig. 4e and f).

Fig. 5a–f shows the NEE as measured and modeled at the Cerrado and pasture sites, in relation to the climate variables. In this category, it is hard to see a clear relation with any of the climate variables. It is likely that this grouping of sites with very different vegetation covers and limited dataset is not suitable to the analysis proposed here.

Fig. 6a–f shows the annual evapotranspiration in the forest sites. We can depict that R_n largely controls annual ET (Fig. 6a), and this pattern is well captured by the models for individual sites (Fig. 6d), but without a significant correlation when all forest sites are grouped (see later, in Table 3). This result corroborates previous studies that showed that there is a strong control of R_n on ET on seasonal scales (Costa et al., 2010; Fisher et al., 2009; Rocha et al., 2009). There is weak relation with precipitation and with the dryness index D, although the models are sensitive to these variables (Fig. 6b, c and e, f).

Finally, Fig. 7a–f shows the annual ET in the Cerrado and pasture sites. The model simulations appear to have a general relation with the climate variables, but this is not so clearly measured at the sites (Fig. 7a–c). It is possible that this is also related to the aggregation of different vegetation covers in the same category.

To give better insight into how individual model simulations are related to the environmental drivers, Table 3 presents the correlation coefficients between the environmental variables and the fluxes, considering the forests group. Only values with significant correlations (p-value < 0.05) are presented. The correlations for measurements of $R_n \times$ ET and $P \times$ NEE corroborate the previous results, showing correlations of 0.87 and -0.63, respectively. As the dryness index D is also inversely related to the amount of precipitation, a significant positive correlation is also observed for $D \times$ NEE. The results for individual models show that only three model formulations reproduce a significant negative correlation of NEE with rainfall, but the ensemble of all models result in a correlation similar to the observations. It is also interesting to note that most of the models and the average of models yield ET fluxes correlated to P, but the tower measurements resulted in annual ET only significantly correlated to the amount of radiation, and not to annual rainfall.

4. Discussion and concluding remarks

This study analyzes simulations of 21 different land surface/terrestrial ecosystem model formulations, driven by meteorological conditions measured at 8 flux towers that were gathered in the scope the LBA-DMIP project (Gonçalves et al., 2013). The results show that the magnitude of carbon and water exchange and the IAV as simulated by most of the models is different than what is observed in the towers. However, direct comparisons between model simulations and eddy covariance flux measurements in complex surfaces should always be made with caution.

It is known that eddy flux measurements are inherently uncertain due to different sources of errors, such as random errors associated with the stochastic nature of turbulence, and systematic errors caused by inadequate system design or violation of assumptions in the methodology (as, e.g., low turbulence conditions, cold-air drainage, gravity waves or other 3D flow regimes). These errors have been studied in the flux sites by the different research teams responsible for these sites (e. g. Araújo et al., 2002; Kruijt et al., 2004; Miller et al., 2004; von Randow et al., 2004; Zeri and Sá, 2011), but full accounting of uncertainties at all the sites using a consistent methodology still remains to be quantified.

In general, processes and environmental factors governing inter-annual variability in NEE are also not well understood, largely because NEE is the difference between two large quantities, the Gross Primary Production (GPP) and the Terrestrial Ecosystem Respiration (TER), each with different major climatic drivers (and responding to processes on different scales) and different biotic controls.

Our estimates of the magnitude of IAV, represented by the interquartile range of observed annual fluxes, show that the variability of NEE is of the same order of the mean annual fluxes measured at the sites, and about 10–25% of the mean, for the evapotranspiration. These results are similar to the results obtained by Keenan et al. (2012), who analyzed the IAV at 11 long-term flux sites in North America. The authors also obtained that a suite of 16 terrestrial biosphere models have difficulty in reproducing the IAV, possibly because of misrepresentation of spring canopy phenology, soil thaw and snowpack melting, and lagged response to extreme climatic events.

To gain insight about the main climatic drivers that affect carbon and water exchange in the different sites and biomes, we analyzed in Figs. 4–7 the relations between annual NEE and ET with climatic drivers net radiation, precipitation and dryness index, as measured in each tower or computed by an average of all model simulations in each site-year. However, it should be acknowledged that the fluxes unexplained by the climate factors may be primarily driven by non-climate factors such as stand age, disturbance history, species composition, or canopy leaf area index, reflecting local variation in nutrient and water availability. While it is not possible to develop a predictive relationship of the annual fluxes with these drivers, our results are useful to evaluate the relative importance of particular climatic factors at individual sites.

Other studies have analyzed possible climatic and non-climatic drivers of NEE and ET at terrestrial ecosystems. (Jung et al., 2011; Law et al., 2002; Yi et al., 2010). In the study of Jung et al. (2011), worldwide tower flux measurements were scaled up using a machine learning technique providing global grid products of energy fluxes and NEE and its components Gross Primary Productivity (GPP) and Terrestrial Ecosystem Respiration (TER), and they found that the IAV of NEE is dominated by variability in GPP for the majority of the land surface, but not for Amazonian region, where the dominant variability comes from IAV of ecosystem respiration. Then, analyzing the IAV of TER, the authors found that it is more strongly correlated with precipitation than with temperature, what also corroborates our results. This may be related to soil respiration in tropical forests being more limited by the moisture content of the soil litter than by its temperature.

The correlation coefficients of environmental variables and fluxes simulated by individual models or measured at the forest sites, presented in Table 3, indicate that the negative correlation between NEE and annual rainfall is significant in this dataset. While the average of the models also promote a similar correlation, only three of the individual models show significant values. For the ET fluxes, the situation is reversed: measurements do not show any

Table 3
Correlation coefficients between possible environmental drivers and fluxes (annual totals), as simulated by the suite of surface models of LBA-DMIP in the forest sites. Only values with significant correlations (p-value < 0.05) are shown.

Model Acronym	Rn × NEE	Rn × ET	Precip × NEE	Precip × ET	D × NEE	D × ET
Biome-BGC				0.56		
CLM35-DGVM						
CLM35				0.67		−0.70
CLM4CN						
CN-CLASS				0.68		−0.64
DLEM				0.62		−0.63
ED2						−0.64
H-TESSEL				0.72		−0.70
IBIS			−0.71		0.56	−0.60
ISAM	−0.75					
JULES			−0.75	0.74	0.70	−0.75
LEAF2-HYDRO	0.68	0.56				
LPJ				0.61		−0.62
Noah-MP						
PT-JPL				0.71		−0.71
ORCHIDEE						
SiB2				0.62		−0.67
SiB2(modif.)	−0.63		−0.67	0.71		−0.56
SiB3				0.81		−0.75
SiBCASA						
SSiB2	−0.75					
Average of models	−0.55	0.83	−0.55	0.67		
Observations		0.87	−0.63		0.71	

significant correlation with annual precipitation according to the gathered dataset, but the majority of the simulations of ET is correlated to precipitation.

If we hypothesize that the general characteristics of interaction between the tropical forests and climate variables will be maintained in the future, our findings suggest that future climate scenarios of decreases in precipitation could weaken terrestrial CO_2 uptake in Amazonia. The surface models are able to reproduce, to some extent, these general responses, but improvements are still needed to better capture the inter-annual variability characteristics.

Acknowledgements

We thank innumerous scientists and field technicians who operated the flux towers under the LBA program, funded by the Brazilian Ministry of Science, Technology and Innovation, NASA and European Agencies. We also thank the LBA-Data-Model-Intercomparison project funded by NASA's Terrestrial Ecology Program (grant NNX09AL52G), which organized the datasets that made this work possible.

References

Arain, M.A., Yuan, F.M., Black, T.A., 2006. Soil–plant nitrogen cycling modulated carbon exchanges in a western temperate conifer forest in Canada. Agric. For. Meteorol. 140 (1–4), 171–192, http://dx.doi.org/10.1016/j.agrformet.200603021.

Araújo, A.C., Dolman, A.J., Waterloo, M.J., Gash, J.H.C., Kruijt, B., Zanchi, F.B., Lange, J.M.E., Stoevelaar, R., Manzi, A.O., Nobre, A.D., 2010. The spatial variability of CO_2 storage and the interpretation of eddy covariance fluxes in central Amazonia. Agric. For. Meteorol. 150, 226–237, http://dx.doi.org/10.1016/j.agrformet.200911005.

Araújo, A.C., Nobre, A.D., Kruijt, B., Elbers, J.A., Dallarosa, R.G., Stefani, P., von Randow, C., Manzi, A.O., Culf, A.D., Gash, J.H.C., Valentini, R., Kabat, P., 2002. Comparative measurements of carbon dioxide fluxes from two nearby towers in a central Amazonian rainforest: the Manaus LBA site. J. Geophys. Res. 107, 1–20, http://dx.doi.org/10.1029/2001JD000676.

Baker, I.T., Prihodko, L., Denning, A.S., Goulden, M.L., Miller, S.D., Rocha, H.R., 2008. Seasonal drought stress in the Amazon: reconciling models and observations. J. Geophys. Res. Biogeosci. 113, 1–10, http://dx.doi.org/10.1029/2007JG000644.

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., van den Hurk, B., Hirschi, M., Betts, A.K., 2009. A revised hydrology for the ECMWF model: verification from field site to terrestrial water storage and impact in the integrated forecast system. J. Hydrometeorol. 10 (3), 623–643, http://dx.doi.org/10.1175/2008jhm10681.

Betts, R.A., Cox, P.M., Lee, S.E., Woodward, F.I., 1997. Contrasting physiological and structural vegetation feedbacks in climate change simulations. Nature 387, 796–799.

Borma, L.S., Rocha, H.R., Cabral, O.M.R., von Randow, C., Collicchio, E., Kurzatkowski, D., Brugger, P.J., Freitas, H.C., Tannus, R.N., Oliveira, L., Rennó, C.D., Artaxo, P., 2009. Atmosphere and hydrological controls of the evapotranspiration over a floodplain forest in the Bananal Island region, Amazonia. J. Geophys. Res. 114, 1–12, http://dx.doi.org/10.1029/2007JG000641.

Bruno, R.D., da Rocha, H.R., de Freitas, H.C., Goulden, M.L., Miller, S.D., 2006. Soil moisture dynamics in an eastern Amazonian tropical forest. Hydrol. Processes 20 (12), 2477–2489, http://dx.doi.org/10.1002/hyp.6211.

Clark, D.B., Mercado, L.M., Sitch, S., Jones, C.D., Gedney, N., Best, M.J., Pryor, M., Rooney, G.G., Essery, R.L.H., Blyth, E., Boucher, O., Harding, R.J., Huntingford, C., Cox, P.M., 2011. The Joint UK Land Environment Simulator (JULES), model description – part 2: carbon fluxes and vegetation dynamics. Geosci. Model Dev. 4 (3), 701–722, http://dx.doi.org/10.5194/gmd-4-701-2011.

Costa, M.H., Biajoli, M.C., Sanches, L., Malhado, A.C.M., Hutyra, L.R., Rocha, H.R., Aguiar, R.G., Araújo, A.C., 2010. Atmospheric versus vegetation controls of Amazonian tropical rain forest evapotranspiration: are the wet and seasonally dry rain forests any different? J. Geophys. Res. Biogeosci. 115, 1–9, http://dx.doi.org/10.1029/2009JG001179.

Costa, M.H., Foley, J.A., 1997. Water balance of the Amazon Basin: dependence on vegetation cover and canopy conductance. J. Geophys. Res. 102 (D20), 23973–23989.

Davidson, E.A., de Araujo, A.C., Artaxo, P., Balch, J.K., Brown, I.F., Bustamante, M.M.C., Coe, M.T., DeFries, R.S., Keller, M., Longo, M., Munger, J.W., Schroeder, W., Soares-Filho, B.S., Souza Jr., C.M., Wofsy, S.C., 2012. The Amazon basin in transition. Nature 481 (7381), 321–328, http://dx.doi.org/10.1038/nature10717.

Desai, A.R., 2010. Climatic and phenological controls on coherent regional interannual variability of carbon dioxide flux in a heterogeneous landscape. J. Geophys. Res. Biogeosci. 115 (G3), G00J02, http://dx.doi.org/10.1029/2010jg001423.

Fisher, J.B., Malhi, Y., Bonal, D., Rocha, H.R., Araújo, A.C., Gamo, M., Goulden, M.L., Hirano, T., Huete, A.R., Kondo, H., Kumagai, T., Loescher, H.W., Miller, S.D., Nobre, A.D., Nouvellon, Y., Oberbauer, S.F., Panuthai, S., Roupsard, O., Saleska, S.R., Tanaka, K., Tanaka, N., Tu, K.P., von Randow, C., 2009. The land-atmosphere water flux in the tropics. Global Change Biol. 15, 2694–2714, http://dx.doi.org/10.1111/j.1365-2486200801813x.

Fisher, J.B., Tu, K.P., Baldocchi, D.D., 2008. Global estimates of the land–atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites. Remote Sens. Environ. 112 (3), 901–919, http://dx.doi.org/10.1016/j.rse.200706025.

Foken, T., 2008. Eddy flux measurements the energy balance closure problem: an overview. Ecol. Appl. 18, 1351–1367, http://dx.doi.org/10.1890/06-09221.

Fu, R., Chen, M., Li, W., Dickinson, R.E., 2001. How do tropical seas surface temperatures influence the seasonal distribution of precipitation in the equatorial Amazon? J. Clim. 14, 4003–4026.

Gonçalves, L.G.G., Borak, J.S., Costa, M.H., Saleska, S.R., Baker, I., Restrepo-Coupe, N., Muza, M.N., Poulter, B., Verbeeck, H., Fisher, J.B., Arain, M.A., Arkin, P., Cestaro, B.P., Christoffersen, B., Galbraith, D., Guan, X., van den Hurk, B.J.J.M., Ichii, K., Imbuzeiro, H.M.A., Jain, A.K., Levine, N., Lu, C., Miguez-Macho, G., Roberti, D.R., Sahoo, A., Sakaguchi, K., Schaefer, K., Shi, M., Shuttleworth, W.J., Tian, H., Yang, Z.-L., Zeng, X., 2013. Overview of the

Large-Scale Biosphere–Atmosphere Experiment in Amazonia Data Model Intercomparison Project (LBA-DMIP). Agric. For. Meteorol. 182–183, 111–127.

Goulden, M.L., Miller, S.D., Rocha, H.R., Menton, M.C., Freitas, H.C., Figueira, A.M.S., Sousa, C.A.D., 2004. Diel and seasonal patterns of tropical forest CO_2 exchange. Ecol. Appl. 14, 42–54, http://dx.doi.org/10.1890/02-6008.

Hutyra, L.R., Munger, J.W., Saleska, S.R., Gottlieb, E., Daube, B.C., Dunn, A.L., Amaral, D.F., Camargo, P.B., Wofsy, S.C., 2007. Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. J. Geophys. Res. Biogeosci. 112, 1–16, http://dx.doi.org/10.1029/2006JG000365.

Iwata, H., Malhi, Y., von Randow, C., 2005. Gap-filling measurements of carbon dioxide storage in tropical rainforest canopy airspace. Agric. For. Meteorol. 132, 305–314, http://dx.doi.org/10.1016/j.agrformet.200508005.

Jung, M., Reichstein, M., Margolis, H.A., Cescatti, A., Richardson, A.D., Arain, M.A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B.E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E.J., Papale, D., Sottocornola, M., Vaccari, F., Williams, C., 2011. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. J. Geophys. Res. 116, http://dx.doi.org/10.1029/2010jg001566.

Kanda, M., Inagaki, A., Letzel, M.O., Raasch, S., Watanabe, T., 2004. Les study of the energy imbalance problem with eddy covariance fluxes. Boundary Layer Meteorol. 110, 381–404, http://dx.doi.org/10.1023/B:BOUN.0000007225455487a.

Keenan, T.F., Baker, I., Barr, A., Ciais, P., Davis, K., Dietze, M., Dragoni, D., Gough, C.M., Grant, R., Hollinger, D., Hufkens, K., Poulter, B., McCaughey, H., Raczka, B., Ryu, Y., Schaefer, K., Tian, H., Verbeeck, H., Zhao, M., Richardson, A.D., 2012. Terrestrial biosphere model performance for inter-annual variability of land-atmosphere CO_2 exchange. Global Change Biol. 18 (6), 1971–1987, http://dx.doi.org/10.1111/j.1365-2486201202678x.

Keller, M., Alencar, A., Asner, G.P., Braswell, B.H., Bustamante, M.M.C., Davidson, E.A., Feldpausch, T.R., Fernandes, E.C.M., Goulden, M.L., Kabat, P., Kruijt, B., Luizão, F.J., Miller, S.D., Markewitz, D., Nobre, A.D., Nobre, C.A., Filho, N.P., Rocha, H.R., Dias, P.L.S., von Randow, C., Vourlitis, G.L., 2004. Ecological research in the large-scale biosphere-atmosphere experiment in Amazonia: early results. Ecol. Appl. 14, 3–16, http://dx.doi.org/10.1890/03-6003.

Krinner, G., Viovy, N., Ducoudre, N.N., Ogée, J., Polker, J., Friedlingstein, P., Ciais, P., Sitch, S., Prentice, I.C., 2005. A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. Global Biogeochem. Cycles 19, 1–33, http://dx.doi.org/10.1029/2003GB002199.

Kruijt, B., Elbers, J.A., von Randow, C., Araújo, A.C., Oliveira, P.J.C., Culf, A.D., Manzi, A.O., Nobre, A.D., Kabat, P., Moors, E.J., 2004. The robustness of eddy correlation fluxes for Amazon rain forest conditions. Ecol. Appl. 14 (4), S101–S113.

Kucharik, C.J., Foley, J.A., Delire, C., Fisher, V.A., Coe, M.T., Lenters, J.D., Molling, C.Y., Ramankutty, N., 2000. Testing the performance of a Dynamic Global Ecosystem Model: water balance, carbon balance, and vegetation structure. Global Biogeochem. Cycles 14, 795–825, http://dx.doi.org/10.1029/1999GB001138.

Law, B.E., Falge, E.M., Gu, L., Baldocchi, D.D., Bakwin, P.S., Berbigier, P., Davis, K.J., Dolman, A.J., Falk, M., Fuentes, J.D., Goldstein, A.H., Granier, A., Grelle, A., Hollinger, D.Y., Janssens, I.A., Jarvis, P.G., Jensen, N.O., Katul, G.G., Malhi, Y., Matteucci, G., Meyers, T.P., Monson, R.K., Munger, J.W., Oechel, W., Olson, R., Pilegaard, K., Paw, U.K.T., Thorgeirsson, H., Valentini, R., Verma, S.B., Vesala, T., Wilson, K.B., Wofsy, S.C., 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agric. For. Meteorol. 113, 97–120, http://dx.doi.org/10.1016/S0168-1923(02)00104-1.

Levis, S., Bonan, G.B., Vertenstein, M., Oleson, K.W., 2004. The Community Land Model's Dynamic Global Vegetation Model (CLM-DGVM): Technical Description and User's Guide. National Center for Atmospheric Research, Boulder, CO, USA.

Lola da Costa, A.C., Galbraith, D., Almeida, S., Portela, B.T.T., da Costa, M., de Athaydes Silva Junior, J., Braga, A.P., de Gonçalves, P.H.L., de Oliveira, A.A.R., Fisher, R., Phillips, O.L., Metcalfe, D.B., Levy, P., Meir, P., 2010. Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. New Phytol. 187 (3), 579–591, http://dx.doi.org/10.1111/j.1469-81372010.03309x.

Malhi, Y., Roberts, J.T., Betts, R.A., Killeen, T.J., Li, W., Nobre, C.A., 2007. Climate change, deforestation, and the fate of the Amazon. Science 319, 169–172, http://dx.doi.org/10.1126/science.1146961.

Marengo, J.A., 1992. Interannual variability of surface climate in the Amazon Basin. Int. J. Climatol. 12, 853–863.

Marengo, J.A., Tomasella, J., Uvo, C.R., 1998. Trends in streamflow and rainfall in tropical South America: Amazonia, eastern Brazil and northwestern Peru. J. Geophys. Res. 103 (D2), 1775–1783.

Markewitz, D., Devine, S., Davidson, E.A., Brando, P., Nepstad, D.C., 2010. Soil moisture depletion under simulated drought in the Amazon: impacts on deep root uptake. New Phytol. 187 (3), 592–607, http://dx.doi.org/10.1111/j.1469-81372010.03391x.

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

Medvigy, D., Wofsy, S.C., Munger, J.W., Hollinger, D.Y., Moorcroft, P.R., 2009. Mechanistic scaling of ecosystem function and dynamics in space and time: ecosystem demography model version 2. J. Geophys. Res. Biogeosci. 114, 1–21, http://dx.doi.org/10.1029/2008JG000812.

Miguez-Macho, G., Fan, Y., Weaver, C.P., Walko, R., Robock, A., 2007. Incorporating water table dynamics in climate modeling. 2. Formulation, validation, and soil moisture simulation. J. Geophys. Res. 112 (D13), D13108, http://dx.doi.org/10.1029/2006jd008112.

Miller, S.D., Goulden, M.L., Menton, M.C., Rocha, H.R., Freitas, H.C., Figueira, A.M.S., Sousa, C.A.D., 2004. Tower-based and biometry-based measurements of tropical forest carbon balance. Ecol. Appl. 14 (1–46), S114–S126.

Negrón-Juárez, R.I., Hodnett, M.G., Fu, R., Goulden, M.L., von Randow, C., 2007. Control of dry season evapotranspiration over the Amazonian forest as inferred from observations at a Southern Amazon Forest site. J. Clim. 20, 2827–2839 http://dx.doi.org/10.1175/JCLI41841

Niu, G.-Y., Yang, Z.-L., Mitchell, K.E., Chen, F., Ek, M.B., Barlage, M., Kumar, A., Manning, K., Niyogi, D., Rosero, E., Tewari, M., Xia, Y., 2011. The community Noah land surface model with multiparameterization options (Noah-MP). 1. Model description and evaluation with local-scale measurements. J. Geophys. Res. 116 (D12), D12109, http://dx.doi.org/10.1029/2010jd015139.

Nobre, C.A., Obregon, G.O., Marengo, J.A., Fu, R., Poveda, G., 2009. Characteristics of Amazonian climate: main features. In: Keller, M., Bustamante, M., Gash, J.H.C., Silva Dias, P. (Eds.), Amazonia and Global Climate. Geophysical Monograph Series. American Geophysical Union, Washington, DC, p. 149-162.

Nobre, C.A., Sellers, P.J., Shukla, J., 1991. Amazonian Deforestation and Regional Climate Change. J. Clim. 4, 957–988, http://dx.doi.org/10.1175/1520-0442(1991)004<0957:ADARCC>20.CO;2.

Oleson, K.W., Niu, G.Y., Yang, Z.L., Lawrence, D.M., Thornton, P.E., Lawrence, P.J., Stockli, R., Dickinson, R.E., Bonan, G.B., Levis, S., Dai, A., Qian, T., 2008. Improvements to the Community Land Model and their impact on the hydrological cycle. J. Geophys. Res. 113 (G1), G01021, http://dx.doi.org/10.1029/2007jg000563.

Polley, H.W., Emmerich, W., Bradford, J.A., Sims, P.L., Johnson, D.A., Saliendra, N.Z., Svejcar, T., Angell, R., Frank, A.B., Phillips, R.L., Snyder, K.A., Morgan, J.A., 2010. Physiological and environmental regulation of interannual variability in CO_2 exchange on rangelands in the western United States. Global Change Biol. 16 (3), 990–1002, http://dx.doi.org/10.1111/j.1365-2486.2009.01966.x.

Poveda, G., Waylen, P.R., Pulwarty, R., 2006. Annual and inter-annual variability of the present climate in northern South America and southern Mesoamerica. Palaleo 234, 3–27.

Restrepo-Coupe, N., da Rocha, H.R., Hutyra, L.R., da Araujo, A.C., Borma, L.S., Christoffersen, B., Cabral, O.M.R., de Camargo, P.B., Cardoso, F.L., da Costa, A.C.L., Fitzjarrald, D.R., Goulden, M.L., Kruijt, B., Maia, J.M.F., Malhi, Y.S., Manzi, A.O., Miller, S.D., Nobre, A.D., von Randow, C., Sá, L.D.A., Sakai, R.K., Tota, J., Wofsy, S.C., Zanchi, F.B., Saleska, S.R., 2013. What drives the seasonality of photosynthesis across the Amazon basin? A cross-site analysis of eddy flux tower measurements from the Brasil flux network. Agric. For. Meteorol., http://dx.doi.org/10.1016/j.agrformet.2013.04.031 (in press).

Richardson, A.D., Hollinger, D.Y., Aber, J.D., Ollinger, S.V., Braswell, B.H., 2007. Environmental variation is directly responsible for short- but not long-term variation in forest-atmosphere carbon exchange. Global Change Biol. 13, 788–803, http://dx.doi.org/10.1111/j.1365-2486.2007.01330.x.

Richey, J.E., Nobre, C.A., Deser, C., 1989. Amazon river discharge and climate variability: 1903–1985. Science 246, 101–103.

Rocha, H.R., Freitas, H.C., Rosolem, R., Tannus, R.N., Dias, M.A.F.S., 2002. Measurements of CO_2 exchange over a woodland savanna (Cerrado Sensu stricto) in southeast Brasil. Biotaneotropica 2, 1–11.

Rocha, H.R., Goulden, M.L., Miller, S.D., Menton, M.C., Pinto, L.D.V.O., Freitas, H.C., Figueira, A.M.S., 2004. Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia. Ecol. Appl. 14, 1–31, http://dx.doi.org/10.1890/02-6001.

Rocha, H.R., Manzi, A.O., Cabral, O.M.R., Miller, S.D., Goulden, M.L., Saleska, S.R., Coupe, N.R., Wofsy, S.C., Borma, L.S., Artaxo, P., Vourlitis, G.L., Nogueira, J.S., Cardoso, F.L., Nobre, A.D., Kruijt, B., Freitas, H.C., von Randow, C., Aguiar, R.G., Maia, J.F., 2009. Patterns of water and heat flux across a biome gradient from tropical forest to savanna in Brazil. J. Geophys. Res. 114, 1–8, http://dx.doi.org/10.1029/2007JG000640.

Sakai, R.K., Fitzjarrald, D.R., Moraes, O.L.L., Staebler, R.M., Acevedo, O.C., Czikowsky, M.J., Rodrigo, S., Brait, E., Miranda, V., 2004. Land-use change effects on local energy, water, and carbon balances in an Amazonian agricultural field. Global Change Biol. 10, 895–907, http://dx.doi.org/10.1111/j.1529-8817200300773x.

Saleska, S.R., Miller, S.D., Matross, D.M., Goulden, M.L., Wofsy, S.C., Rocha, H.R., Camargo, P.B., Crill, P., Daube, B.C., Freitas, H.C., Hutyra, L.R., Keller, M., Kirchhoff, V., Menton, M.C., Munger, J.W., Pyle, E.H., Rice, A.H., Silva, H., 2003. Carbon in Amazon forests: unexpected seasonal fluxes and disturbance-induced losses. Science 302, 1554–1557, http://dx.doi.org/10.1126/science.1091165.

Sampaio, G., Nobre, C.A., Costa, M.H., Satyamurty, P., Filho, B.S.S., Cardoso, M.F., 2007. Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. Geophysical Research Letters 34, 1–7, http://dx.doi.org/10.1029/2007GL030612.

Schaefer, K., Collatz, G.J., Tans, P., Denning, A.S., Baker, I., Berry, J., Prihodko, L., Suits, N., Philpott, A., 2008. Combined Simple Biosphere/Carnegie-Ames-Stanford Approach terrestrial carbon cycle model. J. Geophys. Res. 113 (G3), G03034, http://dx.doi.org/10.1029/2007jg000603.

Sellers, P.J., Mintz, Y., Sud, Y.C., Dalcher, A., 1986. A simple biosphere model (SIB) for use within general circulation models. J. Atmos. Sci. 43 (6), 505–531.

Sellers, P.J., Randall, D.A., Collatz, G.J., Berry, J.A., Field, C.B., Dazlich, D.A., Zhang, C., Collelo, G.D., Bounoua, L., 1996. A revised land surface parameterization (SiB_2) for atmospheric GCMS. Part I. Model formulation. J. Clim. 9 (4), 676–705, http://dx.doi.org/10.1175/1520-0442(1996)009<0676:ARLSPF>20.CO;2.

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the

LPJ dynamic global vegetation model. Global Change Biol. 9, 161–185, http://dx.doi.org/10.1046/j.1365-2486200300569x.

Thornton, P.E., Lamarque, J.-F., Rosenbloom, N.A., Mahowald, N.M., 2007. Influence of carbon-nitrogen cycle coupling on land model response to CO_2 fertilization and climate variability. Global Biogeochem. Cycles 21 (4), GB4018, http://dx.doi.org/10.1029/2006gb002868.

Thornton, P.E., Law, B.E., Gholz, H.L., Clark, K.L., Falge, E., Ellsworth, D.S., Goldstein, A.H., Monson, R.K., Hollinger, D., Falk, M., Chen, J., Sparks, J.P., 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. Agric. For. Meteorol. 113, 185–222.

Tian, H., Xu, X., Liu, M., Ren, W., Zhang, C., Chen, G., Lu, C., 2010. Spatial and temporal patterns of CH4 and N2O fluxes in terrestrial ecosystems of North America during 1979–2008: application of a global biogeochemistry model. Biogeosciences 7 (9), 2673–2694, http://dx.doi.org/10.5194/bg-7-2673-2010.

von Randow, C., Kruijt, B., Holtslag, A.A.M., Oliveira, M.B.L., 2008. Exploring eddy-covariance and large-aperture scintillometer measurements in an Amazonian rain forest. Agric. For. Meteorol. 148, 680–690, http://dx.doi.org/10.1016/j.agrformet.200711011.

von Randow, C., Manzi, A.O., Kruijt, B., Oliveira, P.J.C., Zanchi, F.B., Silva, R.L., Hodnett, M.G., Gash, J.H.C., Elbers, J.A., Waterloo, M.J., Cardoso, F.L., Kabat, P., 2004. Comparative measurements and seasonal variations in energy and carbon exchange over forest and pasture in South West Amazonia. Theor. Appl. Climatol. 78, 5–26, http://dx.doi.org/10.1007/s00704-004-0041-z.

von Randow, C., Sá, L.D.A., Gannabathula, P.S.S.D., Manzi, A.O., Arlino, P.R.A., Kruijt, B., 2002. Scale variability of atmospheric surface layer fluxes of energy and carbon over a tropical rain forest in southwest Amazonia 1 Diurnal conditions. J. Geophys. Res. 107, 1–12, http://dx.doi.org/10.1029/2001JD000379.

Yang, X., Wittig, V., Jain, A.K., Post, W., 2009. Integration of nitrogen cycle dynamics into the Integrated Science Assessment Model for the study of terrestrial ecosystem responses to global change. Global Biogeochem. Cycles 23 (4.).

Yi, C., Ricciuto, D.M., Xu, X., Aires, L., Albertson, J.D., Ammann, C., Arain, M.A., Araújo, A.C., Aubinet, M., Aurela, M., Baldocchi, D.D., Barcza, Z., Barr, A.G., Berbigier, P., Beringer, J., Bernhofer, C., Black, T.A., Bolstad, P.V., Bosveld, F.C., Broadmeadow, M.S.J., Buchmann, N., Burns, S.P., Cellier, P., Chen, J.M., Ciais, P., Clement, R.J., Cook, B.D., Curtis, P.S., Dail, D.B., Davis, K.J., Dellwik, E., Delpierre, N., Desai, A.R., Dolman, H., Dore, S., Dragoni, D., Drake, B.G., Dufrêne, E., Dunn, A.L., Elbers, J.A., Eugster, W., Falk, M., Feigenwinter, C., Flanagan, L.B., Foken, T., Frank, J., Fuhrer, J., Gianelle, D., Goldstein, A.H., Goulden, M.L., Granier, A., Grunwald, T., Gu, L., Guo, H., Hammerle, A., Han, S., Hanan, N.P., Haszpra, L., Heinesch, B., Helfter, C., Hendriks, D.M.D., Hollinger, D.Y., Hutley, L.B., Ibrom, A., Jacobs, C., Johansson, T., Jongen, M., Katul, G.G., Kiely, G., Klumpp, K., Knohl, A., Kolb, T., Kutsch, W.L., Lafleur, P., Laurila, T., Law, B.E., Leuning, R., Lindroth, A., Liu, H., Loubet, B., Manca, G., Marek, M., Margolis, H.A., Martin, T.A., Massman, W.J., Matamala, R., Matteucci, G., McCaughey, J.H., Merbold, L., Meyers, T.P., Migliavacca, M., Miglietta, F., Misson, L., Molder, M., Moncrieff, J.B., Monson, R.K., Montagnani, L., Helu, M.M., Moors, E.J., Moureaux, C., Mukelabai, M.M., Munger, J.W., Myklebust, M., Nagy, Z., Nilsson, M., Noormets, A., Oechel, W., Oren, R., Pallardy, S.G., Papale, D., Paw, U.K.T., Pereira, J.S., Pilegaard, K., Pintér, K., Pio, C., Pita, G., Powell, T.L., Rambal, S., Randerson, J.T., von Randow, C., Rebmann, C., Reichstein, M., Richardson, A.D., Rinne, J., Rossi, F., Roulet, N., Ryel, R.J., Sagerfors, J., Saigusa, N., Sanz, M.J., Mugnozza, G.S., Schmid, H.P., Seufert, G., Siqueira, M.B.S., Soussana, J.F., Starr, G., Stoy, P.C., Sutton, M.A., Tenhunen, J., Tuba, Z., Tuovinen, J.P., Valentini, R., Vesala, T., Vogel, C.S., Wang, S., Wang, W., Smith, L.R.W., Wen, X., Wharton, S., Wilkinson, M., Williams, C.A., Wofsy, S.C., Wohlfahrt, G., Yamamoto, S., Yu, G.R., Zampedri, R., Zhang, X., Zhao, B., Zhao, X., Chuixiang, Y., Li, R., Wolbeck, J., Wang, J., Welp, L.R., 2010. Climate control of terrestrial carbon exchange across biomes and continents. Environ. Res. Lett. 5, 1–26, http://dx.doi.org/10.1088/1748-9326/5/3/034007.

Yuan, W., Luo, Y., Richardson, A.D., Oren, R.A.M., Luyssaert, S., Janssens, I.A., Ceulemans, R., Zhou, X., GrÜNwald, T., Aubinet, M., Berhofer, C., Baldocchi, D.D., Chen, J., Dunn, A.L., Deforest, J.L., Dragoni, D., Goldstein, A.H., Moors, E., William Munger, J., Monson, R.K., Suyker, A.E., Starr, G., Scott, R.L., Tenhunen, J., Verma, S.B., Vesala, T., Wofsy, S.C., 2009. Latitudinal patterns of magnitude and interannual variability in net ecosystem exchange regulated by biological and environmental variables. Global Change Biol. 15 (12), 2905–2920, http://dx.doi.org/10.1111/j.1365-2486.2009.01870.x.

Zeri, M., Sá, L.D.A., 2010. The impact of data gaps and quality control filtering on the balances of energy and carbon for a Southwest Amazon forest. Agric. For. Meteorol. 150, 1543–1552, http://dx.doi.org/10.1016/j.agrformet.2010.08004.

Zeri, M., Sá, L.D.A., 2011. Horizontal and vertical turbulent fluxes forced by a gravity wave event in the nocturnal atmospheric surface layer over the Amazon forest. Boundary Layer Meteorol. 138, 413–431, http://dx.doi.org/10.1007/s10546-010-9563-3.

Zhan, X., Xue, Y., Collatz, G.J., 2003. An analytical approach for estimating CO_2 and heat fluxes over the Amazonian region. Ecol. Model. 162 (1/2), 97–117, http://dx.doi.org/10.1016/s0304-3800(02)00405-2.

Zhao, M., Pitman, A.J., Chase, T., 2001. The impact of land cover change on the atmospheric circulation. Clim. Dyn. 17, 467–477.