Improving the ISBA$_{CC}$ land surface model simulation of water and carbon fluxes and stocks over the Amazon forest

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Abstract

We evaluate the ISBA$_{CC}$ land surface model over the Amazon forest, and propose a revised parameterization of photosynthesis, including new soil water stress and autotrophic respiration functions. The revised version allows the model to better capture the energy, water and carbon fluxes when compared to five Amazonian fluxtowers. The performance of ISBA$_{CC}$ is slightly site-dependent but similar to the widely evaluated land surface model ORCHIDEE, based on different assumptions. Changes made to the autotrophic respiration functions, including a vertical profile of leaf respiration, leads, to simulate yearly carbon use efficiency and carbon stocks consistent with an ecophysiological meta analysis conducted on three Amazonian sites. Despite these major improvements, ISBAcc struggles to capture the apparent seasonality of the carbon fluxes derived from the fluxtower estimations. However, there is still no consensus on the seasonality of carbon fluxes over the Amazon, stressing a need for more observations as well as a better understanding of the main drivers of autrophic respiration.

1. Introduction

The Amazon rainforest plays a crucial role in the regional energy, water and carbon cycles, thereby modulating the global climate system. The forest recycles about 25 to 35 % of the Amazonian precipitation through evapotranspiration (Eltahir et Bras, 1994) and stores about 10 to 15 % of the global above ground biomass (e.g. Potter and Klooster, 1999; Malhi et al., 2006; Beer et al. 2010; Pan et al., 2011). Despite intense deforestation and land use change, this region has acted as a long-term carbon sink (Phillips et al., 2008; Gatti et al., 2010; Gloor et al., 2012; Gatti et al., 2014; Espírito-Santo et al., 2014), meaning that the carbon uptake by photosynthesis exceeded on average, the carbon released by autotrophic respiration and decomposition.

Recent observations showed that the Amazon sink has already been weakened by environmental perturbations such as deforestation (Lewis et al., 2009; Aragao et al., 2014; Pan et al., 2011) and extreme droughts (Marengo et al., 2011; Gatti et al., 2014). Any change from sink to source of carbon would have profound impacts, including enhancement of global

warming through a positive carbon feedback loop (Foley et al., 2003; Cox et al., 2000; Huntingford et al., 2013). The response of the Amazon sink to the combined pressures of deforestation and climate change would be dramatic, especially as a majority of climate models project dryer and longer dry seasons at the end of the century (Fu et al., 2013; Joetzjer et al., 2013).

Given the strong coupling between climate and the carbon cycle and the emergence of holistic Earth System Models (ESM), modeling the Amazon rainforest is an important challenge. However, carbon balance projections are still highly uncertain, especially in the tropics (Friedlingstein et al., 2006; Jones et al., 2013; Anav et al., 2013; Huntingford et al., 2013). Beyond the scenario of anthropogenic CO2 emissions, key uncertainties are related to the carbon cycle response to a given scenario which depends on both model-dependent regional climate sensitivity (Berthelot et al., 2005; Alström et al., 2012) and model-dependent representation of carbon fluxes and stocks themselves (Dalmonech et al., 2014; Huntingford et al., 2013).

Most land surface models (LSMs) still struggle to capture the seasonal pattern of the net ecosystem carbon exchange (NEE) over the Amazon basin (Saleska et al., 2003; Baker et al.,. 2008; Verbeeck et al., 2011), which is defined as the difference between the carbon released by both heterotrophic (R_H) and autotrophic respiration (R_A) and taken up through photosynthesis by Gross Primary Productivity (GPP). Recent model developments have focused on improving the seasonality of the simulated GPP, using an improved soil hydrology (Fisher et al., 2007; Baker et al., 2008; Grant et al., 2009), optimizing model's parameters (Verbeeck et al., 2011), or, and with more success, implementing new phenological processes (De Weirdt et al., 2012; Kim et al., 2012). Despite its major role in the carbon balance, less attention has been paid to ecosystem respiration (R_{ECO}) (Atkin et al. 2014, Rowland et al., 2014). Ecosystem respiration is the sum of R_H and R_A and is the result of multiple contributions (roots, wood, leaves for R_A and litter, soil carbon for R_H) that are all influenced by several environmental factors (temperature, soil water content, microbial dynamics). Ecosystem respiration plays a major role in explaining inter-annual variability of NEE at many forest ecosystems (Valentini et al., 2000; Saleska et al., 2003, Rowland et al., 2014).

In this paper, we evaluate the $ISBA_{CC}$ (Gibelin et al., 2008) LSM over the Amazon forest using in situ measurements and propose an alternative parameterization of both photosynthesis and autotrophic respiration. Such a focus is justified not only because $ISBA_{CC}$ has never been really evaluated on tropical rainforests, but also because $ISBA_{CC}$ has been recently implemented in the CNRM Earth System Model to participate in the forthcoming phases of CMIP (Coupled Model Intercomparison Project) and C4MIP (Coupled Climate Carbon Cycle Model Intercomparison Project). In CMIP3, some early ESMs projected a possible Amazon dieback (represented as the depletion of ecosystem carbon pools) at the end of the 21st century (Cox et al., 2000; 2013; Huntingford et al., 2013). Such dramatic projections are however very uncertain, depending for instance on the projected change in precipitation and dry-season length (Good et al., 2013), on the response of forest water-use efficiency (Keenan et al., 2013), and therefore on the accuracy of the water and carbon stocks and fluxes simulated at the land surface.

Here we conduct a step by step evaluation of the $ISBA_{CC}$ land surface model against in situ observations collected at five instrumental sites over the Amazon forest. To illustrate rather than really quantify model uncertainties, we also compare $ISBA_{CC}$ to the ORCHIDEE LSM (Krinner et al., 2005), which is based on different assumptions for the representation of

photosynthesis, carbon allocation and growth. In section 2, we first briefly describe both models and the available observations. In section 3, we propose alternative parameterizations of photosynthesis and photosynthesis sensitivity to soil water stress and of autotrophic respiration in $ISBA_{CC}$. In section 4, we compare the skill of the various $ISBA_{CC}$ parameterizations to capture the observed water and carbon fluxes and stocks. The main conclusions are summarized in section 5.

2. Material and method

2.1 Observations

To evaluate carbon and water fluxes over the Amazon tropical forest, we use field measurements of five eddy flux towers in Amazonia. Four towers are located in Brazil and were established during the LBA (Large Scale Biosphere atmosphere) project (Da Rocha et al., 2009): Manaus km 34 (M34), Santarem km 67 (K67) and 83 (K83), Reserva Jaru (JRU). The fifth tower is the Guyaflux tower (GFG) located at Paracou in French Guiana (Bonal et al., 2008). At JRU the forest is a semi-deciduous forest, whereas the other sites are representing typical tropical rainforests. Site location is shown in figure 1 together with the corresponding monthly mean climatologies of temperature and precipitation. Large seasonal variations in precipitation are found at GFG and JRU, the two wettest sites, in contrast with the other sites. Most datasets can be downloaded from the LBA website. For a detailed description of each site, please refer to the literature indicated in Table 1 or to Costa et al. (2010) and Baker et al. (2013) for a comparative analysis of the Brazilian sites.

For each site, meteorological forcings, such as incoming solar and infrared radiations, precipitation (P), temperature (T) and specific humidity, are recorded every 30 minutes above the canopy. Observations also include turbulent sensible (H) and latent heat (LE) fluxes and net ecosystem carbon exchange (NEE) measured using the eddy-covariance method (Shuttleworth et al., 1984; Aubinet et al., 2000; Baldocchi et al., 2001). Further information on data acquisition and pre-processing can be found in the references indicated in Table 1. Note that evaluation scores are here computed only against the more reliable daytime measurements (Aubinet et al., 2002). At K83, measurements of soil moisture were collected in two adjacent soil pits which are 10-m deep (Bruno et al., 2006) and 2-m deep (da Rocha et al., 2004) respectively.

Gross Primary Productivity (GPP) and carbon released by the whole ecosystem respiration (R_{ECO}) were retrieved from NEE data using the Reichtein et al. (2005) algorithm.

However, it does not give any information either on the partitioning between autotrophic (R_A) and heterotrophic (R_H) respiration, or on carbon allocation to canopy, wood and roots. Yet, these are essential processes to correctly represent the functioning of the Amazon ecosystem (Malhi et al., 2011). Malhi et al. (2009) gathered ecological measurements from K67, M34 and Caxiuanã (1.72°S 51.46°W, Eastern amazon) to evaluate yearly average carbon cycling and allocation. We here use this dataset to evaluate the annual carbon fluxes (GPP, R_A, NEE), the carbon stocks and the carbon allocation between the different pools in $ISBA_{CC}$ (section 4.4).

Finally, flux data are noisy. Hollinger et Richardson. (2005) evaluated the relative uncertainty of H, LE and CO_2 fluxes to be around 25 % on a temperate site. Energy balance closure in eddy covariance data can also be problematic. At the five sites considered here, the overall

energy balance ratio calculated as the sum of (LE + H) divided by the sum of net radiation over the whole period (Wilson et al 2002) varies between 0.69 at M34 and 1.008 at K67, with values of 0.79 at JRU, 0.87 at K83 and 0.96 at GFG. Energy balance would be achieved with a ratio of one. For the carbon fluxes, according to Desai et al. (2008), the flux partitioning method to retrieve GPP and R_{ECO} from NEE may add up to 10 % uncertainty. Despite these uncertainties, eddy flux measurements are for now the best way to investigate fluxes between the vegetation and the atmosphere especially when combined with ecological measurements like those gathered by Malhi et al. (2009).

2.2 Models and experimental design

$ISBA_{CC}$ (Interaction Soil Biosphere Atmosphere Carbon Cycle, Noilhan et Planton, 1989; Noilhan et Mahfouf, 1996) and ORCHIDEE (Organizing Carbon and Hydrology In Dynamic Ecosystems - version 1187) LSMs compute the exchange of water, energy and carbon between the land surface and the atmosphere. Both models deal with photosynthesis and allocate photosynthetic assimilates in several living biomass carbon pools defined by histological functional type. In both models each carbon pool is associated with a respiration function and a specific turnover rate. None of these two models take into account demography.

Carbon assimilation and allocation in the biomass pools differ greatly between the two models. In ORCHIDEE, carbon assimilation is based on the leaf-scale equation of Farquhar et al., (1980) for C_3 plants and is assumed to scale from leaf to canopy with APAR decreasing exponentially with leaf area index (LAI), according to the "big leaf" approximation. Stomatal conductance is proportional to the product of net CO_2 assimilation by atmospheric relative humidity divided by atmospheric CO_2 concentration in the canopy (Ball et al., 1987). Standard equations are given in Krinner et al. (2005), and Verbeeck et al. (2011) for tropical forest plant functional types. In contrast, $ISBA_{CC}$ has a semi-empirical parameterization of net carbon assimilation and the mesophyll conductance (g_m) following the model of photosynthesis proposed by Jacobs (1994), based on Goudriaan et al. (1985) and implemented by Calvet et al. (1998). In its standard version, $ISBA_{CC}$ uses Goudriaan's (1986) solution of radiative transfer to calculate net photosynthesis in 3 canopy layers. The standard $ISBA_{CC}$ equations are given in Calvet et al. (1998, 2004) and Gibelin et al. (2008). In ORCHIDEE(v1187), the carbon allocation model accounts for 8 biomass compartments (leaves, roots, fruits/harvested organs, reserves, aboveground sapwood, belowground sapwood, aboveground heartwood, belowground heartwood) for tree plant functional types.

$ISBA_{CC}$ represents aboveground metabolic and structural biomass pools, above and below ground woody biomass pools and below ground structural biomass pool adapted from Lemaire and Gastal (1997), implemented in ISBAcc by Calvet and Soussana (2001) and detailed in section 3.3. The description of the litter and soil carbon content and the associated heterotrophic fluxes is similar between the two models and is based on the CENTURY model developed by Parton et al. (1988). We only use the first top meter of soil carbon from the dataset of Malhi et al. (2009) to evaluate $ISBA_{CC}$ since CENTURY was designed to represent the carbon content in the first top meter. The litter is described by 4 pools defined by the lignin content and the location (metabolic and structural above and below ground). The soil organic cycling module differentiates 3 carbon pools (active, slow, passive) according to their turnover times (from a few years for the active pool to 1200 years for the passive pool).

At each site, we ran $ISBA_{CC}$ and ORCHIDEE offline forced by in situ hourly meteorological measurements (gap filled when necessary) made on top of each flux tower (available at "http://beija-flor.onrl.gov/lba", except for GFG, available from the fluxnet website following the "LaThuile" data sharing policy). We imposed the same evergreen tropical broadleaf tree plant functional type at the 5 sites and used the in situ soil texture, root and soil depth information for each site found in the literature and summarized in Table 1. Soil texture is used to compute the wilting point and field capacity, and the hydrological and thermal exchange coefficients following Decharme et al. (2011). The organic content in the upper soil layers, which also affects the hydrological and thermal exchange coefficients, is given by HWSD (Harmonized World Soil Database, Nachtergaele et al., (2012)). Both models were run until the slowest storage pools had reached equilibrium by cycling the atmospheric forcing over the available 3 years including the observed CO_2 concentration. To simulate soil moisture content in the deep Amazonian soils we used the soil multilayer diffusion scheme implemented in ISBA by Decharme et al. (2011, 2013) and in ORCHIDEE by de Rosnay et al. (2000, 2002). Both models impose a vertical distribution of roots following a decreasing exponential function of depth.

3. Towards a new parameterization of the tropical forest in $ISBA_{CC}$

$ISBA_{CC}$ has never been evaluated over the tropical rainforest biome (Gibelin et al., 2008), and as shown below, in this control version (CTL), LE and R_A were seriously biased and needed to be corrected. Large biases in the simulated latent heat and respiration fluxes are indeed not acceptable when modelling a region where precipitation recycling is important and where changes in the carbon fluxes could have profound effects on the global climate. This section describes the original $ISBA_{CC}$ model (CTL) and the implemented modifications. The main parameters of $ISBA_{CC}$ are given in Table 2. We first describe the changes made on the photosynthesis parameterization and its sensitivity to soil moisture as summarized in Table 3. Second, we present the modified autotrophic respiration functions (version PS+R) and the original ones (CTL) as summarized in Table 4.

3.1 $ISBA_{CC}$; selection of the reference version

As pointed out by Carrer et al. (2013), $ISBA_{CC}$ overestimates Gross Primary Productivity (GPP) at global scale, and especially in the tropical forests where the original radiative transfer code (Calvet et al., 1998) resulted in too high available radiation. Carrer et al. (2013) proposed a new radiative transfer scheme, dividing the canopy in 10 layers and accounting for the effect of direct and diffuse light and for sunlit and shaded leaves. As illustrated in figure 2 for the K67 site, the original radiative transfer scheme greatly overestimates the GPP at hourly and seasonal time scales. The other sites have a similar behavior (not shown). The new version of the radiative transfer allows $ISBA_{CC}$ to better capture the amount of GPP thanks to a more detailed and physical approach. To avoid unrealistic GPPs, we chose to test the version of $ISBA_{CC}$ with Carrer et al.(2013) radiative transfer scheme and call it our control version (CTL).

3.2 Water and carbon coupling and drought sensitivity: description of the original and modified parameterization (PS version)

The original $ISBA_{CC}$ photosynthesis model relies on a "mesophyll conductance" (g_m), defined by Jacobs (1994) as the initial slope of the CO_2 response curve at high light intensity and limiting CO_2 concentrations.

$$g_m = \frac{A_m}{C_i - \Gamma} \quad (1)$$

with C_i the leaf-internal CO_2 concentration, Γ the CO_2 compensation point and A_m the photosynthesis rate at saturating light and low C_i.

The model also supposes a constant ratio of C_i to atmospheric CO_2 concentration (C_a) when atmospheric humidity is constant.

$$f = \frac{C_i - \Gamma}{C_a - \Gamma} \quad (2)$$

In drier atmospheric conditions, the ratio decreases according to:

$$f = f_0 \left(1 - \frac{D_s}{D_{max}}\right) + f_{min} \left(\frac{D_s}{D_{max}}\right) \quad (3)$$

where Ds is the atmospheric humidity deficit, D_{max} the deficit resulting in complete stomatal closure, f_{min} the value of f at D_{max}, and f_0 the value of f at saturating humidity (D_s = 0). f_{min}, f_0 and D_{max} are model parameters depending on plant type and based on available observations. Following eq. (2), C_i also decreases with drying air (increase in D_s):

$$C_i = f \,.\, C_a + \Gamma(1 - f) \quad (4)$$

Assimilation is then calculated from light (eq. A7 - A9 in Calvet et al., 1998), air humidity, C_a, the ratio of C_i / C_a and finally, the stomatal conductance (g_s) is deduced from the assimilation rate.

Jacobs (1994) photosynthesis model was designed to simulate the assimilation rate and the stomatal conductance of grapevines in semi arid conditions. While $ISBA_{CC}$ is used for large scale studies using a PFT (Plant Functional Type) approach, there were few attempts to adapt the ecophysiological parameters to each functional group, especially for evergreen tropical broadleaf trees. We used published measurements from about 20 different tree species (Domingues et al., 2005, 2007) from Tapajos National forest to derive $A_{m,max}$, the maximum photosynthesis rate at high light intensity and f_0 (see eq 3.). The original values and the values of these two parameters are given in Table 3.

The soil water stress function (WSF) empirically describes the effect of soil moisture on transpiration and photosynthesis. In the case of $ISBA_{CC}$, soil water content (SWC) weighted by the roots profile, affects transpiration and photosynthesis through changes in g_m and, in the CTL version, f_0. The WSF implemented in $ISBA_{CC}$ by Calvet (2000) was first designed for herbaceous species and adapted for trees (Calvet et al., 2004). As described in Table 3 the parameterization for trees supposes a relationship between f_0 and soil wetness index (SWI) and was derived from measurements taken on saplings from *Pinus pinaster* and *Quercus petraea*. It had never been tested on mature trees and tropical species and doesn't perform well when tested in the Amazon as shown below. Therefore, we propose an alternative parameterization assuming a constant f_0 coherent with in situ observations (Domingues et al.,

2007) and validated against the two artificial droughts experiments lead in the eastern Amazon (Joetzjer et al., 2014, and references within). Further in this paper, we call version PS, $ISBA_{CC}$ version with these different values of $A_{m,max}$, f_0 and the modified WSF.

3.3 Autotrophic respiration and specific leaf area : description of the original and modified parameterization (PS+R version)

An analysis of the yearly carbon use efficiency (CUE) defined by the fraction of GPP invested into the Net Primary productivity (NPP/GPP) (Rowland et al., 2014) shows that $ISBA_{CC}$ overestimates R_A from leaves, roots and wood, leading to a loss of more than 90 % of the carbon assimilated on an annual basis (corresponding to a CUE < 0.1). This result is not realistic. Over the Amazon, the CUE is roughly estimated to be around 0.3 (Chambers et al., 2004; Malhi et al., 2009, 2011; Metcalfe et al., 2010). Therefore, a new parameterization of each respiration term is proposed and described below.

$ISBA_{CC}$ simulates 6 biomass pools, originally described in Gibelin et al. (2008) as:

- leaf biomass (B_l)
- B2, an active structural biomass pool which represents the stem in the case of grass and crop, and can be assimilated to new twigs for trees.
- B3, a small biomass pool used for numerical stability purposes, and accounts for a negligible amount of the carbon actually stored.
- B4, a below ground structural biomass pool representing the roots's sapwood and the fine roots.
- B5, an above ground woody biomass pool representing the above ground wood (trunk and branches).
- B6, a below ground woody biomass pool representing the roots's heartwood.

The evolution of each biomass pool B ($kg.m^{-2}$) is given by:

$$\frac{\Delta B}{\Delta t} = A_B - D_B - R_B \tag{5}$$

where Δt = one day, A_B ($kg.m^{-2}.day^{-2}$) is the increase in biomass coming from photosynthetic assimilation or allocation from another reservoir, D_B ($kg.m^{-2}.day^{-1}$) represents turnover or carbon reallocation to another pool, and R_B ($kg.m^{-2}.day^{-1}$) is a decrease term due to respiration.

3.3.1 Leaf respiration

Originally, leaf dark respiration integrated over the canopy was parameterized, following Van Heemst (1986) as:

$$R_{leaf} = \frac{A_m}{9}.LAI \tag{6}$$

with LAI the Leaf Area Index and A_m, the photosynthetic rate at high light intensities (Table 1). A_m being constant throughout the canopy, respiration is identical from the top to the bottom leaves, while assimilation decreases from top to bottom according to the absorbed fraction of PAR calculated by the radiative transfer scheme (Carrer et al., 2013). However,

observations show that leaf respiration is positively correlated to area based leaf nitrogen content (N_{AREA}) (Meir et al., 2001; Reich et al., 2006; Meir et al., 2008), and N_{AREA} is driven by light availability according to the theory of optimal nutrient allocation availability (Field et Mooney, 1986). Indeed, N_{AREA} is highly correlated to photosynthesis capacity as most of the leaf nitrogen is dedicated to the synthesis of photosynthetic proteins. So, a constant value for dark respiration throughout the canopy as supposed in $ISBA_{CC}$ is not reasonable, particularly for high canopies. Therefore we imposed a vertical profile of respiration based on an exponential profile of leaf nitrogen (section 2.5 Bonan et al., 2011, 2012).

$$R_{leaf} = \frac{A_m}{9} . \exp\left(-k_n . LAI\right) \quad (7)$$

With k_n the within-canopy profile of photosynthetic capacity set to 0.2 according to Mercado et al. (2009) and Bonan et al. (2011). This parametrization greatly reduces the leaf dark respiration of the canopy compared to the original one.

3.3.2 Twigs, stem and trunk

In the original version of $ISBA_{CC}$ (Gibelin et al., 2008) the woody biomass (B5) does not respire. If heartwood does not respire, sapwood made of living cells (including phloema cells) does. We adopted the simple parameterization of sapwood respiration from IBIS (Kucharik et al., 2000). We first calculate an estimated sapwood fraction (λ_{sap}) from an assumed sap velocity, the maximum transpiration rate and the tree height following Kucharik et al. (2000). Then, the respiration of the 5th reservoir, R_5 is computed as:

$$R_5 = B_5 . \lambda_{sap} . \beta_{wood} . f(T) \qquad with\ \beta wood = 0{,}0125\ yr^{-1} \quad (8)$$

where β_{wood} is a maintenance respiration coefficient defined at 15°C and $f(T)$ is given by the Arrhenius temperature function modified by Lloyd et Taylor, (1994).

$$f(T) = \exp\left[E_o \left(\frac{1}{15 - T_0} \right) - \frac{1}{T - T_0} \right] \quad (9)$$

with T the temperature of the given carbon pool in °C (here, the surface temperature because $ISBA_{CC}$ doesn't simulate a vegetation temperature), E_0 a temperature sensitivity factor *(equal to 3500)* and T_0 a temperature reference set at 25°C.

For the *B2* biomass reservoir, (twigs), the function proposed in $ISBA_{CC}$ is:

$$R_2 = B_2 . \eta . Q_{10}^{\frac{T_s - 25}{10}} \quad (10)$$

where Q_{10}=2 and η =0.01 ($g.g^{-1}.day^{-1}$) and T_s (°C) the temperature of the surface. We didn't find any measurement for respiration of twigs and didn't find any other model representing this reservoir. We assumed that respiration per unit biomass of this reservoir had to be lower than respiration of leaves, and similar or slightly larger than sapwood. A comparison with respiration functions from other models showed that (10) is about the same magnitude as respiration functions for leaves from ORCHIDEE, LPJ (Sitch et al., 2003) and IBIS (Foley et

al., 1996) for temperatures up to 30°C but increases strongly at higher temperatures. It is also an order of magnitude larger than respiration of sapwood from these models, which doesn't seem realistic. To be coherent with B5, we adopted Kucharik et al. (2000) formulation. Therefore:

$$R_2 = B_2 . \beta . f(T) \text{ with } \beta = 1.25 \text{ y}^{-1} \quad (11)$$

3.3.3 Root respiration

Originally, root respiration followed the linear respiration given in Ruimy et al. (1996):

$$R_4 = B_4 . R_0 (1 + 0.16\, T_p) \text{ with } R_0 = 1.9\ 10^4 \text{ g. g}^{-1}\text{.day}^{-1} \quad (12)$$

To be consistent with sapwood respiration, R_4 is now computed as:

$$R_4 = B_4 . \beta . f(T) \quad \text{with } \beta = 1.25 \text{ y}^{-1} \quad (13)$$

3.3.4 Specific Leaf Area

ISBA$_{CC}$ calculates interactively the leaf biomass and the Leaf Area Index (LAI) using a simple growth model (Calvet et al., 1998). Leaf biomass results directly from the carbon balance of the leaf: increasing with the carbon assimilated by photosynthesis and depleted by respiration, turnover, and allocation to the other reservoirs (Calvet and Soussana, 2001). LAI is simply calculated as leaf biomass times the Specific Leaf Area (SLA).Hence there is no explicit phenology model in ISBA. Phenology is simply the result of the leaf carbon balance.

In the CTL version the SLA depends on the leaf nitrogen concentration, a fixed parameter depending on the plant type (Gibelin et al., 2006). We replaced the original SLA calculated by Gibelin et al. (2006) by the observed value from Domingues et al. (2007).

Further in this paper, we call version PS+R, ISBA$_{CC}$ version including the Table 3 parameters and functions, and the changed autotrophic respiration and SLA summarized Table 4.

4. Results and discussion

We now evaluate and compare three versions of ISBA$_{CC}$: CTL, PS and PS+R described in section 3.1, 3.2 and 3.3 respectively. We illustrate the uncertainties linked to the choice of model by showing the fluxes simulated by the well evaluated ORCHIDEE (v.1187) land surface model over the same sites. Note that we mostly show results from K83 because deep soil moisture measurements are available.

4.1 Soil moisture

Looking at the top-10m daily soil water content simulated in 2003 at K83 (Fig. 3, bottom panel), the slight wet bias found in the original ISBA$_{CC}$ model (CTL) is reduced when using either the modified PS or PS+R versions. As shown in section 4.2, this is due to the increased LE in the PS and PS+R versions. Note that the ISBA$_{CC}$ soil moisture content was also

successfully evaluated at K67 and at Caxiuanã (Joetzjer et al., 2014, fig 3 top panels). Moving to the vertical profile of soil moisture (Fig. 3 mid panels), and whatever the model version, the vertical profile of organic matter prescribed in $ISBA_{CC}$ (Decharme et al., 2006) allows the model to simulate a relatively wet top-1m horizon as observed (Fig. 3 mid panels). However, it is not sufficient to capture accurately the observed soil moisture dynamics. From February to April the soil moisture increases slowly from the surface to 6 meters while $ISBA_{cc}$ simulates a much more rapid re-wetting, and after a heavy rain (e.g October) water infiltrates too quickly. This might be due to uncertainties in water uptake by roots (prescribed according to Jackson et al, 1996), but also to the vertically uniform soil texture prescribed in $ISBA_{CC}$ due to the lack of in situ observations. In reality, the clay content is usually increasing with depth, which reduces the hydraulic conductivity at lower levels.

4.2 Energy Budget

Focusing again on K83, while net radiation (R_net) is well captured by the three $ISBA_{CC}$ simulations, the CTL experiment overestimates the sensible heat flux (H) and underestimates the latent heat flux (LE) (Fig. 4). As expected, the partitioning of the energy budget is better represented with the simulation using $A_{m,max}$ and f_0 parameters derived from the in situ observations (PS version, Table 3). The increase in LE simulated by PS compared to the CTL explains the reduction of the wet bias in SWC simulated by the CTL run (Fig. 3). Not surprisingly, the modification of the autotrophic respiration functions has little effect (run PS+R, Table 4) on the simulated energy budget and does not impact the temporal variability of Rn, H and LE which are reasonably well simulated at both diurnal and seasonal time scales.

Figure 5 shows a summary of the annual mean scores of H and LE computed for the three versions of $ISBA_{CC}$ and for ORCHIDEE at the five flux towers using Taylor diagrams and a comparison of biases relative to the model mean climatology. Taylor plots are polar coordinate displays of the linear correlation coefficient and centered root mean square error (RMSE, pattern error without considering bias) between the simulated and observed fields, and the ratio of their standard deviations (Taylor, 2001). Correlations mainly reflect the diurnal cycle and are reasonable (above 0.6). The PS (and PS+R) parameterizations barely impact correlations and slightly improve the root mean square error (RMSE) compared to the CTL. However, the standard deviation is improved for all sites compared to the CTL runs. The CTL runs show a systematic overestimation of H (positive bias, fig 5, bottom panel) that is strongly reduced in both PS and PS+R versions. Conversely, LE is greatly underestimated (by about 30 %) by CTL, whatever the season (not shown), at four among the five sites and this bias is reduced in the revised versions. At M34, although CTL overestimates H, it simulates reasonably well LE. The PS model version reduces the bias in H but overestimates LE. This result is coherent with the fairly low level of energy closure at this site (see section 2.1) and suggests that the observed Bowen ratio should be considered with caution at M34.

The PS version improves the simulation of H and LE compared to the CTL version, whatever the season. Interestingly, changes in the parameterization of respiration (PS+R) barely alter the results compared to PS. The scores of ORCHIDEE are very close to those computed with the improved version of $ISBA_{CC}$ with large positive biases for H at JRU and LE at M34 (Fig. 5). The fact that the results are more site-dependent than model-dependent suggests a problem in the prescribed atmospheric forcings or in the eddy-covariance measurements for these sites, as suggested by the level of energy closure on these sites. The $ISBA_{CC}$ and ORCHIDEE models being based on different parameterizations of photosynthesis, respiration and growth,

the likelihood of the models being both wrong at the same location is rather small, except for processes unaccounted for by both models, like particular phenology adapted to the local conditions.

4.3 Carbon fluxes

Moving back to the K83 site, but looking at the carbon fluxes (Fig. 6), the $ISBA_{CC}$ model reasonably captures the annual amount of carbon taken up by photosynthesis (GPP), released by respiration (R_{ECO}) and the net flux defined in the model as the difference between R_{ECO} and GPP (NEE). The annual magnitude of GPP is correctly simulated by the CTL version thanks to the radiative transfer scheme proposed by Carrer et al. (2013) (Fig. 2). While the $A_{m,max}$ chosen in the PS simulation is around six times smaller than initially (Table 3), the increase in f_0 enhances the assimilation rate, leading to little change in GPP between CTL and PS. So, there is a trade-off in the model between f_0 and $A_{m,max}$, that can be expected from the photosynthesis module. A lower maximum assimilation rate ($A_{m,max}$) tends to reduce the carbon assimilation (see eq A7 in Calvet and Soussana, 2001). On the other hand, with a higher f0, intracellular CO2 is higher (see equation 4), which favors carbon assimilation. PS barely impacts simulated R_{ECO} and therefore NEE compared to CTL. While the revised SLA and respiration functions lead to slightly decreased GPP (PS+R), the decrease in R_{ECO} is even stronger and leads to an increased net rate of carbon uptake (more negative NEE).

The annual cycle of GPP, R_{ECO} and NEE, although relatively small in these tropical regions (Fig. 6, right column), is poorly simulated by the model. The model tends to increase GPP at the beginning of the dry season when radiation increases and soil moisture is not yet limiting. As such, the model behaves as expected, radiation being the most limiting factor during the wet season, and the observed annual cycle results probably from processes that are not accounted for by the model, such as leaf phenology. Not surprisingly given the model formulation, but in contrast to the observations, the modelled seasonal cycle of GPP coincides with the seasonal cycle of LE in all $ISBA_{CC}$ simulations.

The statistical skill scores computed for the five flux towers are again summarized in Taylor diagrams (Fig. 7, top). The GPP relative standard deviation (RSD) computed with PS is improved at K67 but is slightly lowered at M34, while there are no substantial changes at K83 and JRU compared to CTL. This is also valid for the NEE. At GFG, the RSD of NEE is also improved. PS+R exhibits scores quite similar to the PS run. The systematic positive bias in GPP (about 10 to 25 %) and in R_{ECO} (about 10 to 100 %) found in the CTL run is reduced in PS, and even more in PS+R (Fig. 7, bottom). Although model modifications reduce the bias in NEE at JRU and M34, they increase it at K67, K83 and GFG. This is not surprising since NEE is a small flux resulting from the difference between two large fluxes. Looking at the absolute RMSE, errors are reasonable (between 5 and 10 $\mu mol.m^{2}.s^{-1}$) compared to observation uncertainties (of the same order) and ORCHIDEE's results once again suggest that scores are more site-dependent than model-dependent.

It is important to note that flux towers measure directly only NEE. The R_{ECO} is reconstructed from nighttime (i.e. when there is no photosynthesis) measurements which are however questionable (e.g. Reichstein et al., 2005). Daytime R_{ECO} is likely to differ from nighttime R_{ECO} because of the temperature diurnal cycle. Also, the lower wind speed at night and thus lower friction velocity (u*) limits the efficiency of the eddy-covariance technique (Aubinet et

al., 2002; Saleska et al., 2003). As GPP is reconstructed from NEE and R_{ECO}, more bias can be expected for this flux and conclusions on GPP should be also considered with caution.

4.4 Carbon Stocks and carbon use efficiency

The data compilation of Malhi et al. (2009) at Caxiuana, K67 and M34 provides valuable insights to evaluate the model ability to simulate the annual carbon storage per carbon pools (Fig. 8). While there are few differences between the CTL and PS+R simulations in terms of GPP and R_{ECO}, the carbon stocks greatly differ (Fig. 8). Over these three sites, observations indicate a total carbon stock around 330 $tC.ha^{-1}$ with an error estimate of about 30 $tC.ha^{-1}$. The original model (CTL) greatly underestimates the stock by a factor of three. While modifications of the photosynthesis components (PS) slightly increases carbon stocks, the underestimation of the carbon storage persists. Changes in respiration functions (PS+R) lead to a more reasonable total amount of carbon stock.

Flux tower data provide high frequency information on the carbon flux between the ecosystem and the atmosphere, but do not allow us to distinguish between vegetation and soil fluxes. The meta analysis from Malhi et al. (2009) however allows us to evaluate the annual fluxes between the different carbon pools at Caxiuanã (Fig. 9). Compared to observations, the CTL run highly overestimates R_A and consequently underestimates the NPP. Therefore, the Carbon Use Efficiency (CUE), computed as the ratio NPP/GPP, is too low. 92 % of the carbon assimilated is directly respired, leaving only 8 % of the GPP to be allocated to the plant biomass pools. This result motivated the changes in autotrophic respiration functions presented in Table 4. These changes (simulation PS+R, Table 4) lead to a more realistic CUE (around 0.3; e.g. Malhi et al. 2009; Rowland et al. 2014.), therefore enhancing the carbon storage in the leaf, wood and root pools, and the litterfall. The litter and the soil organic matter are increased, and, as a result, heterotrophic respiration, largely underestimated by the original model (CTL), is now correctly simulated. Note that the CTL version has a reasonable estimation of R_{ECO} because the overestimation of R_A is partly counterbalanced by an underestimation of R_H through an underestimation of the heterotrophic carbon stock (Fig. 9).

In spite of reasonable R_A at each site, the $ISBA_{CC}$ model tends to overestimate the amount of carbon stored in the stems (Fig. 8). This pattern can very likely be explained by a too low mortality rate. At K67, the high amount of coarse and woody debris (Saleska et al., 2003) and the low amount of above ground biomass observed compared to the other sites suggest a recent higher than normal tree mortality. This could be triggered by drought associated with the strong El Niño events of the 1990s (Rice et al., 2004; Pyle et al., 2008) that these simulations forced by 3 years meteorological forcing cannot represent.

4.5 Annual ratio between carbon stocks and fluxes

The ratio of respiration of a particular pool relative to its size is particularly instructive (Table 5) to evaluate the representation of the respiration process in the model. As can be seen at Caxiuanã, K67 and M34, about 10 % of the carbon stored in the plants is respired annually and between 7 and 9 % of the litter and soil carbon content, depending on the site. As a whole, about 9 % of the total biomass (soil, litter and plant) is respired. These percentages are very well captured by the new (PS+R) version but totally misrepresented by the original scheme (CTL). Ecosystem respiration relative to the stock is three times too high although the absolute value was reasonable. Nevertheless, large uncertainties surrounds the seasonality of R_A (and consequently R_{ECO}).

5. Conclusions

In this study, we proposed and evaluated revised parameterizations of the photosynthesis, its sensitivity to soil water stress and the autotrophic respiration function in the $ISBA_{CC}$ land surface model implemented in the CNRM ESM, over the Amazon forest. As far as the energy and water budgets are concerned, net radiation and soil water dynamics that are driven by observed atmospheric forcing are reasonably well simulated by $ISBA_{CC}$. Our modifications of photosynthesis mainly allow the model to better capture the turbulent energy fluxes (H and LE). While the mean carbon fluxes are slightly better captured with the revised parameterization, $ISBA_{CC}$ still struggles to capture the seasonality of the observed (NEE) or reconstructed (R_{ECO} and GPP) carbon fluxes. Interestingly, when $ISBA_{CC}$ is compared to the ORCHIDEE model based on different parameterizations, scores are systematically more site-dependent than model-dependent. This either suggests problems in the prescribed atmospheric forcing, or in the eddy-covariance measurements, unless both models do not account for a crucial process. Further investigations are thus needed.

Changes made to the parameterization of R_A improve the simulation of the Carbon Use Efficiency, in good agreement with the observations from Malhi et al. (2009) and Rowland et al. (2014). By enhancing the carbon storage, biomass pools become larger and more consistent with observations. However, increasing the carbon stock in $ISBA_{CC}$ by a factor of three between CTL and PS+R versions barely impacts the net carbon flux. This illustrates the weak link between carbon stocks and fluxes in the $ISBA_{CC}$ model and the need for further improvements.

There is no silver bullet for the parameterization of autotrophic respiration, such as the Farquhar model for the carbon assimilation. Because R_A represents a large part of R_{ECO}, and R_{ECO} is crucial to determine the net carbon balance (NEE), both annual amount and seasonality of R_A need to be correctly represented. Indeed, considering the relevance of R_{ECO} in the seasonal changes of the ecosystem carbon budget (Meir et al., 2008; Rowland et al., 2014), and not only over the Amazon forest (Atkin et Macherel, 2009; Atkin et al., 2014), there is an urgent need to better understand the main drivers of autrophic respiration in a wide range of environmental conditions.

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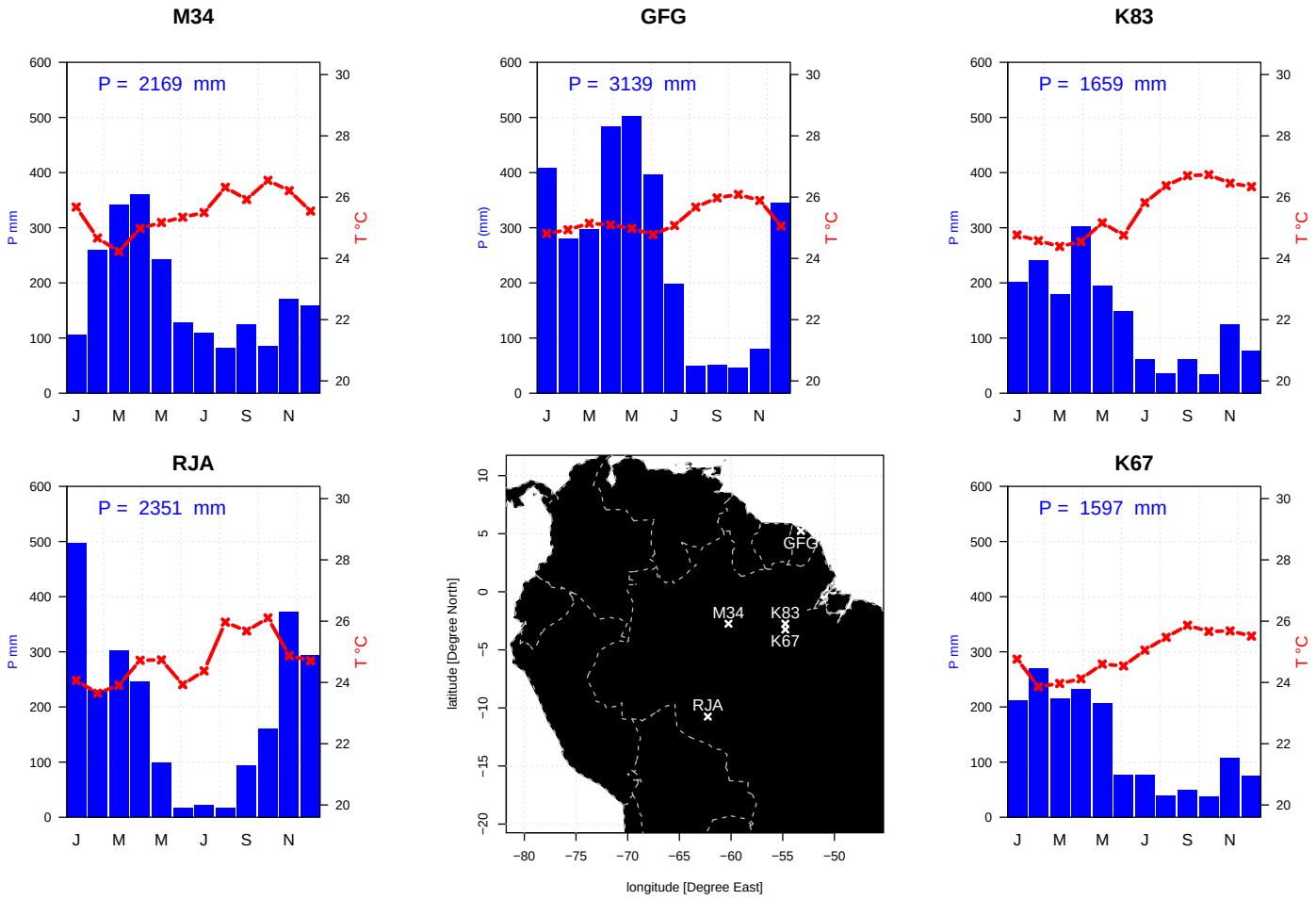

FIGURE 1 – *Mean annual cycle of precipitation (blue), temperature (red) calculated over 3 years (see table 1) and location of the fluxtowers used in this study.*

TABLE 1 – Characteristics and references of fluxtowers used in this study.

Site	**CODE**	**Cover Period**	**Texture (fraction)**	**Root depth**	**Soil depth**	**References**
Manaus km34	M34	2003 → 2005	CLAY=0.68 ; SAND=0.20	8m	12m	Araujo et al (2002)
Paracou	GFG	2007 → 2009	CLAY=0.51 ; SAND=0.33	8m	12m	Bonal et al (2008)
Santarem km83	K83	2001 → 2003	CLAY=0.80 ; SAND=0.18	8m	12m	Goulden et al (2004)
Santarem km67	K67	2002 → 2004	CLAY=0.42 ; SAND=0.52	8m	12m	Saleska et al (2003)
Reserva Jarù	JRU	2000 → 2003	CLAY=0.10 ; SAND=0.80	4m	4m	Kruijt et al (2004)

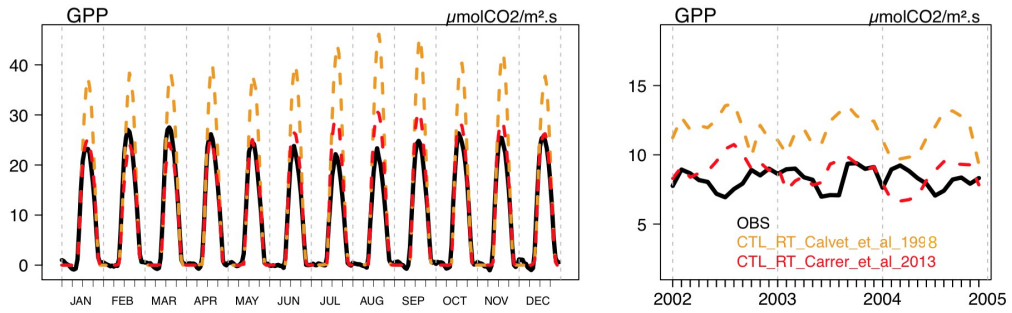

FIGURE 2 – *Observed and simulated GPP with the CTL version of $ISBA_{CC}$ comparing the two radiative transfers at K67. Left panel shows the diurnal cycle for each month averaged over 3 years (2002–2004) ; right panel, monthly mean time series for 2001–2003.*

TABLE 2 – $ISBA_{CC}$: Nomenclature

Symbols	Units	Description
A_m	$kg_{CO2}.m^{-2}.s^{-1}$	Photosynthesis rate (light saturated)
C_a	$ppmv$	Atmospheric CO_2 concentration
C_i	$ppmv$	Leaf internal CO_2 concentration
D_s	$g.kg^{-1}$	Saturation deficit at the leaf surface
D_{max}	$g.kg^{-1}$	Maximum value of D_s
f	unitless	coupling factor
f_0	unitless	coupling factor at saturating air humidity ($D_s = 0$)
f_0^*	unitless	coupling factor in well-watered conditions and at saturating air humidity ($D_s = 0$)
f_{min}	unitless	coupling factor at maximum air humidity deficit ($D_s = D_{max}$)
Γ	$ppmv$	CO_2 concentration compensation point
g_m	$mm.s^{-1}$	Mesophyll conductance defined as the light saturated rate of photosynthesis (Jacobs 1994)
g_m^*	$mm.s^{-1}$	g_m in well-watered conditions
g_s	$mm.s^{-1}$	Stomatal conductace

TABLE 3 – $ISBA_{CC}$ Modifications : **Photosynthesis & Transpiration PS** version

Parameter	**CTL**	**PS**	
$A_{m,max}$	$2.2 \cdot 10^{-6}$	$0.36 \cdot 10^{-6}$	
g_m	$g_m = g_m^*$	$g_m = g_m^*$	$SWI \geq 1$
	$g_m = g_m^* - (g_m^* - g_m^N) \cdot \dfrac{(1-SWI)}{(1-SWIc)}$	$g_m = SWI \cdot g_m^*$	$SWIc < SWI < 1$
	$g_m = g_m^N \cdot \dfrac{SWI}{SWIc}$	$g_m = SWI \cdot g_m^*$	$SWI \leq SWIc$
f_0	$f_0 = \dfrac{4.7 - ln(g_m)}{7}$	$f_0 = 0.74$	$SWIc < SWI$
	$f_0 = \dfrac{2.8 - ln(g_m)}{7}$	$f_0 = 0.74$	$SWI \leq SWIc$

Symbol used

$A_{m,max}$ $(kg_{CO2}.m^{-2}.s^{-1})$	maximum photosynthesis rate for C_3 plants
SWI	Soil Wetness index $\left(SWI = \dfrac{\Theta - \Theta_{wilt}}{\Theta_{fc} - \Theta_{wilt}}\right)$
Θ	Soil water content ($m^3.m^{-3}$)
Θ_{fc}	Field capacity ($m^3.m^{-3}$)
Θ_{wilt}	Wilting point ($m^3.m^{-3}$)
SWI_c	Critical extractable Soil Wetness Index ($SWI_c = 0.3$)
g_m^N	Value of g_m at $SWI = SWI_c$ in $mm.s^{-1}$
g_m^* $(mm.s^{-1})$	Value of g_m in well-watered conditions ($SWI \geq 1$). ($g_m = 2$ $mm.s^{-1}$ for broadleaf tropical forest)

TABLE 4 – $ISBA_{CC}$: Modifications **autotrophic respiration functions PS+R** version

Parameter	**CTL**	**PS+R**
$\frac{1}{SLA}$	$\simeq 68.5\ gDM.m^{-2}$	$= 120\ gDM.m^{-2}$
R_{leaves}	$\frac{A_m}{9}$	$\frac{A_m}{9} \cdot exp(-k_n \cdot LAI) \cdot \frac{1}{LAI}$; $k_n = 0.2$
R_2	$B_2 \cdot \eta \cdot Q_{10}^{\frac{T_s-25}{10}}$; $\eta = 0.01 g/g.day^{-1}$ and $Q_{10} = 2$	$B_2 \cdot \beta \cdot f(T_s)$; $\beta = 1.25$
R_4	$B_4 \cdot R_0(1 + 0.16T_p)$; $R_0 = 1.9 \cdot 10^{-4} g/g.day^{-1}$	$B_4 \cdot \beta \cdot f(T_p)$; $\beta = 1.25$
R_5	0	$B_5 \cdot \lambda_{sap}\beta_{wood} \cdot f(T_s)$; $\beta_{wood} = 0.0125$
		$f(T) = exp\left\{E_0\left(\frac{1}{15-T_0} - \frac{1}{T-T_0}\right)\right\}$; $T_0 = 25^0 C$

Symbol used

T_s	surface temperature
T_p	soil temperature
λ_{sap}	fraction of sap wood

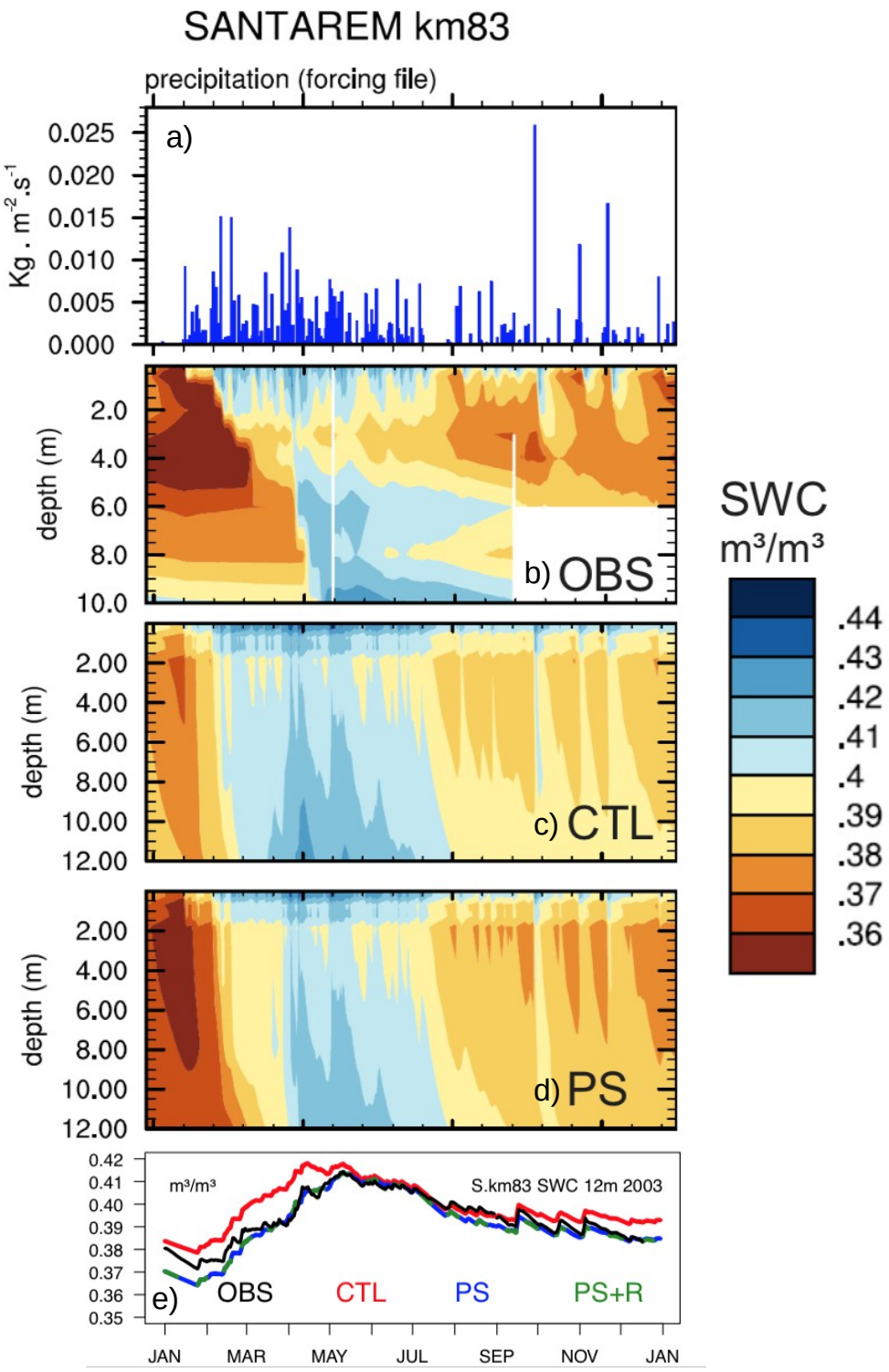

FIGURE 3 – *Daily precipitation (a), observed (b) and simulated (c and d) soil moisture at K83 during 2003. The total soil water content over the whole 12 m column is shown on plot e. We linearly rescaled the soil moisture content of the 10 m pit (Bruno et al., 2006) to the values of the 2 m one (da Rocha et al., 2004) by multiplying the 10m SWC by the ratio of field capacities between the 2m and the 10m pit).*

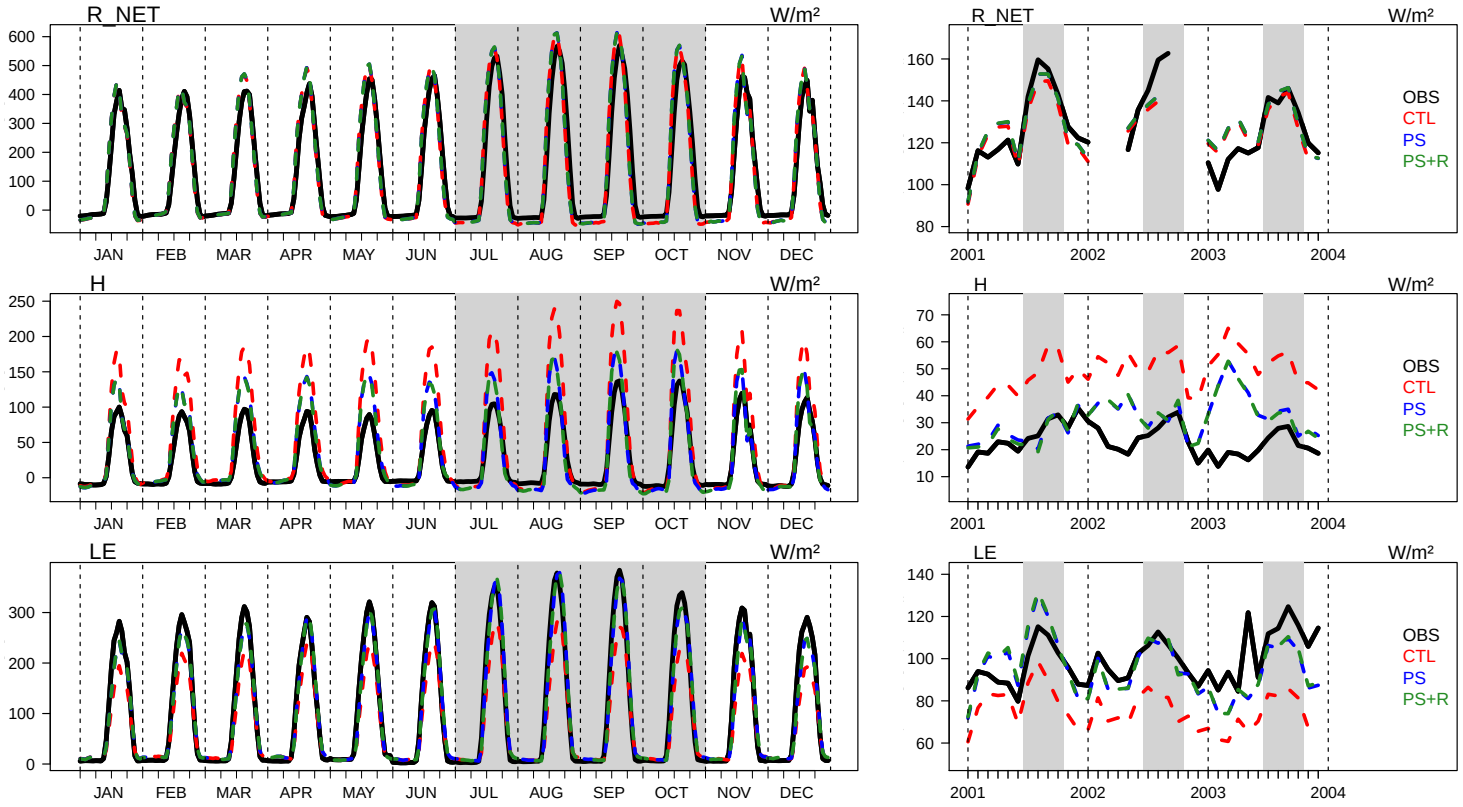

FIGURE 4 – *Observed and simulated net radiation (R_Net), sensible heat (H) and latent heat (LE) at K83. Left panels show the diurnal cycle for each month averaged over 3 years (2001–2003); and right panels, monthly mean time series for 2001–2003. Gray shaded areas indicate dry seasons (defined as periods with precipitation less than 100 mm.month^{-1}).*

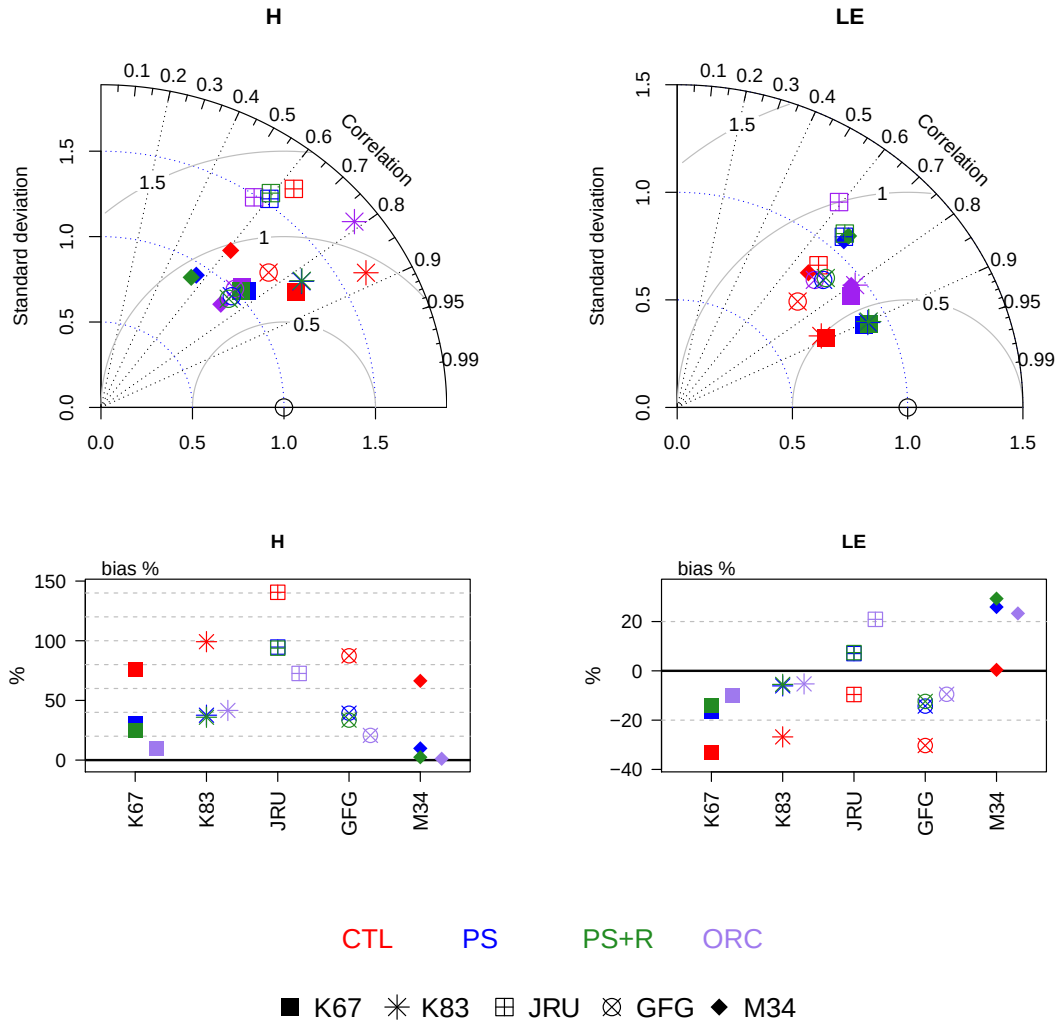

FIGURE 5 – *Taylor diagrams (top) and bias (%) (bottom) calculated among hourly values removing night values (Short Wave down* $\leq$ *5 W.m*$^{-2}$*) for H and LE at the five fluxtowers and for each available period (see table 1). In the Taylor diagrams, correlation extends radially from the origin. The blue lines indicate identical ratios of standard deviation of the simulated flux to the observed flux. The grey lines represent identical root mean square errors (RMSE) of the centered fluxes.*

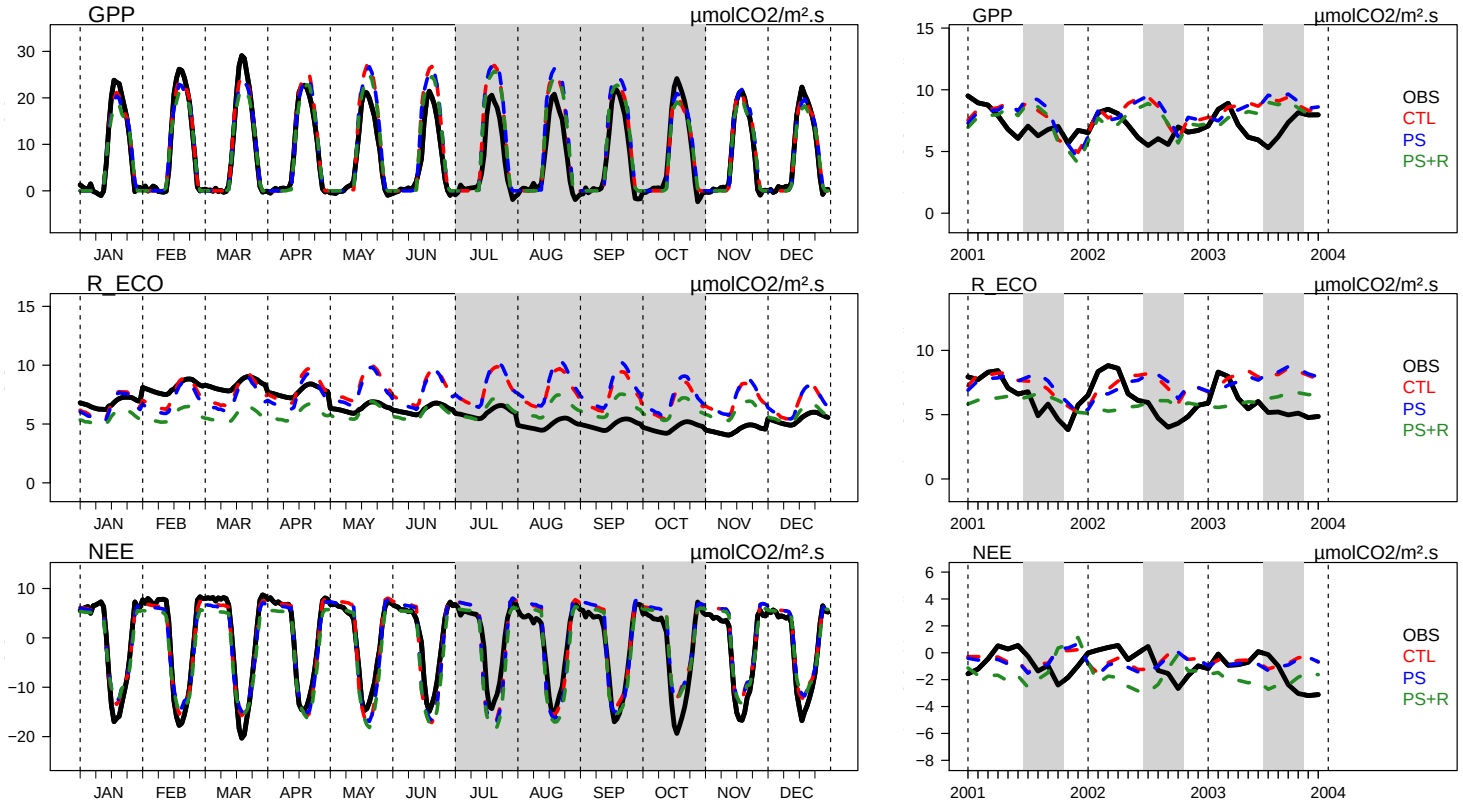

FIGURE 6 – *Observed and simulated GPP, R_{ECO} and NEE at k83. Left panels show the diurnal cycle for each month averaged over 3 years (2001–2003); and right panels, monthly mean time series for 2001–2003. Gray shaded areas indicate dry seasons (defined as periods with precipitation less than 100 mm.month^{-1}).*

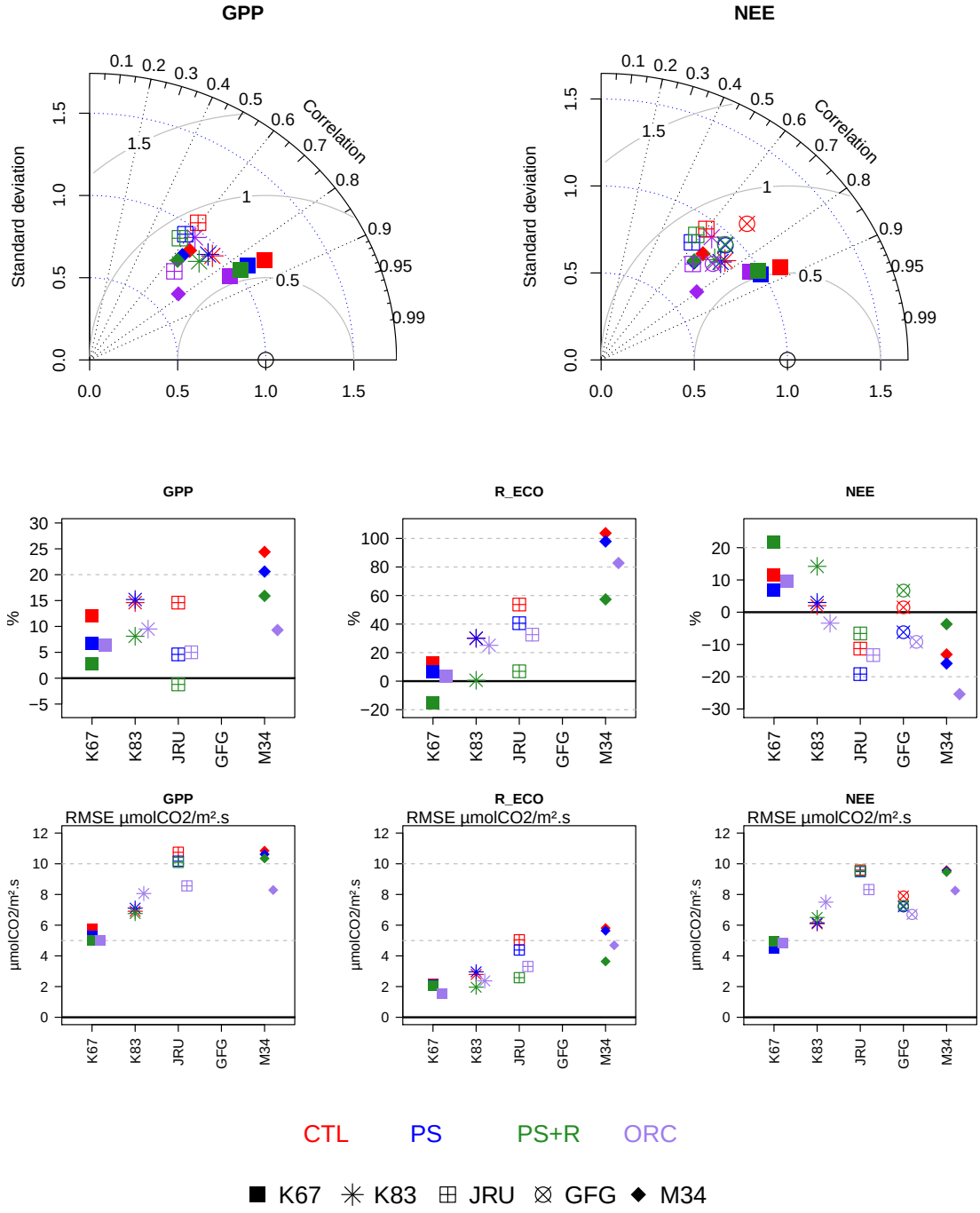

FIGURE 7 – *Taylor diagrams (top) for GPP and NEE and bias for GPP R_{ECO} and NEE (%) (bottom) calculated among hourly values removing night values (Short Wave down $\leq 5\ W.m^{-2}$) at the five fluxtowers and for each available period (see table 1).Note that at GFG only NEE timeseries was available. In the Taylor diagrams, correlation extends radially from the origin. The blue lines indicate identical ratios of standard deviation of the simulated flux to the observed flux. The grey lines represent identical root mean square errors (RMSE) of the centered fluxes.*

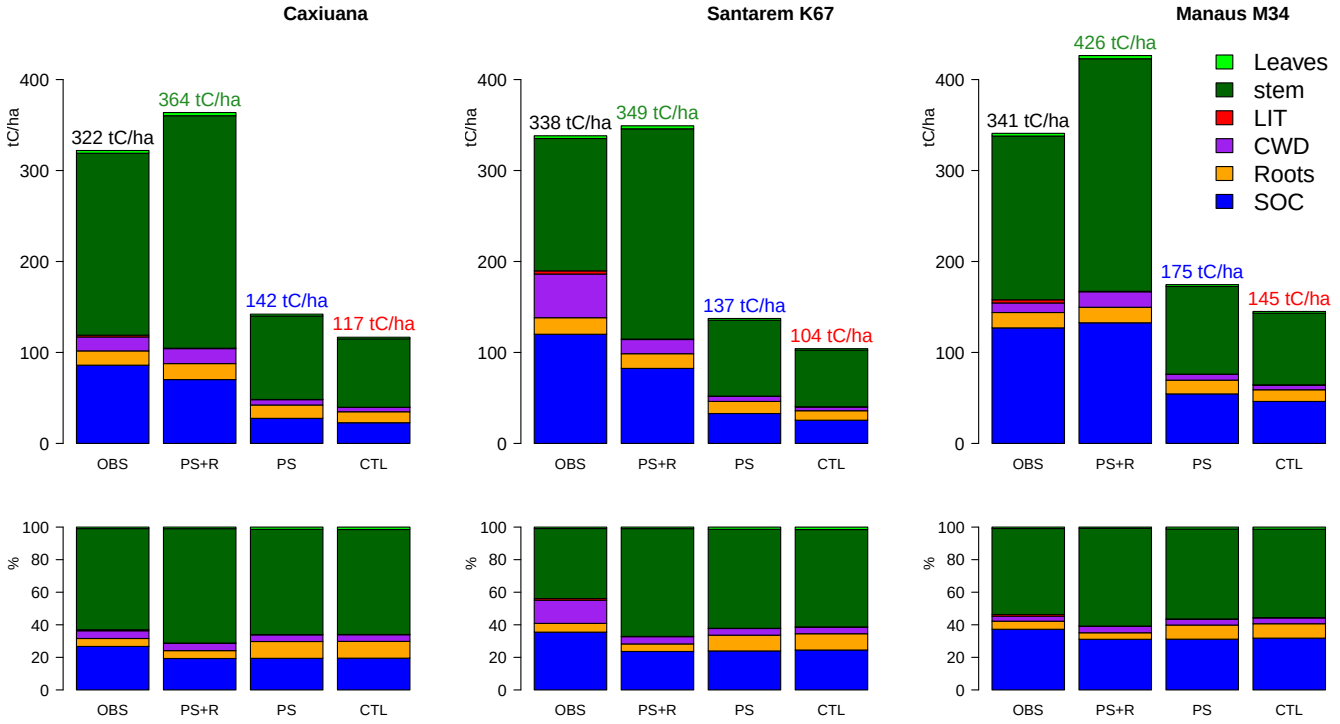

FIGURE 8 – *Observed (Mahli et al 2009) and simulated (CTL, PS and PS+R) annual carbon pools (Leaves (B_L), Stem (B_2 + B_5), Litter (LIT), Coarse and Woody Debris (CWD), Roots (B_4 + B_6) and Soil Organic Content (SOC)) at Caxiuana, K67 and M34. Top panels show the absolute carbon stock in $tC.ha^{-1}$ and below panels the relative carbon stock (%).*

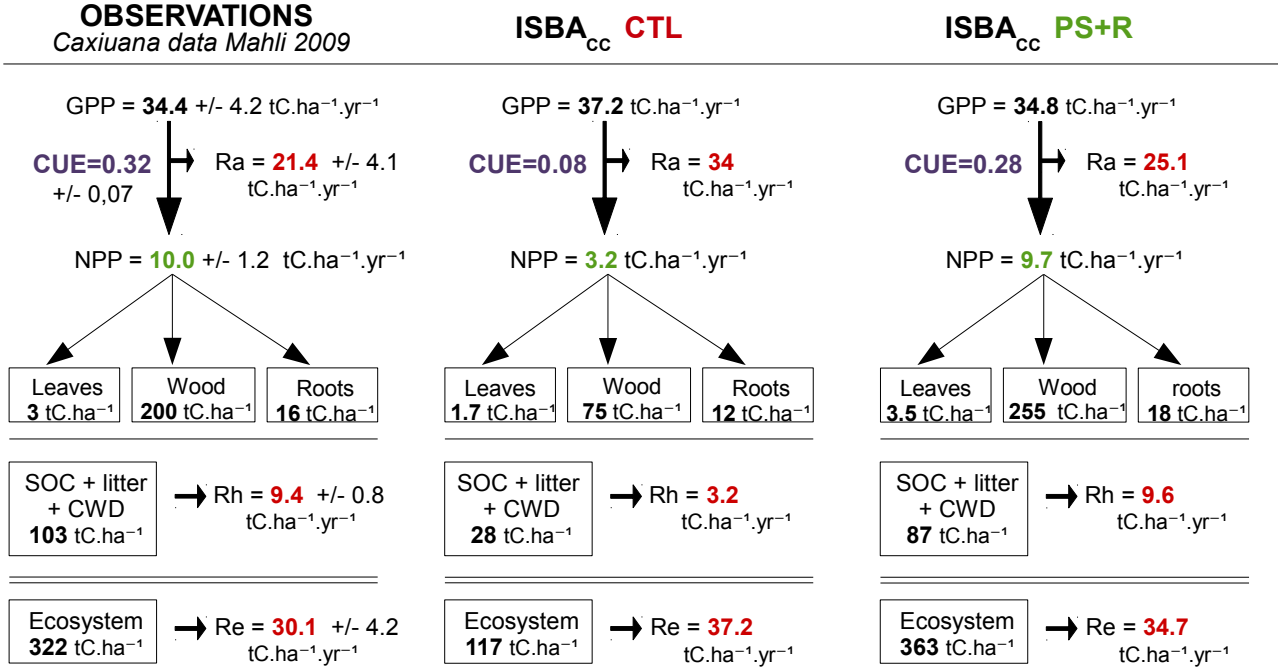

FIGURE 9 – *Annual carbon pools and fluxes from a synthesis of observations at Caxiuana (Mahli et al 2009) compared to $ISBA_{CC}$ (CTL and PS+R simulations). Adapted from Randerson et al. 2009.*

TABLE 5 – Mean annual autotrophic and heterotrophic carbon stocks and respiration flux deduced from the sysnthesis of observations done by Malhi et al. 2009 and simulated by $ISBA_{CC}$ (simulations CTL and PS+R) at Caxiuana, K67 and M34. The ratio defines the % of carbon respirated per carbon pool.

		Caxiuana			**Santarem K67**			**Manaus M34**		
		Auto	Hetero	EcoS	Auto	Hetero	EcoS	Auto	Hetero	EcoS
Stocks	OBS	218.7	103.3	322	166.7	171.5	338.2	199.9	141.0	340.9
	PS+R	276.6	87.1	363.7	250.6	98.5	349.2	276.3	150.1	426.4
	CTL	89	27.7	116.7	74.3	29.9	104.2	93.5	51.6	145.1
Resp	OBS	21.4 ± 4.1	9.4 ± 0.8	30.1± 4.2	14.9 ± 4.2	14.9 ± 1.4	29.8 ± 4.4	19.8 ± 4.6	9.6 ± 1.2	29.3 ± 4.7
	PS+R	25.2	9.6	34.8	22.5	8.6	31.1	25.0	9.6	34.7
	CTL	33.9	3.2	37.2	30.3	2.8	33.1	32.2	3.5	35.7
Ratio %	OBS	9.8	9.1	9.4	8.9	8.7	8.8	9.9	6.8	8.6
	PS+R	9.1	11.0	9.6	9.0	8.7	8.9	9.0	6.4	8.1
	CTL	38.1	11.6	31.9	40.8	9.4	29.8	34.4	6.8	23.9