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The effect of atmospheric aerosol particles and clouds on Net Ecosystem Exchange in Amazonia

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Abstract

Carbon cycling in Amazonia is closely linked to atmospheric processes and climate in the region as a consequence of the strong coupling between the atmosphere and biosphere. This work examines the effects of changes in net radiation due to atmospheric aerosol particles and clouds on the Net Ecosystem Exchange (NEE) of CO₂ in the Amazon region. Some of the major environmental factors affecting the photosynthetic activity of plants, such as air temperature and relative humidity were also examined. An algorithm for clear-sky irradiance was developed and used to determine the relative irradiance f , which quantifies the percentage of solar radiation absorbed and scattered due to atmospheric aerosol particles and clouds. Aerosol optical depth (AOD) was calculated from irradiances measured with the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, onboard the TERRA and AQUA satellites, and was validated with ground-based AOD measurements from AERONET sun photometers. Carbon fluxes were measured using eddy-correlation techniques at LBA (The Large Scale Biosphere–Atmosphere Experiment in Amazonia) flux towers. Two sites were studied: the Biological Reserve of Jaru (located in Rondonia) and the Cuieiras Biological Reserve (located in a preserved region in central Amazonia). In the Jaru Biological Reserve, a 29 % increase in carbon uptake (NEE) was observed when the AOD ranged from 0.10 to 1.5. In the Cuieiras Biological Reserve, this effect was smaller, accounting for an approximately 20 % increase in NEE. High aerosol loading (AOD above 3 at 550 nm) or cloud cover leads to reductions in solar flux and strong decreases in photosynthesis up to the point where NEE approaches 0. The observed increase in NEE is attributed to an enhancement (~50 %) in the diffuse fraction of photosynthetic active radiation (PAR). Significant changes in air temperature and relative humidity resulting from changes in solar radiation fluxes under high aerosol loading were also observed at both sites. Considering the long-range transport of aerosols in Amazonia, the observed changes in NEE for these two sites may occur over large areas in Amazonia, significantly altering the carbon balance in the largest rainforest of the world.

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1 Introduction

Clouds and aerosols influence both the surface energy balance and hydrological cycle through the modification of incoming solar radiation flux and precipitation (Benner and Curry, 1998; Gu et al., 1999, 2001). Consequently, clouds and aerosols exert direct influence on terrestrial ecosystems and are, therefore, expected to modify CO₂ exchanges in the biosphere–atmosphere interface. Over the past 20 yr, field observations over many regions, have shown that the highest rates of carbon uptake in forest ecosystems often occur on slightly cloudy rather than sunny days (Gu et al., 1999; Law et al., 2002; Yamasoe et al., 2006; Oliveira et al., 2007; Jing et al., 2010). Other studies have found that for a given level of irradiance, cloudy days, compared to clear days, generally have higher absolute values of Net Ecosystem Exchange (NEE) (Baldocchi, 1997; Goulden et al., 1997; Gu et al., 1999; Doughty et al., 2010) due to the increase in diffuse radiation, except for highly overcast conditions. Several mechanisms have been proposed to explain these observations including: increases in diffuse radiation (Gu et al., 1999; Yamasoe et al., 2006; Oliveira et al., 2007; Mercado et al., 2009; Jing et al., 2010; Zhang et al., 2010), reduced respiration of sunlit leaves (Baldocchi, 1997; Miller et al., 2004; von Randow et al., 2004), reduction in water vapor pressure difference (VPD) and, finally, modifications in stomatal dynamics associated with ambient light fluctuations. Although these observations have been limited to flux tower measurements (i.e., a few point measures), it is expected that an increase in carbon uptake under increasing cloudiness and atmospheric aerosol load has implications for regional and global climate (Abakumova et al., 1996; Gu et al., 1999). This is of particular interest for regions where the percentage of cloud cover and vegetated areas have increased recently (Keeling et al., 1996; Myneni et al., 1997; Gu et al., 1999, 2003).

Long-term studies coordinated by the LBA experiment (The Large Scale Biosphere–Atmosphere Experiment in Amazonia) have shown that total annual emissions of CO₂ derived from land use change are between 150 and 200 megatons of C per year (Houghton et al., 2000). On the other hand, studies of forest inventories (Phillips et al.,

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1998) indicate that intact Amazonian forest may represent a sink of carbon at rates ranging from 0.5 up to a high value of 7 tC ha^{-1} annually (Araújo et al., 2002; Ometto et al., 2005; Malhi, 2010, 2012). Although there is a significant uncertainty regarding the role of the Amazon as a sink or as a source of carbon to the atmosphere (Keller et al., 1996), due to the balance between deforestation and biomass burning emissions vs. enhanced carbon uptake, recent numbers indicate a kind of balance in uptake/emissions. In Amazonia, biomass burning is the main driver of changes in atmospheric composition, accounting for a significant increase in the concentration of gases and particles in the dry season (Artaxo et al., 2002, 2009; Davidson et al., 2012). This translates into a large anthropogenic impact on the local energy balance, and brings important environmental consequences for the entire Amazon ecosystem (Artaxo et al., 1998; Schafer et al., 2002; Procopio et al., 2004; Sena et al., 2013). In the dry season, where biomass burning emissions are widespread, the reduction in the ground-based flux of photosynthetic active radiation (PAR) can reach values of the order of 70 % (Eck et al., 2003; Procopio et al., 2004), strongly impacting Amazon rainforest primary production (Artaxo et al., 2013). This augmented aerosol loading boosts the fraction of diffuse radiation in the atmosphere, which, in turn, increases the penetration of solar radiation into the forest canopy. The vegetation uses diffuse radiation more efficiently for photosynthesis, which increases forest carbon uptake; a fact that partly balances the effects of reducing direct radiation flux. Most of the Amazon, even outside the region of the so-called “arc of deforestation” experiences the effects of biomass burning emissions to some extent, with the resulting modification in the ecosystem functioning (Oliveira et al., 2007; Doughty et al., 2010; Artaxo et al., 2013).

Atmospheric aerosol lifetime is of the order of days to weeks and thus long-range transport of aerosol particles implies that biomass burning may impact the radiation budget of areas thousands of kilometers away (Seinfeld and Pandis, 2006; Martin et al., 2010b). More knowledge is needed with respect to the impacts that clouds and aerosols have on carbon absorbed by the Amazon forest annually, especially in regions of the Central Amazon, which suffer smaller impacts from biomass burning emissions.

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perature and relative humidity within the canopy. Separated by approximately 1000 km, each site experiences a different precipitation regime and nearby land-use activities. The Forest Reserve of Jaru – RBJ is a protected area located in southeastern Rondonia and is strongly affected every year by biomass burning emissions (Andreae et al., 2004; Oliveira et al., 2007; Silva Dias et al., 2002). Previous studies have shown strong seasonality and carbon assimilation, around -18 and -8 kg C ha⁻¹ day⁻¹ during on the wet and dry season, respectively (von Randow et al., 2004). At this site, this study analyzed approximately 4 yr of measurements of carbon flux and associated meteorological variables (March 1999 to November 2002). The second LBA site (Cuieiras Forest Reserve), located in Central Amazonia 60 km northwest of Manaus, was chosen as representative of an intact, well-preserved forest site with little disturbance or deforestation in recent decades. In the Cuieiras Reserve, the seasonal variations in net carbon uptake by the ecosystem are small (de Araujo et al., 2002, 2010). At this site, this work has analyzed a long time series (~ 10 yr) of carbon flux and meteorological variables, between June 1999 and December 2009. Figure 1 shows the locations of the two sites used in this study.

2.1.1 Jaru Biological Reserve (RBJ)

The Biological Reserve of Jaru ($10^{\circ}05'00''$ S and $61^{\circ}55'00''$ W) is densely forested and located approximately 100 km north of the urban area of Ji-Parana, Rondonia, Brazil. It consists of approximately 268 000 ha of primary forest at an altitude ranging between 100 and 150 m a.s.l. with typical canopy height of 30–35 m. Although the forest reserve is protected by Brazilian Environmental Protection Agency (IBAMA), in recent years it has suffered from forest fires and deforestation relatively close to the sampling site (von Randow et al., 2004). The different geological substrates and diverse rainfall patterns at this site promote numerous vegetation types and five phyto-ecological formations, namely: Open Tropical Rain Forest, Rain Forest, Vegetation Transition or Contact, Cerrado and Alluvial Pioneer Formations. Average annual rainfall ranges from 1400–2600 mm yr⁻¹ with the dry season (rainfall < 60 mm per month) extending from

June to September (Machado et al., 2004; da Rocha et al., 2009). The average annual air temperature is about 24–26 °C, with average relative humidity being around 90 %, although dropping to around 40 % in August. During the dry season, weak cold fronts locally called “friagens”, can also lower temperatures substantially (~ 15 °C) (Fisch et al., 1998).

2.1.2 Cuieiras Biological Reserve (K34)

The second sampling site is the so-called K34 LBA tower flux, located in the central Amazon’s Cuieiras Biological Reserve (2°36′32.67″ S, 6°12′33.48″ W). The K34 tower has been widely utilized for over 10 yr for a range of meteorological studies, including energy and trace gases fluxes (de Araujo et al., 2002, 2010) and even tropospheric variables such as precipitable water vapor (Adams et al., 2011). The study area is densely forested with typical canopy height of 30 m with significant variation (20–45 m) throughout the Reserve. Topography is complex containing a sequence of plateaus, hills and lowlands. The topography of this site, which has a maximum altitude of 120 m, is distributed between 31 % plateau, 26 % slope and 43 % valley (Rennó et al., 2008). More detailed characteristics of the soil in this region can be found in Ferraz et al. (1998); Higguchi et al. (1998) and Oliveira and Amaral (2005). The climate is characterized by an average annual temperature of 26.0 °C, with minimum and maximum values of 23.5 °C and 31.0 °C, respectively, and an average annual relative humidity of 84 %. The average annual precipitation is approximately 2300 mm. Although rainfall can occur in any month of the year, the annual cycle of precipitation is characterized by a punctuated wet season from January to April and a strong dry season from July to September. The dry season (rainfall less than 100 mm) can also vary from year-to-year in length (da Rocha et al., 2009).

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2.2 Measurements

2.2.1 Meteorological and flux measurements of CO₂

In this study, a long time series of flux measurements of CO₂ and meteorological variables are used. Our database includes measurement of the net flux of CO₂ (NEE), obtained using eddy correlation techniques and micrometeorological measurements (1999 to 2009), derived from automatic weather stations (Automatic Weather Stations – AWS) distributed vertically along the tower. Micrometeorological measurements and carbon fluxes were recorded by data loggers at different time steps and were averaged for every 30 to 60 min. AWS stations are comprised of a set of instruments and sensors for measuring solar radiation (0.3–3 μm), thermal radiation (4.5–42 μm) and reflected radiation (all to within ±1 %), a net radiometer to measure net radiation, wet and dry bulb thermometers (±0.1 °C), anemometers with a minimum wind speed of 0.3 to 0.4 ms⁻¹ and a rain gauge with accuracy of ±0.2 mm. The vertical profile of CO₂ concentrations between the soil and atmosphere were obtained using a closed path infrared gas analyzer. The fluxes of H₂O and CO₂ were performed through the eddy covariance system similar to that described by Moncrieff et al. (1997). The system is comprised of a sonic anemometer (~ 10.4 Hz), and an infrared gas analyzer. Fluxes, means and variances were averaged every 30 min, with data processed using Alteddy (version 3.1) based on Aubinet et al. (2000). Table 1 contains a detailed list of the sensors employed. The instrumentation and data acquisition systems are similar at both study sites. However, the procedures for data collection, calibration of sensors, and other operational issues do differ to a small extent between the two sites. The data collection heights can be seen in Table 1 as well as canopy heights for both sites.

2.2.2 Measurements of Aerosol Optical Depth

Remotely sensed aerosol optical depth measurements at 550 nm are taken from two sources, the MODIS instrument on Aqua and Terra platform (MODIS Atmosphere Prod-

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ucts, MOD/MYD-04L2) and from the solar radiometer network AERONET (Aerosol Robotic Network). The CIMEL CE 318-A radiometers have detectors capable of performing direct solar radiation as well as almucantar measurements (Holben et al., 1998). Direct solar measurements have a field of view of 1.2° for eight spectral bands centered at 340, 380, 440, 500, 670, 870, 940 and 1020 nm, determined by rotational interference filters located within the sensor. Each measurement takes approximately 10 s. In this study, the AERONET measurements were considered the standard measurement of AOD and used only to validate the MODIS retrieved AOD. MODIS AOD was calculated from February 2000 to September 2010 (at the RBJ site) and February 2000 to November 2002 (at the K34 site). In order to minimize cloud contamination issues, only AERONET, level 2.0 AOD data were used in the comparison with MODIS AOD. The remotely sensed estimations of AOD are typically made daily between 09:30 a.m. to 11:55 a.m. (Local Time, LT) in the case of MODIS-Terra, and between 12:40 to 14:55 (LT) in the case of MODIS-Aqua. For consistent comparisons between the estimates of AOD (MODIS) and AERONET, only the radiation flux between solar zenithal angles from 10 to 55° were considered. The number of days with AOD data were maximized by combining the estimates from both the Terra and Aqua satellites. These estimates are averages of an area of $50 \times 50 \text{ km}^2$ collocated with the LBA flux towers. Periods when either measurements of CO_2 (eddy flux) or MODIS AOD were absent were not employed in this study.

2.3 Methods

In this section, a description of the procedures employed to observe aerosol and clouds effects on net radiation fluxes is provided. Firstly, the variables used to estimate the cloudiness are presented. In meteorological observations, the cloudiness is usually measured in tenths or eighths of sky covered. However, in the present study, the word “cloud” will be used to refer to the presence, quality or quantity of clouds in the sky. A method to identify clear-sky conditions was also developed. The procedures used

to evaluate cloud/aerosol influence on NEE including the environmental factors that possibly contribute to changes in the carbon flux are also described.

2.3.1 Calculation of net ecosystem CO₂ exchange

At both sites, NEE is obtained from turbulent flux measurements by means of the eddy covariance technique taking into account the storage term (de Araújo et al., 2010; von Randow et al., 2004). Micrometeorological sensors distributed vertically along the tower are essential for the NEE calculations (Richardson and Hollinger, 2005), using continuous measurements of the CO₂ profile between soil and top of the tower. Under these conditions, NEE can be approximated by:

$$NEE \approx F_c + Stg \quad (1)$$

Where F_c is called “CO₂ turbulent flow”, calculated by the eddy correlation system above the treetops; Stg (the storage term) is the CO₂ concentration (non-turbulent term), measured in a vertical profile at discrete levels z_i of Δz_i thickness, from the soil surface to the point of eddy correlation measurements around 53 m and 63 m on the K34 and RBJ towers, respectively (Finnigan, 2006; Loescher et al., 2006; Dolman et al., 2008). At RBJ, procedures for calculating the NEE were made following von Randow et al. (2004). At K34, vertical profiles of CO₂ concentrations were calculated following Albinet et al. (2001) and de Araújo et al. (2010).

$$Stg = \frac{P_a}{RT_a} \int_0^z \left(\frac{\partial c}{\partial t} \right) \partial z \quad (2)$$

Where P_a is the atmospheric pressure (Nm⁻²), R is the molar gas constant (Nm^{mol}⁻¹K⁻¹), T_a is the air temperature (K), c is the [CO₂] (μmol mol⁻¹), t is the time (s) and z is the maximum height (m) between the ground and the canopy (Finnigan, 2006; Loescher et al., 2006).

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quality or quantity, of clouds in the sky (Gu et al., 1999). The concept of relative irradiance, f , was used to determine the reduction of incident solar irradiance due to clouds and/or aerosols and associate this with the changes in NEE, which also changes with temperature and relative humidity variations. In this study, the quantity f was calculated following Oliveira et al. (2007):

$$f = \frac{S\{\text{AOD, cloudiness}\}}{S_0\{\text{AOD}_{0.10}, \text{cloudless}\}} \times 100 \quad (3)$$

Where S (W m^{-2}) is the total incident solar radiation measured on the surface at a given time (with or without the presence of aerosols and clouds) and S_0 (W m^{-2}), the expected total incident solar irradiance at the surface in a cloudless atmosphere with an aerosol optical depth of 0.10 at 550 nm. Previous studies in Amazonia have shown that the background AOD, due to atmospheric natural conditions is about 0.1 at 550 nm (Holben et al., 1996; Guyon et al., 2003). There are few models assessed in the literature for the calculation of S_0 (Ricchiazzi et al., 1998; Duchon and O'Malley, 1999). In this study, we chose to employ an algorithm for clear-sky irradiance that would include the intrinsic characteristics of local conditions in the Amazon. S_0 and f were calculated employing the methodology of Gu et al. (1999), which establishes a set of criteria to find clear-sky days. These criteria are based on the concept of clearness index, k_t , which is discussed in detail in the next section. In this study, k_t was used to find S_0 and thus determine f . To observe only the aerosol effect on the solar irradiance flux (computed from f), and consequently on the NEE measurements, the aerosol effect has to be isolated from the cloud effect. Radiation measurements were classified as affected only by aerosols if they were performed under cloudless conditions, that is, under clear-sky conditions (Oliveira et al., 2007). The MODIS sensor has a reasonable algorithm to exclude cloud contamination of the AOD measurements (King et al., 1999, 2003; Remer et al., 2005).

2.3.3 The definition of the clearness index

The relative irradiance, f , provides an estimation of changes in cloudiness and AOD as a result of changes in measured solar radiation fluxes. However, the concept requires that S_0 be available. When clear-sky irradiance is not available, sky conditions can be described in terms of the “clearness index”, kt , defined as the ratio of solar radiation received at the surface to the solar irradiance at the top of the atmosphere (TOA). For a given solar elevation angle, small kt values indicate an increase in the cloud coverage and/or aerosol loading, while higher values indicate more clear sky conditions (Gu et al., 1999; Zhang et al., 2010; Bai et al., 2012). Mathematically, the clearness index can be expressed by:

$$kt = S/S_e \quad (4a)$$

$$S_e = S_{sc} \left[1 + 0.033 \cos \left(\frac{360 td}{365} \right) \right] \sin \beta \quad (4b)$$

Where S is the ground-based total solar irradiance actually measured at the surface, while S_e is the TOA solar irradiance, where S_{sc} ($\sim 1367 \text{ W m}^{-2}$) is the solar constant, and td the Julian Day. For the calculation of $\sin \beta$ the following equation is used:

$$\sin \beta = \sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \cos \omega \quad (5)$$

Where (β) is the solar elevation angle and (φ), (δ) and (ω) are, respectively, the latitude, the declination of the Sun (in degrees) and the hour angle. An interesting characteristic of this definition is that it is possible establish a clearness index for clear skies (i.e., cloud free and AOD ~ 0.10). Under these conditions, it is possible to denominate a clear-sky clearness index, kt^* , and Eq. (4a) can be rewritten as:

$$kt^* = \frac{S_0}{S_e} \quad (6)$$

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afternoons clear-sky selected were plotted with the solar zenith angle again to check if the clear-sky days selected met the two criteria set out above.

The degree of dependence between kt^* (clear-sky clearness index) and $\cos(z)$ was used to assess whether the mornings and clear afternoons were accurately selected.

5 This relationship can be expressed as follows:

$$kt_0 = a_1 \cos^3(z) + a_2 \cos^2(z) + a_3 \cos(z) + a_4 \quad (7)$$

Where kt_0 is the clear-sky clearness index from the regression curves (Fig. 3a and b); z is the solar zenith angle calculated Gates (1980); a_1 , a_2 , a_3 and a_4 are the regression coefficients specific to the selected clear mornings and afternoons, calibrated to local conditions of the tropical forest at K34 and RBJ, respectively. The clear-sky irradiance (S'_0) was also determined, obtained similarly to Eq. (7). The coefficients kt_0 and S'_0 are fixed as showed in Table 3.

Figure 3 show asymmetries between the period of morning and afternoon light at both sites. The values of kt^* selected during afternoons are slightly higher when compared with the indexes of selected mornings, especially for low angles (less than $\cos^{-1} 0.45$). Similar results were obtained by Gu et al. (1999) and Zhang et al. (2010). For a given solar zenith angle, decreases in the clearness index generally indicate an increase in the depth of the clouds, with the exception for situations in which the clouds are not distributed uniformly across the sky; i.e., when there is a cloud gap effect (Gu et al., 1999; Oliveira et al., 2007).

2.3.5 Determination of NEE on clear-sky days

In this study, the influence of aerosols and clouds on carbon uptake is analyzed mainly in terms of variations in NEE and environmental factors through their impact on f . The observed NEE on clear days was used also as a basis of comparison for cloudy days and/or days with high aerosol loading. Equation (1) and NEE (clear-sky) were used to calculate the percentage effect of aerosols and clouds on the carbon flux (%NEE) by

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way of the following relationship (Gu et al., 1999; Oliveira et al., 2007; Bai et al., 2012):

$$\%NEE = \left(\frac{NEE(z) - NEE(z)_{\text{csky}}}{NEE(z)_{\text{csky}}} \right) \times 100 \quad (8)$$

Where $NEE(z)$ is a measure of NEE under a given condition sky throughout the day and NEE_{csky} is the NEE calculated under sky conditions with low aerosol loading in the atmosphere and minimal cloud cover ($f \approx 1.0$, $AOD \sim 0.10$).

To eliminate the interference of sun elevation angle on the variation of NEE% or NEE on the relative irradiance parameter f , data grouped at intervals of solar zenithal angle between 10–20 and 20–35 were initially analyzed. Zenith angles of 5° intervals proved too small to develop a robust statistical analysis (Gu et al., 1999). Values above 50° or around 0° (solar angle very near the horizontal and vertical plane, respectively) were in general too heavily contaminated by clouds. Therefore, a 10 to 35° elevation angle was chosen to be optimal for measuring the ecosystem response to changes in cloudiness and AOD rather than the effect of variations in solar zenith angles.

The results shown in Fig. 4a and b show the solar zenith angle interval for which carbon fluxes experiences the greatest variation. The statistical parameters R^2 and p value (Fig. 4a and b) are satisfactory in view of the measurement sample size; For K34 > 59 000 points, and for RBJ > 26 000 values. The coefficient of determination R^2 is relatively low, but the level of statistically significant p values in all cases are smaller than 0.001, indicating a high degree of relationship between the NEE and solar zenithal angle. The obtained coefficients of NEE (clear-sky) are listed in Table 4. These coefficients are consistent with those of the Tapajos National Forest in Amazonia, reported by Oliveira et al. (2007), but are quite different from those obtained in other ecosystems, such as temperate deciduous forests, mixed forests and pine forest, found in southern Canada and Northwest China, respectively (Gu et al., 1999; Zhang et al., 2010).

The relationship between NEE and some variables that directly interferes with the uptake of carbon by forests, such as: total PAR, diffuse PAR, air temperature, canopy temperature and VPD were also studied. This discussion about methods used to calcu-

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late total PAR downward radiation, diffuse PAR and canopy temperature are discussed in Sects. 2.3.6 and 2.3.7.

2.3.6 Methods to derive total and diffuse PAR

Unfortunately, measurements of diffuse PAR, were not available at either K34 or RBJ. Therefore, to determine the diffuse component of total PAR, we followed the methods derived by Spitters et al. (1986) and Reindl et al. (1990) which have been widely used in the literature (Gu et al., 1999; Jing et al., 2010; Zhang et al., 2010; Bai et al., 2012). The calculation is performed deriving the diffuse PAR radiation PAR_f from the following formulation (Spitters, 1986):

$$PAR_f = \left[\frac{[1 + 0.3(1 - q^2)]q}{1 + (1 - q^2)\cos^2(90^\circ - z)\cos^3z} \right] \times PART \quad (9)$$

Where PAR_f is the diffuse PAR radiation ($\mu\text{mol photon m}^{-2} \text{s}^{-1}$) and $q = (S_f/S_e)/kt$; S_f denotes the total diffuse radiation (visible plus near infrared) received on a horizontal plane at the Earth's surface ($W m^{-2}$). The fraction of diffuse PAR was defined as the ratio between PAR_f and total PAR ($PART$). To express the light use efficiency (LUE) of vegetation and the fraction of diffuse PAR (D_f), respectively, the NEE and PAR_f values were normalized by $PART$ as follows (Jing et al., 2010):

$$LUE = NEE/PART \quad (10)$$

$$D_f = PAR_f/PART \quad (11)$$

2.3.7 Canopy top temperature

As there are no direct measurements of skin temperature of the canopy at either study sites, we used the data sets of pyrgeometers operated around 15–20 m high inside the canopy on both sites (Table 1) to measure the emission of long wave radiation from the

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surface ($L \uparrow$) (W m^{-2}). The Eq. (11) was derived from the Stefan–Boltzmann equation and used to calculate the temperature of the canopy (T_c) of the K34 and RBJ sites K34. Doughty et al. (2010) used similar procedures to estimate the canopy temperature (skin temperature) in FLONA-Tapajos (Santarem-PA).

$$T_c = \left(\frac{L \downarrow}{\sigma \varepsilon} \right)^{0.25} \quad (12)$$

Where ε is the emissivity, assumed 0.98 (Monteith and Unsworth, 1990) and σ the Stefan–Boltzmann constant ($5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$).

3 Results and discussions

This section presents and discusses the main results of this study. The first task was to validate MODIS AOD estimations with the AOD measurements from the AERONET sun-photometer network. Following this, the radiative effects of aerosols and clouds on the CO_2 fluxes for both sites was analyzed. Measurements of NEE, PAR_t , PAR_f , AOD, relative humidity, air temperature and surface temperature of the forest canopy are further analyzed as a function of the relative irradiance parameter (f), during the biomass burning season at both sites.

3.1 MODIS AOD validation for the Central and Southwestern Amazon

The estimates of the MODIS AOD allowed to observe the atmospheric aerosol loadings from two geographic regions with very different characteristics. One region less impacted by anthropogenic activities (Manaus and Balbina), Central Amazon (Fig. 5a), and the other, heavily impacted by biomass burning smoke, represented by the site RBJ in Rondonia (Fig. 5c). Balbina (coordinates $1^\circ 55' 1.14'' \text{ S}$ and $59^\circ 29' 12.48'' \text{ W}$) is a site close to K34, where AERONET measurements were done from 2000 to 2002. During the wet season, AOD values are small (around 0.10, a typical background value

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when the AOD varied from 0.10 to 0.70 at the site of K34 (Fig. 6c) and approximately 25% when the AOD varies from 0.10 to 2.5 in the forest area of RBJ.

Figure 6c and d shows the calculated fraction of diffuse radiation as a function of AOD. The calculation shows an increase of about 25% in diffuse radiation as AOD increases from 0.2 to 0.60 (K34) and from 0.10 to 2.2 (RBJ). These results are particularly important because diffuse PAR penetrates more efficiently in the canopy and contributes to an increase in carbon uptake (Doughty et al., 2010). The joint analyses of Fig. 6 with the results shown in Sect. 3.5 helps to understand how the increase in AOD and PAR_f affect carbon uptake by the forest.

The Fig. 7a and b show that for f ranging from 0.80 to 1.2, the PAR_t is reduced by approximately 30–35% at both sites K34 and RBJ. This behavior was observed both during the biomass burning season and the wet season. Oliveira et al. (2007) showed similar decreases ($\sim 20\%$) when f varied from 1.0 to 0.80. These figures also show a strong reduction in PAR_t when the cloud cover changes from a “clear sky” conditions ($f > 1.0$, AOD ~ 0.10) to completely overcast by clouds and aerosols ($f < 1.0$, AOD $\gg 0.10$). Although the PAR_t decreases almost linearly with the relative irradiance (Fig. 7a and b), the relationship between the diffuse PAR radiation and f is not linear (Fig. 7c and d). In this case, the PAR_f increases $\sim 500 \mu\text{mol m}^{-2} \text{s}^{-1}$ when the relative irradiance f decreases from 1.2 to 0.75. This corresponds to a 50% increase in PAR (diffuse) during biomass burning season due to scattering by aerosols and clouds. In the RBJ, these changes are mainly due to the dense aerosol layer observed during the biomass burning season.

3.3 The effect of PAR (diffuse) radiation on the light use efficiency (LUE) through forest

In Sects. 3.1 and 3.2, strong AOD seasonality was observed, with important effects in the atmospheric radiation balance, in particular, PAR radiation. In this section, the effect of these changes on the efficiency of radiation used by forests (LUE) was evaluated

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and the values of radiation efficiency use for which this efficiency is maximum were identified.

Figure 8a and b shows NEE as a function of total PAR observed during clear-sky days and high aerosol loading/cloudy days during the dry season for both K34 and RBJ. The assimilation of carbon gradually increases with increasing total downward PAR (PAR_t) radiation reaching its maximum saturation at around 1800–2000 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for both sites (Fig. 8a and b). Additionally, it was observed that for the same level of irradiance at the surface (e.g., between 0–1800 $\mu\text{mol m}^{-2} \text{s}^{-1}$) the forest tends to absorb more carbon (more negative NEE) under high aerosol loading/cloudy atmospheric conditions (Fig. 8a and b). These results show that the fraction of diffuse solar radiation affects NEE at both sites in Amazonia.

Figure 8c and d shows the NEE normalized by the total PAR flux plotted against the diffuse fraction of PAR radiation. It is possible to analyze vegetation LUE analyzing the ratio of NEE/PAR-total (Jing et al., 2010). This relationship represents the photosynthetic efficiency, which is related to the ability of the canopy to convert solar energy into biomass. At both sites, it is possible to observe that LUE is low ($\sim 1\text{--}2\%$), requiring large amounts of energy for photosynthesis. Furthermore, peaks of up to 4% (K34) and 6% (RBJ) in photosynthetic efficiency were observed in cases where the diffuse fraction reaches values around 1, during situations when the sky is obscured by clouds and aerosols ($f < 1.0$, AOD > 0.10). A gradual increase in LUE was observed (Fig. 8c and d) with increasing PAR (diffused) for irradiance values around 0.80, falling sharply after this value until the maximum fraction PAR_f which is 1.0. These results are similar to those obtained in the semiarid region of northeastern China (Jing et al., 2010).

3.4 Effect of aerosols and clouds on the Net Ecosystem Exchange (NEE)

Figure 9a and b shows the relationship between NEE and relative irradiance f for the experimental forest sites K34 and RBJ. In Fig. 9c and 9d the changes in net carbon absorbed by these forests (Relative Change of NEE, NEE %) due to aerosols (green dots) and clouds (black dots) can be observed. These analyses were performed with

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and clouds becomes smaller and similar in both sites, for solar zenithal angles $< 20^\circ$ (Fig. 9c and d). Near zenith, solar radiation is less scattered by particles suspended in the atmosphere due to decreased path length, mitigating the diffuse radiation effects on the photosynthetic process.

The results from Fig. 9 shows that the photosynthetic efficiency of the forest is relatively larger on days with the atmosphere loaded with small amounts of aerosol particles and/or low cloud cover. The effect is clearly nonlinear, reaching a point where NEE begins to decrease. The value of this behavior varies for each solar zenith angle range. For measurements between $10\text{--}20^\circ$, a reduction in solar irradiance of up to 30 % does not inhibit CO_2 uptake in the forest canopy. For measurements taken for solar zenith angle between $20\text{--}35^\circ$, a 40 % reduction in irradiance does not show effects on CO_2 uptake. This result is important since much of the Amazon area is often impacted by the presence of aerosols in small amounts (low AOD) similar to those observed for Manaus. The increases in CO_2 uptake are significant and could have major impacts on the Amazon forest carbon budget. Peak CO_2 uptake is often observed for f values near 0.80, a value typically encountered in dense forest ecosystems (Gu et al., 1999; Yamasoe et al., 2006; Oliveira et al., 2007; Doughty et al., 2010) but quite different from what is found in grasslands and other temperate forested regions (Niyogi, 2004; Jing et al., 2010; Zhang et al., 2010).

3.6 The relationship between the current patterns of aerosols and clouds and carbon uptake

Figure 10 shows the percentage distribution of the kt (clearness index) throughout the year at K34 (1999–2009) and RBJ (1999–2002) sites. The percentage of cloud cover (not shown), as well as the distributions of kt (Fig. 10a and b) are similar for both sites, but differ from wet and dry seasons, as expected. Using brightness temperature from GOES10, 60 % of the time during the rainy season, both K34 and RBJ experienced some degree of cloud cover. This percentage, decreases during the dry season (August through October) reaching a minimum of 20 % at RBJ and 30 % at K34 in

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September. The frequency distribution of kt (Fig. 10a and b), is compatible with the observations of cloud cover observed using GOES10 analysis (around 60–70 %).

The analysis of kt frequency distributions (Fig. 10a and b), indicates that current patterns of cloudiness do not yet exceed the maximum limit for which the forests of K34 and RBJ sites reach the maximum amounts of carbon uptake. The peak kt distribution at both sites is near 0.75 (Fig. 10b), which is smaller than the values of f for which the NEE reaches its maximum negative value during the burning season ($kt \sim 0.57$). This is the limit at which the cloudiness and/or aerosol load result in the maximum carbon uptake at RBJ and K34 (Fig. 10c). Larger quantities of aerosols and clouds in the region could cause these forests to absorb even greater amounts of carbon throughout the day, considering the combined effect of NEE enhancement by aerosols and clouds. The distribution patterns of the frequency occurrence of kt found throughout the years in both forest sites (Fig. 10) are similar to those found by Oliveira et al. (2007) in the Tapajos National Forest, in Santarem and Rondonia also in RBJ. These results are also consistent with calculations from Gu et al. (1999) in temperate forests of Canada, where kt values are centered at 0.75 and the maximum negative NEE is at about 0.55–0.60.

3.7 Effects of temperature and VPD on CO_2 uptake

Figure 11 shows the direct influence that clouds and aerosols have on some of the major environmental factors that also affect the photosynthetic activity of plants. The attenuation of incident solar irradiance due to the presence of aerosols and clouds, cause significant reductions in air temperature near the canopy forest and also in the vapor pressure deficit (VPD) associated with relative humidity (Fig. 11). At the K34 site, the combined effect of aerosols and clouds (in this case, more aerosols than clouds) produced, respectively, a cooling of 1.5 and 2.5 °C in air temperature of the canopy when f ranged from 1.2 to 0.80 (Fig. 11a and c). At RBJ, considering the same variations in f , a cooling of 3–4 °C was observed (Fig. 11b and d). These values are on the relatively high side, but are similar to results found by Davidi et al. (2009). Another

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forest photosynthesis process. The results show higher photosynthetic efficiency in situations where the atmosphere is lightly loaded with particles and/or clouds. A more efficient use of the diffuse solar radiation can be pointed to as the main source of increased CO₂ flux in the forest areas of the sites studied. In addition, in view of the increased cloudiness and aerosol loading, significant variations were observed in other meteorological variables, such as temperature and vapor pressure deficit (VPD). The variations of these quantities may also influence carbon uptake.

The increase in VPD associated with decreased air temperature due to aerosols and clouds may be causing reductions in the rate of respiration of forest and hence an increase in NEE, during biomass burning aerosols exposure. Many physiological and environmental factors also are involved in the dynamics and control of carbon fluxes in the Amazon, thereby attributing and separating the different effects on CO₂ fluxes difficult.

The increase in NEE due to the increased amount of aerosols and clouds constitute an effect of considerable relevance due to the importance of carbon cycling in Amazonia. A regional study of this effect, based on vegetation maps, remote sensing estimates, assimilated meteorological data and environmental modeling, will help to better understand how climate and ecosystem functioning in Amazonia are affected by natural and anthropogenic environmental factors.

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Table 1. List of measurements, instruments and measurement heights for the automatic weather station and eddy correlation instrumentation installed on the K34/Manaus-AM and RBJ/Ji-Paraná LBA towers.

Set list instruments and measurements					
Measurements	Instruments	[Unit]	Measurements height [m]		
			K34	RBJ	
Net Radiation	NR-LITE Kipp & Zonen	W m^{-2}	44.0	19.0	
Incident and reflected short wave radiation	Pyranometers Kipp & Zonen (CM21)	W m^{-2}	44.6	19.3 ^a	
Incident and emitted long wave radiation	Pygeometers Kipp & Zonen (CG1)	W m^{-2}	44.6	19.3 ^a	
Photosynthetically Active Radiation (PAR)	LI-COR LI-190SZ quantum sensor	$\mu\text{mol m}^{-2} \text{s}^{-1}$	51.6	25.6 ^a	
Vertical profile of air temperature	Vaisala thermohygrometer (HMP35A)/PT100 resistors	$^{\circ}\text{C}$	51.1, 42.5, 35.5, 28.0, 15.6, 5.2	60.0, 45.2, 35.0, 25.3, 15.3, 5.3	
Vertical profile of $[\text{CO}_2]$ and water vapour $[\text{H}_2\text{O}]$	IRGA PP Systems CIRAS SC	ppm	51.1, 42.5, 35.5, 28.0, 15.6, 5.2	62.7, 45.0, 35.0, 25.0, 2.7, 0.05	
Relative Humidity	Vaisala thermohygrometer (HMP35A) and (HMP45AC)/PT100 resistors	%	51.1	60.0	
Rainfall	Rain gauge EM ARG-100	mm	51.3	60.3	
Atmospheric pressure	Barometer Vaisala (PTB100A)	hPa (mb)	32.0	40.0	
u, v, w (wind vector)	Eddy correlation system (Gill Sonic Anemometer and LI-COR 6262 IRGA)	m s^{-1}	53.1 and 46.1	62.7	

^aHeight above canopy top (~35 m)

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Table 3. Regression coefficients of relationships between clear-sky irradiance (S_0) and solar zenith angles $\cos(z)$ as well as relationships between clear-sky clearness index (kt^*) and solar zenith angles $\cos(z)$ of Eq. (7) for the morning and afternoon periods of the K34 and RBJ sites. Periods of measurements: K34: 2000–2009, and RBJ: 2000–2002.

Regression Coef.	Trop. Rainforest Manaus (K34)		Trop. Rainforest Ji-Parana (RBJ)	
	Morning	Afternoon	Morning	Afternoon
Clear-sky irradiance [S_0] – [$S'_0 = p_1 \cos^3(z) + p_2 \cos^2(z) + p_3 \cos(z) + p_4$]				
p_1	–1026	–685	–813	–644
p_2	2027	1210	1867	1188
p_3	–110	240	–170	295
p_4	10	14	11	18
R^2	0.95	0.85	0.95	0.92
Clear-sky clearness index [kt^*] – [$kt_0 = a_1 \cos^3(z) + a_2 \cos^2(z) + a_3 \cos(z) + a_4$]				
a_1	–0.01	–0.31	–0.14	–0.54
a_2	–0.69	0.16	–0.29	0.63
a_3	1.39	0.41	1.13	0.13
a_4	–0.02	0.31	–0.04	0.41
R^2	0.85	0.30	0.87	0.41

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Table 4. Regression coefficients of relationship between NEE and solar zenithal angle (SZA) for clear-sky conditions ($f \sim 1.0$) observed during the dry seasons at the K34 and RBJ sites.

Measurements (morning) Clear-sky	Regression of Parameters			
	n_1^*	n_2^*	n_3^*	R^2
Trop. Rainforest (RBJ)/2000–2002				
NEE of CO ₂ – $\mu\text{mol m}^{-1} \text{s}^{-1}$	0.002	0.100	–24.8	0.60
Trop. Rainforest (K34)/2000–2009				
NEE of CO ₂ – $\mu\text{mol m}^{-1} \text{s}^{-1}$	0.004	–0.152	–15.7	0.27

* n indicate coefficients of the regression curve (Fig. 5).

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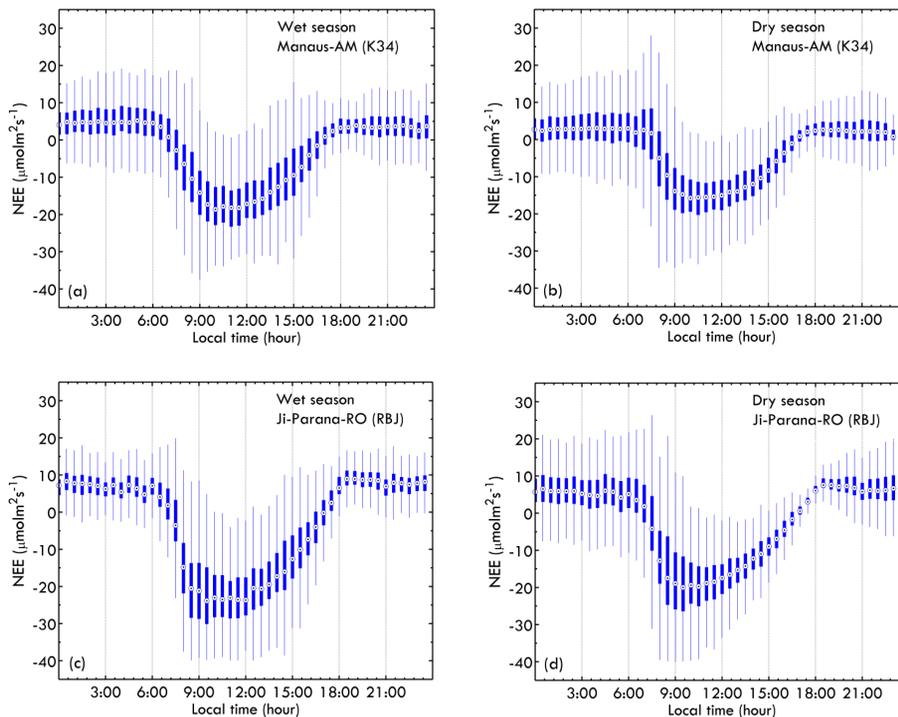


Fig. 2. Seasonally averaged diurnal cycles of NEE for the wet and dry seasons in the tropical rainforests in: (a) and (b) Manaus/K34 (1999–2009) and (c) and (d): Ji-Parana/RBJ (1999–2002).

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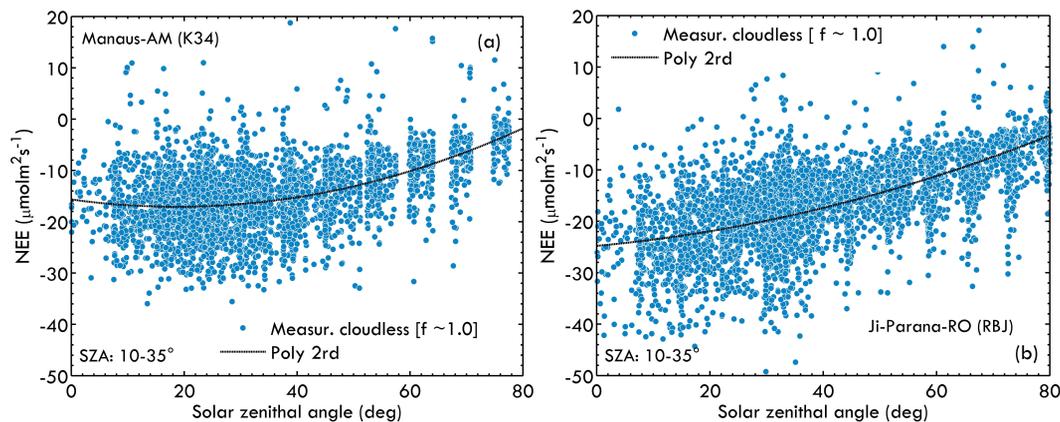


Fig. 4. Relationship between NEE and solar zenithal angle (SZA) for clear-sky conditions ($f = 1.0$) at the K34 **(a)**, for a poly 2rd fit with $R^2 = 0.27$ and $p < 0.01$, and at the RBJ **(b)**, for a poly 2rd fit with $R^2 = 0.60$ and $p < 0.001$.

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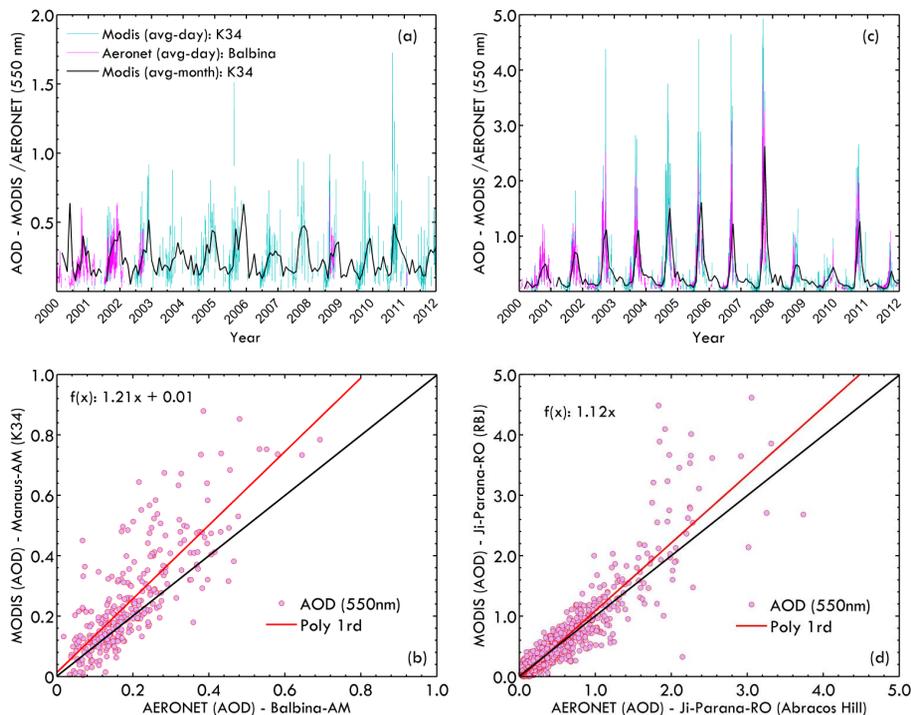


Fig. 5. Time series of AOD (at 550 nm) from 2000 to 2012 estimated by MODIS and measured by the AERONET sun photometer at 550 nm at the K34 site **(a)** and at the RBJ site **(c)**. **(b)** and **(d)** show regressions of the estimation of AOD by MODIS on the K34 sites **(b)** and at RBJ **(d)**. The red lines represent the linear fits at the both sites, with R^2 equal 0.64 (K34) and 0.84 (RBJ). The AOD values (AERONET) at 550 nm were calculated through Angström $\alpha \sim 1.01$ at the Balbina-AM **(b)** and $\alpha \sim 1.48$ at the Abracos Hill **(d)** sites. The differences between linear fit found between the estimates made by the MODIS (550 nm) and by sun photometer AERONET (500 nm) are less than $\sim 5\%$ (not shown results).

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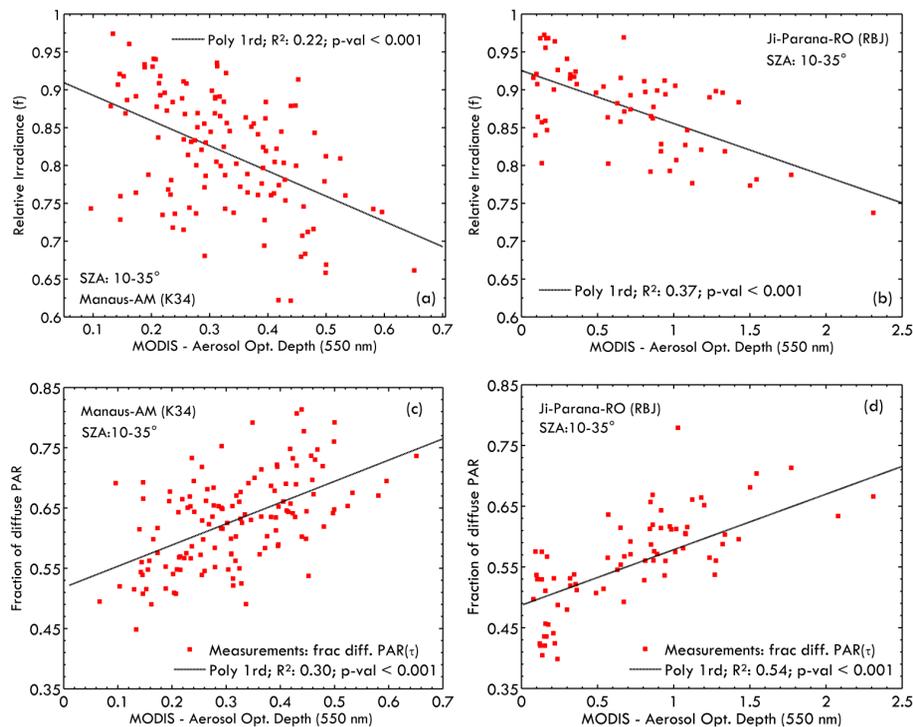


Fig. 6. Relationships between relative irradiance f and AOD (MODIS) for Manaus-K34 (a) and Ji-Parana (RBJ) (b). The lower part shows the fraction of diffuse PAR for K34 (c) (2000–2009) and RBJ (d) (2000–2002).

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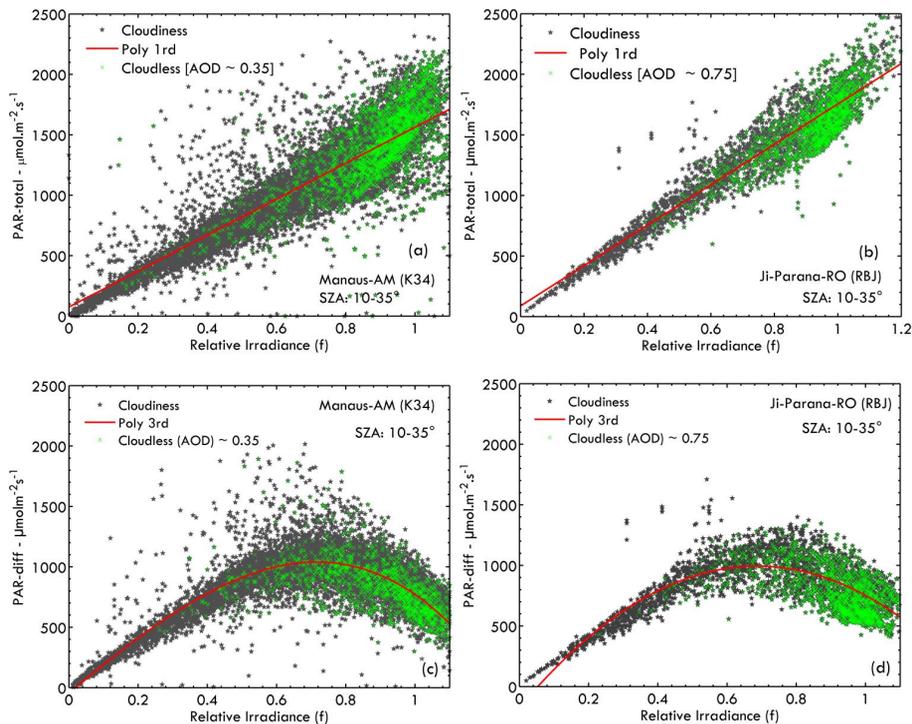


Fig. 7. Relationships between total PAR and relative irradiance f for the K34 site **(a)** and RBJ **(b)**. The lower part shows the diffuse PAR vs. relative irradiance f for K34 **(c)** and RBJ **(d)** sites. The period of the data used are: K34 site (2000–2009) and RBJ site (2000–2002).

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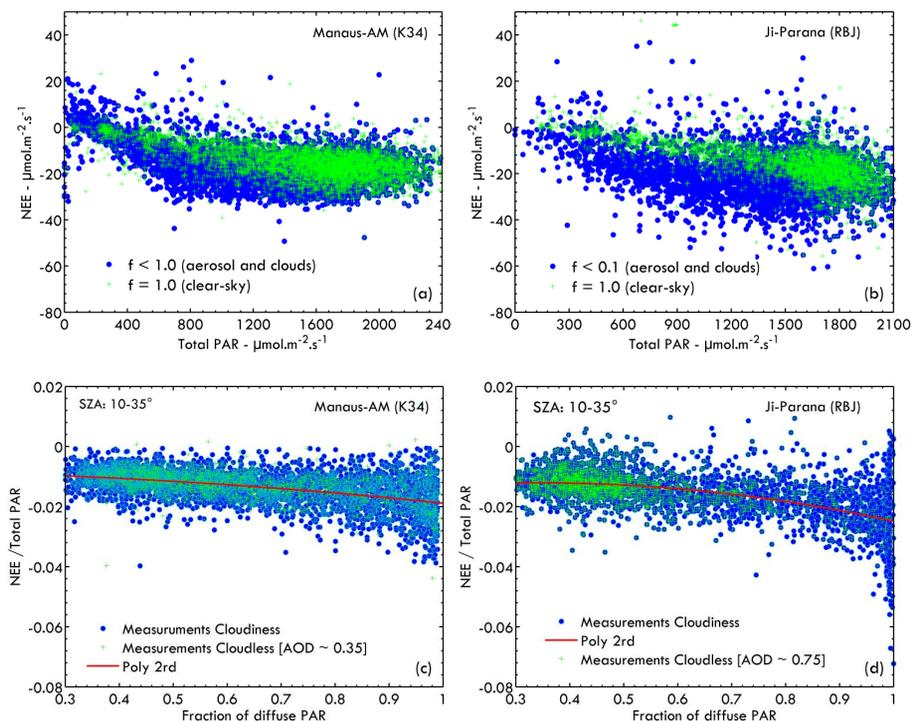


Fig. 8. NEE as a function of total downward PAR radiation for measurements between the 08:30 and 17:30 LT, for the K34 (a) and RBJ (b) sites. (c) and (d) shows the Light Use Efficiency (LUE) of vegetation as a function of the fraction of diffuse PAR at the K34 ($R^2 = 0.21$, p value < 0.001) in Manaus (2000–2009) (c) and RBJ ($R^2 = 0.30$, p value < 0.001) in Ji-Parana (2000–2002).

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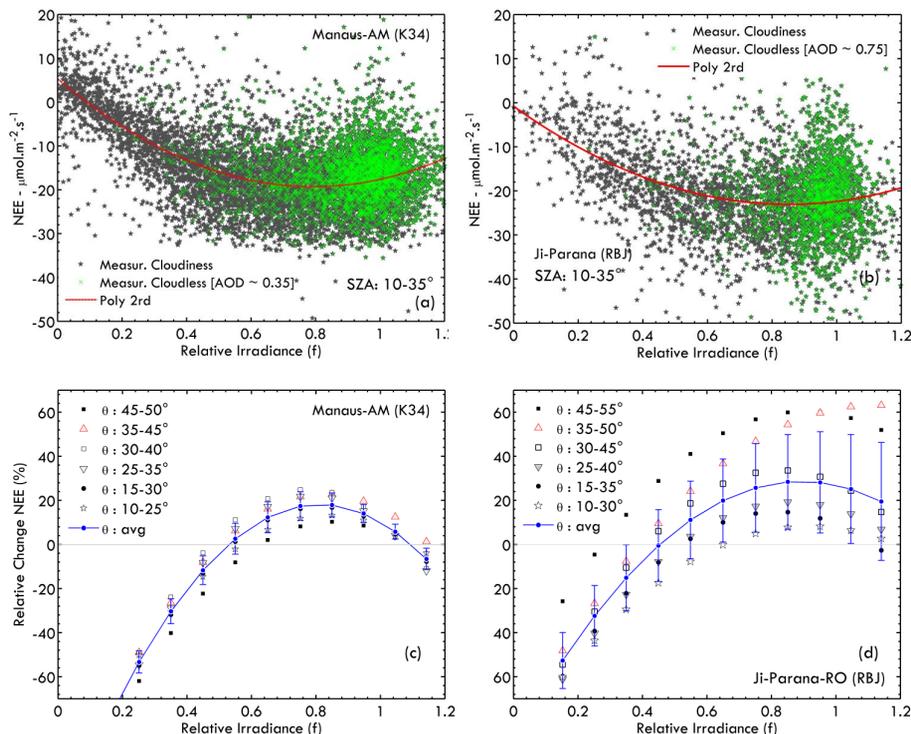


Fig. 9. Variability of NEE with the relative irradiance f for the K34/Manaus ($R^2 = 0.32$) and RBJ/Ji-Parana ($R^2 = 0.12$) sites for solar zenith angle interval (z) between 10° and 35° (a) and (b). Relative change of NEE (%NEE) as a function of the relative irradiance f , averaged for all solar zenith angle intervals (z), from 10° to 55° (c) and (d). Note that this plot includes clouds and aerosol effects.

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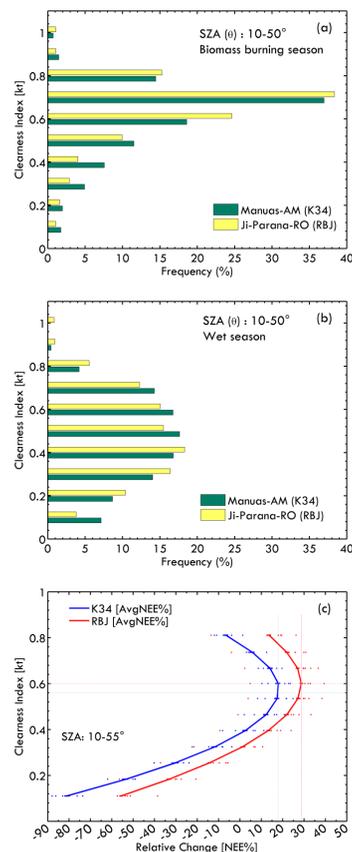


Fig. 10. Histograms of values of the clearness index for K34 and RBJ along the biomass burning season **(a)** and wet season **(b)**. The limit at which the cloudiness and/or aerosol load result in the maximum carbon uptake at RBJ and K34 are shown on the figure **(c)**. The relative change values (NEE%) were calculated for solar zenithal angles between 10° and 55°.

The effect of atmospheric aerosol particles and clouds on NEE in Amazonia

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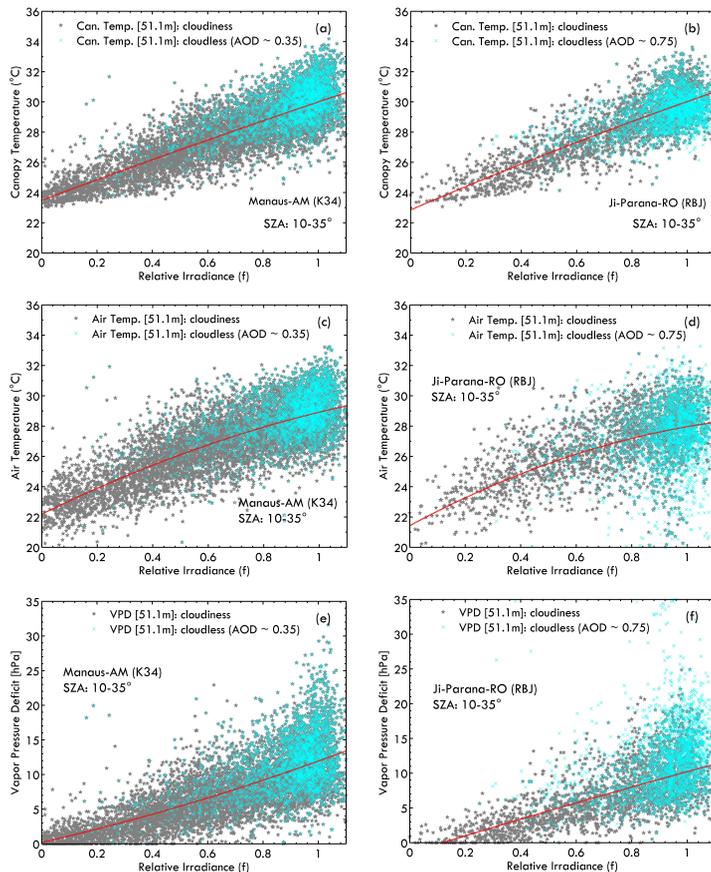


Fig. 11. Relationship between the relative irradiance parameter f with: **(a–b)** canopy temperature; **(c–d)** Air temperature and **(e–f)** Vapor Pressure Deficit. Values calculated for SZAs between 10–35°. Air temperature was measured at 51.1 and 60.0 m over the ground in the K34 and RBJ, respectively.