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The Response of the Amazon Ecosystem to the Photosynthetically Active Radiation Fields: Integrating Impacts of Biomass Burning Aerosol and Clouds in the NASA GEOS ESM

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Abstract

The Amazon experiences fires every year, and the resulting biomass burning aerosols, together with cloud particles, influence the penetration of sunlight through the atmosphere, increasing the ratio of diffuse to direct photosynthetically active radiation (PAR) reaching the vegetation canopy and thereby potentially increasing ecosystem productivity. In this study, we use the NASA Goddard Earth Observing System (GEOS) model running with coupled aerosol, cloud, radiation, and ecosystem modules to investigate the impact of Amazon biomass burning aerosols on ecosystem productivity, as well as the role of the Amazon's clouds in tempering the impact. The study focuses on a seven-year period (2010-2016) during which the Amazon experienced a variety of dynamic environments (e.g., La Niña, normal years, and El Niño). The radiative impacts of biomass burning aerosols on ecosystem productivity—call here the aerosol light fertilizer effect—are found to increase Amazonian Gross Primary Production (GPP) by 2.6% via a 3.8% increase in diffuse PAR (DFPAR) despite a 5.4% decrease in direct PAR (DRPAR) on multiyear average. On a monthly basis, this increase in GPP can be as large as 9.9% (occurring in August 2010). Consequently, the net primary production (NPP) in the Amazon is increased by 1.5%, or ~92 $TgCyr^{-1}$– equivalent to ~37% of the carbon lost due to Amazon fires over the seven years considered. Clouds, however, strongly regulate the effectiveness of the aerosol light fertilizer effect. The efficiency of the fertilizer effect is highest for cloud-free conditions and linearly decreases with increasing cloud amount until the cloud fraction reaches ~0.8, at which point the aerosol-influenced light changes from being a stimulator to an inhibitor of plant growth. Nevertheless, interannual changes in the overall strength of the aerosol light fertilizer effect are primarily controlled by the large interannual changes in biomass burning aerosols rather than by changes in cloudiness during the studied period.

1. Introduction

The Amazon is home to more than 34 million people and hosts a large variety of plants and animals. The rainforest plays a vital role in the global climate, regulating temperatures and storing vast quantities of carbon dioxide (Laurance 1999; Nepstad et al., 2008). It is matter of intense research whether light or water is the limiting factor that controls plant growth over Amazonia. Considerable evidence demonstrates that sunlight indeed drives Amazon forest growth (Doughty et al., 2019; Huete et al., 2006; Myneni et al., 2007) although water deficit could be a limiting factor during severe droughts (Doughty et al., 2015; Feldpausch et al., 2016; Saatchi et al., 2013). Satellite observations show a clear seasonal cycle with a gradual crescendo in both leaf area and incoming surface sunlight beginning at the onset of the dry season (~August – November) (Myneni et al., 2007). Vegetation index maps also show that a majority of Amazonia is greener in the dry season than in the wet season (~mid-December – mid-May) (Huete et al., 2006). It is in the dry season, when light becomes a key-controlling factor for forest productivity, that the Amazon forest thrives.

Plant photosynthesis requires sunlight to reach the leaves of the canopy. While aerosols and clouds in the atmosphere decrease the total amount of light that reaches the canopy, they also increase scattering, thereby increasing the ratio of diffuse radiation to direct radiation. This is important because the efficiency of plant photosynthesis increases under diffuse sunlight – a phenomenon both explained theoretically (Rap et al., 2015; Roderick et al., 2001; Zhou et al., 2020) and observed in the field (Cirino et al., 2014; Doughty et al., 2010; Ezhova et al., 2018; Gu et al., 2003; Lee et al., 2018; Niyogi et al., 2004; Oliveira et al., 2007). Leaf photosynthesis increases nonlinearly with solar radiation, becoming saturated on bright days at light levels above which leaves cannot take more light (Gu et al., 2003; Mercado et al., 2009). Under clear and clean sky conditions, particularly around midday, sunlight is mainly direct, and while this allows the sunlit leaves on top to be light saturated, the shaded leaves below them receive relatively little sunlight and thus participate less in photosynthesis (Rap et al., 2015; Roderick et al., 2001). In contrast, under cloudy conditions or in the presence of aerosols, much of the midday light is diffuse, and diffuse light can penetrate deeper into the canopy and illuminate shaded leaves. Li and Yang (2015) conducted a chamber experiment to explore diffuse light on light distribution within a canopy and the resulting effects on crop photosynthesis and plant growth. They concluded that diffusion of the incident light improves spatial light distribution, lessens the variation of temporal light distribution in the canopy, and allows more light-stimulated growth of shade-tolerant potted plants.

The situation is more profound during the Amazon dry season when intensive seasonal fires release large amounts of primary aerosol particles as well as gas precursors that form secondary organic and inorganic aerosols. Using stand-alone radiation and vegetation models, Rap et al. (2015) concluded that fires over the Amazon dry season increase Amazon net primary production (NPP) by 1.4–2.8% by increasing diffuse radiation. This enhancement of Amazon basin NPP (78–156 Tg C a^{-1}) is equivalent to 33–65% of the annual regional carbon emissions from biomass burning and accounts for 8–16% of the observed carbon sink across mature Amazonian forests. Moreira et al. (2017) advanced this analysis by coupling an ecosystem module and aerosol model within a Eulerian transport model. Their study indicated that biomass burning aerosols lead to increases of about 27% in Amazonian Gross Primary Production (GPP) and 10% in plant respiration as well as a decline in soil respiration of 3 %. However, their approach assumes cloud-free conditions through their use of a diffuse irradiance parameterization based on the multiwavelength aerosol optical depth (AOD) measurement. Malavelle et al. (2019) explored the overall net impact of biomass burning aerosol on the Amazon ecosystem using an Earth System Model (ESM) (HadGEM2-ES). They estimated NPP to increase by +80 to +105 TgC yr^{-1}, or 1.9% to 2.7%, ascribing this net change to an increase in diffuse light, a reduction in the total amount of radiation, and feedback from climate adjustments in response to the aerosol forcing. Their study takes into account the dynamic feedback of short lifetime cloud fields. However, it does not address the role of Amazon background clouds and their interannual changes on the aerosol-ecosystem impact.

When clouds and aerosol co-exist, the impact from clouds on the ecosystem typically dominates because clouds are optically thicker. The surface sunlight for cloudy versus cloud-free conditions can differ greatly even if the AOD is the same. (Note that, unless specified otherwise, solar radiation in this study refers to the wavelength range of 400-700 nm, i.e., photosynthetically active radiation, or PAR). Measurements indicate that the desirable range of clearness index (CI) -- the fraction of incoming total sunlight that reaches the canopy -- is around 0.4-0.7 for some forest ecosystems and above 0.3 for peatland (Butt et al., 2010, Letts and Lafleur, 2005). Quite often a low CI occurs during a cloudy day, but on occasion it might result from the presence of a very thick aerosol layer. As suggested above, if CI is high, the diffuse fraction of the total solar radiation is low, and the overall productivity of the canopy is reduced. For example, Cirino et al. (2014) found that the net ecosystem exchange (NEE) of CO_2 is increased by 29% and 20% in two Amazon stations (the Jaru Biological Reserve (RBJ) and the Cuieiras Biological Reserve at the K34 Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) tower), respectively, when AOD is 0.1-1.5 at 550nm under clear conditions. Higher AOD (> 3) leads to a strong reduction in photosynthesis (via reducing PAR) up to the point where NEE approaches zero. Oliveira et al. (2007) found that Amazon forest productivity was enhanced under moderately thick smoke loading because of an increase of diffuse solar radiation, but large aerosol loading (i.e., AOD > 2.7) results in lower net productivity of the Amazon forest.

Despite its name, the Amazon's "dry season" (June-November) still features significant cloudiness, and the interannual variations in the clouds can be large. Furthermore, rain does fall during the dry season – close to 40% of the total annual precipitation falls therein. Clouds in the dry season are mostly formed by small-scale processes that influence the weather (see an example of a uniform layer of "popcorn" clouds observed by Moderate Resolution Imaging Spectroradiometer (MODIS) on 08/19/2009 in http://earthobservatory.nasa.gov/IOTD/view.php?id=39936). It is during this period, when sunlight (particularly diffuse light) drenches the trees due to reduced rain (and fewer clouds) relative to the wet season, that the forest grows the most. Consideration of the joint effects of clouds and biomass burning aerosols on diffuse and direct PAR during the dry season is thus particularly important.

This study has two objectives. First, we investigate how Amazon biomass burning aerosols (BBaer) affect the land productivity (i.e., GPP and NPP) via their impact on direct and diffuse PAR (DRPAR and DFPAR). Second, we investigate the sensitivity of the BBaer light fertilizer effect to the presence of the Amazon dry season cloud fields within the range indicated by the potential interannual variation of the clouds. We use in our analysis a version of the NASA

GEOS ESM that includes coupling between aerosol, cloud, radiation, and ecosystem processes. To our knowledge, only one other study has used an ESM to investigate such fire impacts across Amazonia (Malavelle et al., 2019), and as noted above, this study did not address the ability of Amazon clouds to temper the BBaer impacts. Accordingly, our study is the first ESM-based study to investigate the BBaer light fertilizer effect within a range of interannual Amazon cloud levels. Together our objectives provide a full and comprehensive study of BBaer light fertilizer effect in a context of potential Amazon dry season atmospheric conditions.

It is necessary to point out, however, that our study focuses only on the impact of Amazon biomass burning aerosol. We do not consider the radiative impacts of other potentially important aerosols. These other aerosol types have been examined in various observational studies (e.g., Cirino et al., 2014; Ezhova et al., 2018; Hemes et al., 2020; Wang et al., 2018, Yan et al., 2014) and model investigations that focus, for example, on anthropogenic aerosol (Keppel et al., 2016); O'Sullivan et al., 2016), dust (Xi et al., 2012), biogenic aerosol (Rap et al., 2018; Sporre et al., 2019), volcanic aerosol (Gu et al., 2003), and the general aerosol field (Feng et al., 2019).

The paper is organized as follows. Section 2 describes the NASA GEOS ESM and its relevant modules (section 2.1), the observational data used for model evaluation and explanation (section 2.2), and the experimental setup (section 2.3). Section 3 provides an evaluation of the model (section 3.1), basic theory regarding the impact of aerosol and cloud on the surface downward radiation (section 3.2), results regarding the simulated ecosystem response to BBaer-induced radiation changes (section 3.3), and the impacts of Amazon background clouds on this response (section 3.4). A final summary is provided in section 4.

2. Model description, data application, and experiment setup

2.1 Model description

The GEOS modeling system connects state-of-the-art models of the various components of the Earth's climate system together using the Earth System Modeling Framework (ESMF) (Molod et al., 2015; 2012; Rienecker et al., 2011; https://gmao.gsfc.nasa.gov/). We discuss here the components of the system that are particularly relevant to our study, including aerosol, cloud microphysics, radiative transfer, and land ecosystem modules.

GEOS Goddard Chemistry Aerosol Radiation and Transport (GOCART) simulates a number of major atmospheric aerosol species and precursor gases from natural and anthropogenic sources, including sulfate, nitrate, ammonium, black carbon (BC), organic aerosol (OA, including primary and secondary OA), dust, sea salt, dimethyl sulfide (DMS), SO_2, and NH_3 (Bian et al., 2010, 2013, 2017, 2019; Chin et al., 2009, 2014; Colarco et al., 2010, 2017; Murphy et al., 2019; Randles et al., 2013). Monthly emissions from shipping, aircraft, and other anthropogenic sources are obtained from the recent CMIP6 CEDS emission inventory. Daily biomass burning emissions are provided by GFED4s (https://daac.ornl.gov/VEGETATION/guides/fire_emissions_v4.html). Estimates of degassing and eruptive volcanic emissions are derived from Ozone Monitoring Instrument (OMI) satellite (Carn et al., 2017). Emissions of dust, sea salt, and DMS are dynamically calculated online as a function of the model-simulated near-surface winds and other surface properties. A more recent augmentation of GOCART relevant to this study involves the modification of the absorbing

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properties of "brown carbon" (Colarco et al., 2017). The simulation of primary organic carbon (POA) and secondary organic carbon (SOA) is particularly important for this study. Previous versions of GOCART in GEOS were simple regarding SOA productions, relating biogenic SOA to a prescribed "climatological" monthly terpene emission – SOA production was assumed to be 10% of terpene emission (i.e., SOA yield of 10%). The new version calculates the emission of VOCs online as a function of light and temperature using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.1 (Guenther et al., 2012). The biogenic SOA is then derived by applying an SOA yield of 3% to isoprene and 5% to monoterpene following the suggestion of Kim et al. (2015). This newer version of GOCART also introduces a parameterization of SOA from anthropogenic and biomass burning sources based on Hodzic et al. (2011) and Kim et al. (2015).

The GEOS two-moment cloud microphysics module is used in this study. The module includes the implementation of a comprehensive stratiform microphysics module, a new cloud coverage scheme that allows ice supersaturation, and a new microphysics module embedded within the moist convection parameterization (Barahona et al., 2014). At present, aerosol number concentrations are derived from the GEOS/GOCART-calculated aerosol mass mixing ratio and prescribed size distributions and mixing state, which are then used for cloud condensation nuclei (CCN) activation (following the approach of Abdul-Razzak and Ghan, 2000) and ice nucleation (following the approach of Barahona and Nenes, 2009) processes. Aerosol-cloud interactions are thus accounted for in our simulation. The model calculates various cloud properties, including cloud fraction, cloud droplet and ice crystal number concentrations and effective radii, and cloud liquid and ice water paths. These fields have been evaluated against satellite observations and field measurements; the model shows a realistic simulation of cloud characteristics despite a few remaining deficiencies (Barahona et al., 2014, Breen et al., 2020).

The current default GEOS solar radiation transfer module is the shortwave rapid radiation transfer model for GCMs (RRTMG_SW), a correlated k-distribution model (Iacono et al., 2008). This GCM version utilizes a reduced complement of 112 g-points, which is half of the 224 g-points used in the standard RRTMG_SW, and a two-stream method for radiative transfer. Total fluxes are accurate to within 1-2 W/m^2 relative to the standard RRTMG_SW (using DISORT) with aerosols in clear sky and within 6 W/m^2 in overcast sky. RRTMG_SW with DISORT is itself accurate to within 2 W/m^2 of the data-validated multiple scattering model, CHARTS. RRTMG_SW specifically calculates the direct and diffuse components of PAR (400-700 nm) separately. The GEOS atmospheric radiative transfer calculation is designed in a way that allows users to examine the impact of various combinations of atmospheric aerosol and cloud fields on radiation. In addition to the standard calculation of solar radiation for ambient atmospheric conditions, diagnostic calculations can be carried out by repeating the calculation of the radiation transfer scheme with different combinations of atmospheric conditions: clean air (no aerosols), clear air (no clouds), and clean plus clear air. Using this architecture, for this study we modify the radiation scheme to allow the additional diagnosis of radiation fields under conditions of zero BB-aerosols but retained non-BB-aerosols and ambient clouds.

The catchment land surface model (LSM) with carbon and nitrogen physics (Catchment-CN) in GEOS is in essence a merger of the C-N physics within the NCAR–DOE Community Land Model (CLM) (Oleson et al. 2010, 2013; Lawrence et al., 2019) version 4.0 and the energy and

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water balance calculations of the NASA GMAO catchment LSM (Koster et al. 2000). The original NASA catchment LSM used a prescribed representation of phenology (leaf area index, or LAI, and greenness fraction) to compute the canopy conductance, the parameter describing the ease with which the plants transpire water. In Catchment-CN, photosynthesis and transpiration depend non-linearly on solar radiation. The canopy is assumed to consist of sunlit leaves and shaded leaves, and the DRPAR and DFPAR absorbed by the vegetation is apportioned to the sunlit and shaded leaves as described by Thornton and Zimmermann (2007). The prognostic carbon storages underlying the phenological variables are computed as a matter of course along with values of canopy conductance that reflect an explicit treatment of photosynthesis physics. These canopy conductances, along with the LAIs diagnosed from the new carbon prognostic variables, are fed into the energy and water balance calculations in the original catchment LSM. The output fluxes from the merged system include carbon fluxes in addition to traditional fluxes of heat and moisture. The merger of the two models allows Catchment-CN to follow 19 distinct vegetation types. Koster and Walker (2015) have used Catchment-CN within an atmospheric global circulation model (AGCM) framework to investigate interactive feedback among vegetation phenology, soil moisture, and temperature. In this study, the modeled atmospheric CO_2 from the AGCM is used to drive the carbon, water, and energy dynamics in the Catchment-CN model.

In addition to the GEOS ESM, we use a photolysis scheme, FastJX, in its stand-alone mode to explore how incoming solar radiation penetrates the atmosphere in the presence of aerosols and clouds in order to enhance our basic understanding of the role of atmospheric particles on radiation. FastJX is based on the original Fast-J scheme, which was developed for tropospheric photochemistry with interactive consideration of aerosol and cloud impacts at 291–850 nm (Wild et al., 2000), and Fast-J2, which extended the scheme into the deep UV spectrum range of 177-291 nm (Bian and Prather, 2002).

2.2 Observational data

We mostly rely on the GoAmazon ("Green Ocean Amazon") field campaign (http://campaign.arm.gov/goamazon2014/) for in situ site-level aerosol surface observations and local-area vertical distribution measurements used to assess the model OA concentrations. GoAmazon is an integrated field campaign conducted in the central Amazon Basin (Martin et al., 2010). Specifically, we use the surface OA concentration measured in 2014 by the Aerosol Chemical Speciation Monitor (ACSM) operated by the Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) Mobile Facility located 70 km downwind of Manaus, Brazil (Ng et al., 2011). We also use the measurement of surface CO volume mixing ratio in 2014 at Manaus by Los Gatos Research (LGR) N_2O/CO Analyzer that uses LGR's patented Off-axis Integrated Cavity Output Spectroscopy (ICOS) technology. Also used is the vertical profile of OA concentration measured by a time-of-Flight Aerosol Mass Spectrometer (ToF-AMS) instrument on the ARM Aerial Facility Gulfstream-1 (G-1) aircraft during the dry season of 2014 (Sept 06-Oct 04, 2014) (Shilling et al., 2018). The G-1 aircraft was based out of the Manaus International airport and flew patterns designed to intersect the Manaus urban plume at increasing downwind distance from the city (e.g., 59-61°W and 4-2.5°S). In addition, we evaluate the model with AOD and single scattering albedo (SSA) measurements taken at a central Amazon station (Alta_Floresta) in the ground-based Aerosol Robotic Network (AERONET) sun photometer network (http://aeronet.gsfc.nasa.gov). We also use MODIS

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collection 6.1 level-3 AOD product (http://modis.gsfc.nasa.gov/data/dataprod/index.php), which is characterized by observations with large spatial coverage.

MODIS cloud products (https://modis-atmosphere.gsfc.nasa.gov/data/dataprod/), specifically total cloud fraction and cloud optical depth in liquid and ice particles, were used to evaluate the model cloud simulation. We use the cloud data from MODIS collection 6.1 MYD08_D3, a level-3 1°×1° global gridded monthly joint product derived from the MODIS level-2 pixel level products. MODIS level 2 cloud fraction is produced by the infrared retrieval methods during both day and night at a 5×5 1-km-pixel resolution. Level 2 cloud optical thickness used in this study is derived using the MODIS visible and near-infrared channel radiances from the Aqua platform.

The satellite-derived Clouds and the Earth's Radiant Energy System product CERES-EBAF was used to evaluate the GEOS simulation of radiation fields. CERES-EBAF retrieves surface downward shortwave radiation (R_{SFC}) using cloud information from more recent satellite data (MODIS, CERES, CloudSat and CALIPSO) and aerosol fields from AERONET/MODIS validation-based estimates (Kato et al., 2013). This global product is provided at a 1°×1° horizontal resolution and covers the years 2000-2015 for both all- and clear-sky conditions. The multiyear R_{SFC} products provide both a regional and a time evolution view of radiation over Amazonia.

Two observations-based GPP products were used to evaluate the GEOS ecosystem simulations. Through upscaling using machine learning methods (Jung et al., 2020), the FluxCom GPP product provides globally distributed eddy-covariance-based estimates of carbon fluxes between the biosphere and the atmosphere. FluxSat GPP is estimated with models that use satellite data (e.g., MODIS reflectances and solar-induced fluorescence (SIF)) within a simplified light-use efficiency framework (Joiner et al., 2018). We used monthly GPP for August through October of 2010-2015 in this study.

2.3 Experiment setup

All experiments were run with the coupled atmosphere and land components of the NASA GEOS ESM system discussed above. The sea surface temperature (SST) for the atmospheric dynamic circulation is provided by the GEOS Atmospheric Data Assimilation System (ADAS) that incorporates satellite and in situ SST observations and assimilates Advanced Very High Resolution Radiometer (AVHRR) brightness temperatures. The experiments were run in replay mode, which means that the model dynamical variables (winds, pressure, temperature, and humidity) were set, every 6 hours, to the values archived by the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) meteorological reanalysis (Gelaro et al. 2017); a 6-hourly forecast provided the dynamical and physical fields between the 6-hour resets. In effect, the replay approach forces the atmospheric "weather" simulated in the model to agree with the reanalysis. All designed experiments were run over 2010-2016, a period that includes La Niña (2010-2011), El Niño (2015-2016), and neutral years as indicated by the Oceanic Niño Index (ONI, https://origin.cpc.ncep.noaa.gov/).

Our experimental design makes extensive use of GEOS's highly flexible configuration. First, the GEOS GOCART module includes a tagged aerosol mechanism. Each specific aerosol

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component in GOCART is simulated independently from the others, and the contribution of each emission type to the total aerosol mass is also not interfered by that of other emission types. Thus, additional aerosol tracers can easily be "tagged" according to emission source types. This makes it possible for GOCART to calculate and transfer two sets of aerosol fields (e.g., one with and one without a biomass burning source) to the radiation module. Second, the radiation module can in turn calculate a set of atmospheric radiation fields corresponding to each set of aerosol fields, and it can then disseminate both sets of radiation fields to the various components of interest (i.e., cloud module, land ecosystem module, etc.) according to the needs of our experiments (see below).

Table 1 provides a brief summary of the experiments performed for this study. First, we designed a pair of experiments (allaer and nobbaer, hereafter referred to as "pair1") to explore the BBaer light fertilizer effect on the land productivity via PAR (objective 1). The allaer and nobbaer experiments are designed to simulate the same atmospheric dynamics but send different PAR fluxes into the Catchment-CN model. Specifically, both the allaer and nobbaer experiments used all atmospheric aerosols including real-time biomass burning emissions over 2010-2016 to calculate a set of radiation fields (R^1) to drive atmospheric circulation; however, with the help of GEOS's flexible configuration, the nobbaer experiment also calculated a second set of radiation fields (R^2) that used non-BB aerosols only. R^1 was sent to Catchment-CN in the allaer experiment whereas R^2 was sent to Catchment_CN in the nobbaer experiment. In this way, the only difference between the allaer and nobbaer experiments was the PAR fluxes used to drive the ecosystem model – only the PAR fluxes used in allaer reflected the presence of biomass burning aerosols. The atmospheric meteorological fields in the two experiments, including clouds, skin temperature, and soil moisture, show only minor differences stemming from land feedback (Figure S1-2, Table S1e and Table S2e).

Table 1. Designed experiments (2010-2016) with their perturbation on aerosol fields and subsequent impact on radiation and ecosystem

Exp Name		Aerosol	R in RRTMG	R driving circulation	R driving Catchment-CN	Purpose
Pair 1	allaer	Standard all, w/ Realtime AERbb emission	R^1_{top}, R^1_{dir}, R^1_{diff} (all aerosol)	R^1_{top}, R^1_{dir}, R^1_{diff}	R^1_{dir}, R^1_{diff}	Check atmospheric BB aerosol impact on plants via radiation fields during 2010-2016
	nobbaer		R^1_{top}, R^1_{dir}, R^1_{diff} (all aerosol) R^2_{top}, R^2_{dir}, R^2_{diff} (all non-bb aerosol)	R^1_{top}, R^1_{dir}, R^1_{diff}	R^2_{dir}, R^2_{diff}	
Pair 2	callaer	Standard all, w/ AERbb emission fixed at 2010	R^1_{top}, R^1_{dir}, R^1_{diff} (all aerosol)	R^1_{top}, R^1_{dir}, R^1_{diff}	R^1_{dir}, R^1_{diff}	Check how clouds adjust the above impact
	cnobbaer		R^1_{top}, R^1_{dir}, R^1_{diff} (all aerosol) R^2_{top}, R^2_{dir}, R^2_{diff} (all non-bb aerosol)	R^1_{top}, R^1_{dir}, R^1_{diff}	R^2_{dir}, R^2_{diff}	

We also designed a pair of experiments (callaer and cnobbaer, hereafter referred to as "pair2") to address the sensitivity of the BBaer light fertilizer effect to the presence of the Amazon dry season cloud fields (objective 2). The pair2 experiments are similar to those in pair1 except that the particular BB emissions of year 2010 were repeated during all seven years. Applying a fixed aerosol emission allows us to attribute the interannual variation of the ecosystem solely to the influence of interannual variations in atmospheric metrological fields, including clouds. In addition, combining the pair1 and pair2 experiments provides two biomass burning aerosol emissions for each year except 2010, which allows us to compare the impacts of different emissions under similar meteorological environments (Figure S1-2, Table S1e and Table S2e).

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Given that the experiment period covers strong La Niña and El Niño years, we can examine BBaer impacts on ecosystem productivity under the full range of Amazon background cloud fields.

3. Results and Discussion

3.1 Evaluation of GEOS simulations of aerosol, cloud, radiation, and ecosystem response

The NASA GEOS ESM model, including its aerosol, cloud, radiation, and ecosystem modules as used in the baseline simulation (i.e., experiment allaer), has been evaluated extensively and utilized in a number of scientific studies. However, a majority of the aerosol studies have focused on the simulation of aerosols over the Northern Hemisphere. Past studies with GEOS have not provided a detailed model evaluation over South America during our study period. We provide such an evaluation here.

The simulated tracer fields are compared with measurements over the Amazon in Figures 1 and 2. Figure 1 shows results for surface OA concentration, surface CO concentration, and the OA concentration vertical profile. We focus primarily on the OA evaluation since we are interested in biomass burning aerosols from fires. Figure 1a shows the comparison of surface daily OA concentration between the model simulation and the GoAmazon measurements at Manaus, Brazil, in 2014 (The location is indicated in Figure 2c with an open-diamond). The simulated OA broadly captures the seasonal trend in OA concentrations measured at the ARM site, but it is lower than observed OA values by ~24% during Sept-Oct and ~ 30% annually. For the period of interest, the model simulates a large fire signal in August that is not seen in the measurements. However, this strong August biomass burning signal does show up in the GoAmazon CO measurements (Figure 1b). Generally, it is challenging for a model to capture an aerosol plume, particularly one from biomass burning, at the right time and location due to the aerosols' high spatial inhomogeneity and short lifetime.

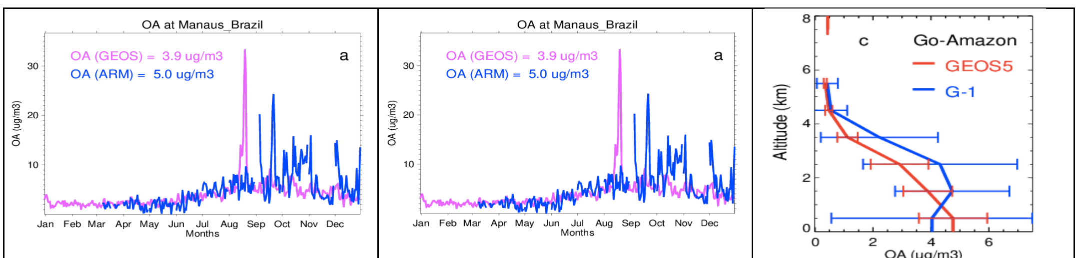

Figure 1. (a) Comparison of the ACMS measured organic aerosol (OA) daily surface mass concentration at the GoAmazon DOE ARM facility in Manaus, Brazil in 2014 with GEOS simulated values. (b) Similar to (a) but for carbon monoxide (CO) volume mixing ratio. (c) GoAmazon G-1 aircraft measurement of vertical OA mass concentration during Sept 6 -Oct 4, 2014, compared to GEOS simulations. The location of the station Manaus is marked in Figure 2c as an open-diamond.

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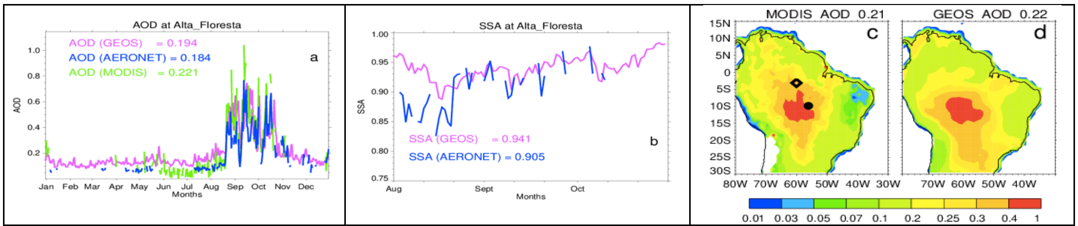

Figure 2. (a) Comparison of GEOS simulated AOD simulation with AERONET and MODIS daily measurements at the Alta Floresta AERONET site for 2014. (b) similar comparison for aerosol single scattering albedo at 440nm during Aug-Oct, 2014. (c) Mean MODIS collection 6.1 AOD during the period Aug-Oct, 2014. (d) GEOS simulated AOD for the same period as in (c) with daily model data sampled following MODIS measurements. Note that the mean AOD values shown for (c) and (d) are averaged over the Amazon region (i.e. the land area within 80°W-30°W, 25°S-5°N). Station locations of Alta Floresta (filled-circle) and Manaus (open diamond) are marked in (c).

When compared with aircraft G-1 measurements over a ~2°×2° region around the center of Manaus during the biomass burning season (Sept. 6 – Oct. 4, 2014) (Figure 1c), the simulated vertical OA concentrations underestimate the measurements in the free troposphere but overestimate them in the boundary layer, although they overlap within their standard deviations for all altitudes. Here the model data have been sampled spatially and temporally along the G-1 flight paths. This surface OA overestimation by the model seems to contradict the model's underestimation seen in Figure 1a, indicating again that capturing aerosols at the right times and locations is a challenge.

Figure 2 shows the AOD (550nm) and SSA (440nm) comparison at a specific station and over South America. We consider AERONET observational data at Alta_Floresta, which is located close to the central Amazon fires (The location is marked in Figure 2c as a filled-in circle). The model-simulated, AERONET-measured, and MODIS-retrieved AOD at this site agree within 20% (Figure 2a), and all show a peak of AOD during the biomass burning season. SSA during the burning season generally ranges between 0.85 – 0.95 (Figure 2b). The model agrees with the measurements well except during the first half of August, when the model aerosols are too scattering. However, it is puzzling to observe the extremely low measured SSA in the beginning of August given that the AOD is still low then, as shown in Figure 2a. Regionally over the Amazon region, defined throughout the study as the land area within 80°W-30°W, 25°S-5°N, the model-simulated AOD (0.22 in Figure 2d) during the biomass burning season generally agrees with MODIS satellite retrievals (0.21 in Figure 2c). A simulated high bias is seen over the east Amazon; however, though this region is in our area of interest, the bias should have only a minor impact on our study given that the area is relatively bare, with little vegetation coverage.

The accurate simulation of cloud fields is also important for our study. In Figure 3 we evaluate the GEOS-simulated cloud cover fraction and cloud optical depth with MODIS satellite products. Here the GEOS data have been sampled with MODIS overpass time and location. GEOS generally captures the magnitude and main features of the cloud fields observed in MODIS, though with some differences; the model overestimates the cloud quantities over the central Amazon and underestimates them in northwest South America. The overall difference over the Amazon region between simulated and MODIS-based estimates is less than 7% for cloud cover fraction, 10% for liquid water cloud optical depth, and 15% for ice cloud optical

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depth. It is worth mentioning that cloud quantities are notoriously difficult to retrieve over the Amazon, and thus these differences are within the margin of error of the retrievals.

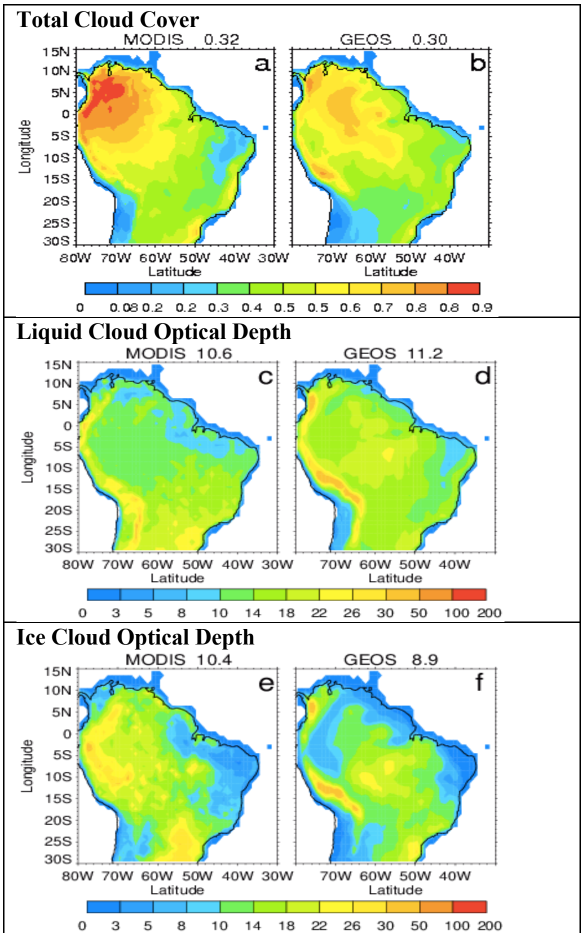

Figure 3. Multiyear seasonal (Aug-Oct, 2010-2016) cloud field comparison between MODIS retrieved (a,c,e) and GEOS simulated (b, d, f) total cloud cover (a,b), liquid cloud optical depth (c, d), and ice cloud optical depth (e, f).

Figure 4 shows a comparison between the simulated downward shortwave radiation at the surface and CERES-EBAF measurements averaged over Aug-Oct., 2010-2016 for both clear-sky and all-sky conditions. GEOS captures the observed spatial patterns with ~4% high bias for both clear and all sky conditions over the Amazon region.

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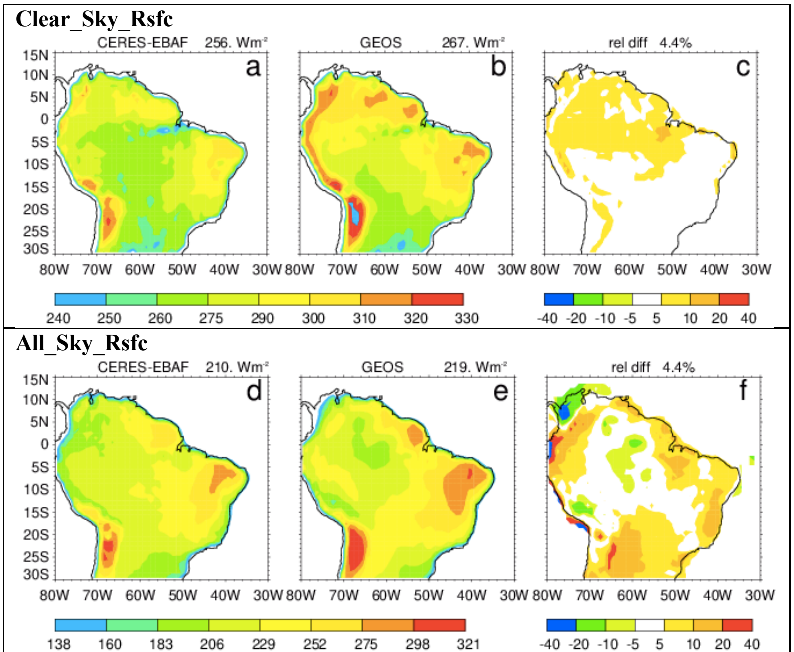

Figure 4. Comparison of surface downward shortwave radiation Rsfc (Wm^{-2}) between CERES-EBAF measurement and GEOS simulation averaged over Aug-Oct., 2010-2016 for clear-sky (upper panel, a, b) and all-sky (bottom panel, d, e) conditions. The right column (c, f) shows the relative difference between GEOS and CERES-EBAF.

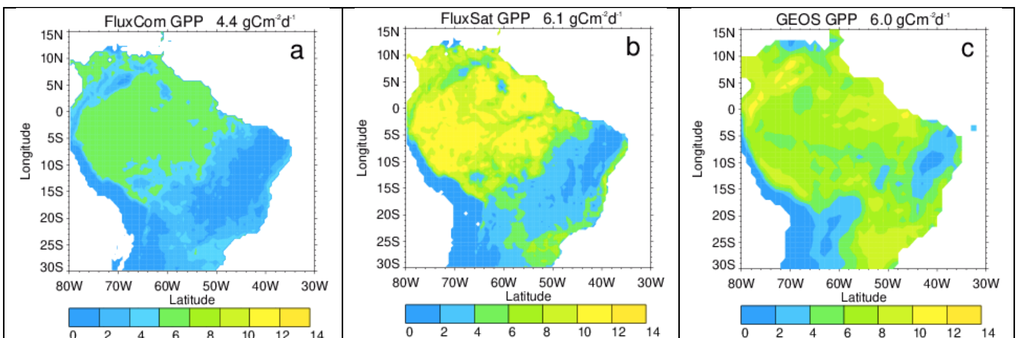

Figure 5. The multi-year (2010 – 2015) August – October mean Amazon GPP from (a) FluxCom (Jung et al., 2020), (b) FluxSat (Joiner et al., 2018) and (c) the GEOS ecosystem simulation with unit of gC m^{-2} day^{-1}. The Amazon regional average value is shown in the top.

Figure 5 shows GPP averaged over August to October of 2010-2015 from the two observations-based products (i.e., FluxCom and FluxSat) and the GEOS simulation. As we mentioned in section 2.2, FluxCom GPP is derived from surface measurements of carbon fluxes while FluxSat GPP is derived from satellite data. The overall spatial distributions of GEOS GPP (Figure 5c) over South America are similar to both of the observations-based datasets (Figures 5a and 5b)

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with higher values over the eastern part of the domain but lying between the two datasets in other areas. Over the studied period and the Amazon region, the GEOS GPP is comparable to the FluxSat GPP and is about 35% higher than the FluxCom GPP.

3.2 Principle of aerosol and cloud impact on surface downward radiation

Radiative responses to aerosols and cloud fields are nonlinear. To better explain the phenomenon examined here – that plant growth increases at low-to-intermediate AOD but decreases at high AOD – we ran the column version of a radiation model, fast-JX (Bian and Prather, 2002). The model calculations provide two ratios: (i) CIdir, the ratio of direct downward solar radiation at the surface (R_{dir}) to the incoming total solar radiation flux at the top of the atmosphere (R_{top}), and (ii) CIdiff, the ratio of the downward diffuse solar radiation flux (R_{diff}) to R_{top}. Results for different biomass burning AODs (including the clean air condition, where AOD = 0) for cloud-free conditions are shown in Figure 6a. When the sky is clear and clean (both cloud-free and without aerosols), roughly 90% of the incoming solar radiation at the top of the atmosphere can reach the plant canopy (i.e., CIdir + CIdiff ≈ 0.9 at BBAOD = 0). The direct solar flux decreases rapidly as the atmosphere becomes polluted (i.e., as BBAOD increases), but for BBAOD levels less than ~0.75, the majority of this reduction is compensated by an increase in the diffuse solar flux. The two are equivalent at AOD ~ 0.5. This light redistribution from direct to diffuse can significantly stimulate plant photosynthesis given that plants use diffuse light more efficiently. Ecosystems could still respond positively to increasing BBAOD even if the incident diffuse radiation diminishes below its peak value, though for some value of BBAOD, the reduction in total radiation will be large enough to overwhelm the impact of increased diffuse radiation, and plant photosynthesis will be lower than that for clean sky conditions.

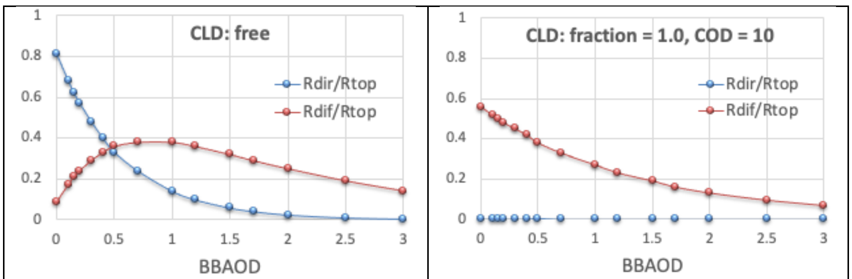

Figure 6. The ratio of R_{dir} to R_{top} (blue), which presents clearness index of direct radiation portion (CIdir) and the ratio of R_{diff} to R_{top} (red) for diffuse radiation portion (CIdiff). Here, R_{top} is incoming total solar flux at the top of atmosphere (TOA), R_{dir} is surface downward direct solar flux, and R_{dif}f is surface downward diffuse solar flux. All Rs are over 400-700 nm. Left: there is a layer of biomass burning derived aerosol varying in AOD (BBAOD) under clear sky condition. Note that when BBAOD = 0, the sky is clear and clean. Right: atmosphere has a layer of biomass burning aerosol underneath a layer cloud with the cloud fraction 1.0 and cloud optical depth of 10. Calculations use fast-JX radiation model column version adopting a standard atmospheric condition of typical tropics at ozone column = 260 DU, SZA = 15°N and surface albedo = 0.1.

The Amazon dry season is characterized by high biomass burning aerosol loading combined with low cloud cover, a good match to obtain more diffuse radiation without the loss of too much total radiation. However, as we have pointed out, cloud impacts on radiation typically dominate those

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of aerosols. To examine this, we repeated the radiation model calculations after adding, at the top of the aerosol layer, a cloud layer with a cloud fraction of 1.0 and a cloud optical depth (COD) of 10, which is close to the mean liquid cloud COD over the Amazon dry season (Figure 3). The impact on R_{dir} and R_{diff} is quite large (Figure 6b). Without BBaer, the clouds already fill the sky with abundant diffuse light that can reach the surface (i.e., CIdiff > 50%), while almost shutting down the direct light (i.e., CIdir < 1%). Accordingly, for full cloud coverage, a clean sky (i.e., no aerosols) would provide the best conditions for plant growth. When fires start, the diffuse light declines rapidly, reducing the potential for plant growth. At BBAOD ~ 3 the two curves look similar, that is essentially no radiation at the surface.

The simple examples in Figure 6 illustrate the complicated responses of direct and diffuse light to the presence of aerosol and cloud. Measurements indicate that plant growth peaks for a clearness index (CI, defined as CIdir+CIdiff) of about 0.4-0.7 for some forest ecosystems (Butt et al., 2010, Letts and Lafleur, 2005). This CI range translates, based on Figure 6, to a BBAOD range of about 0.3~1.5 in clear sky and 0~0.5 in cloudy-sky conditions.

3.3 How the ecosystem responds to the BBaer light fertilizer effect

We first examine the two pair1 experiments by taking a close look at the time series of aerosol, cloud, radiation, and ecosystem responses generated at a selected site (54°W, 15°S) during Aug-Oct 2010 (Figure 7) (site location marked in Figure 8), with the aim of extending the general

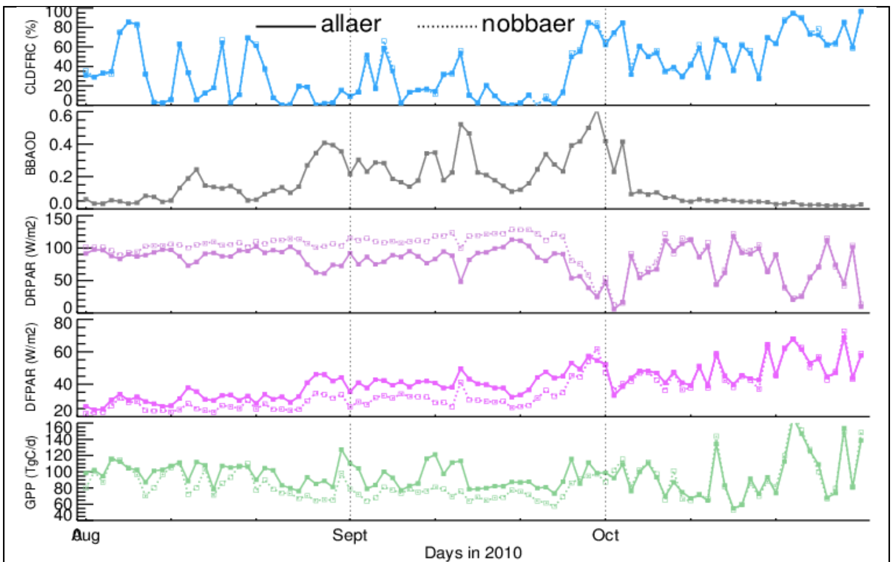

Figure 7. GEOS simulated daily values of total cloud fraction (CLDFRC, %), biomass burning AOD (BBAOD), direct PAR (DRPAR, Wm^{-2}), diffuse PAR (DFPAR, Wm^{-2}), and gross primary growth (GPP, TgC/d) from the two experiments of pair1 at a selected site (54°W, 15°S) marked as diamonds in Figure 8 during Aug-Oct 2010.

understanding gained in section 3.2 to a real case study at a single site in the Amazon. This is an interesting site and period, showing a large DFPAR change (Figure 8f) and providing a wide variety of conditions for study – the sky alternates between clear and cloudy conditions in August, is relatively clear in September, and is relatively cloudy in October, and the biomass

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burning aerosols increase in August, peak in September, and diminish greatly in early October (Figure 7). During August-September, when the atmosphere experiences biomass burning pollution, the allaer (with BBAOD light fertilizer) and nobbaer (without BBAOD light fertilizer) results differ significantly: DRPAR for allaer (solid line) lies below that for nobbaer (dotted-line), while DFPAR and GPP for allaer are generally higher than those for nobbaer. In October, the sky is almost clean (i.e., low BBaer), leading to very similar results for DRPAR, DFPAR, and GPP between the two experiments. Looking closer, we see that the changes of DRPAR, DFPAR, and GPP between allaer and nobbaer are more prominent when the atmosphere has low cloudiness and high aerosol (e.g., at the end of August), confirming both that BBaer does transform some of the direct light at the surface into diffuse light and that plants are more efficient in their use of diffuse light. When both cloudiness and aerosols are high (e.g., at the end of September), the influence of aerosols is overwhelmed by clouds, and the impact of the aerosols on radiation and the ecosystem becomes secondary.

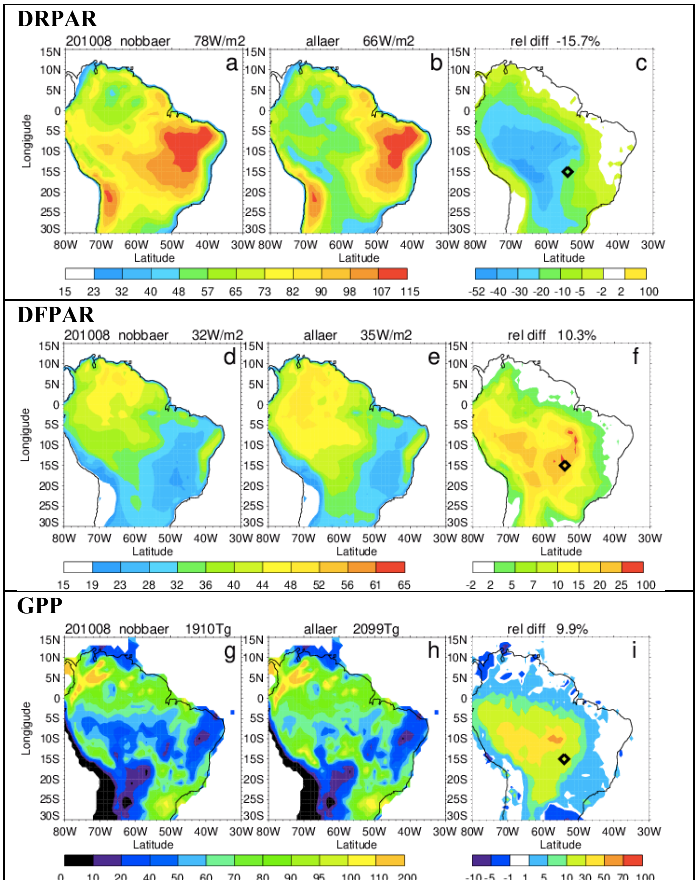

Figure 8. August 2010 Amazon DRPAR (W m-^{2}) (a, b, c), DFPAR (W m-^{2}) (d, e, f), and GPP (kg m^{-2} s^{-1}) (g, h, i) from the nobbaer (a, d, g) and allaer (b, e, h) GEOS experiments. The (c, f, i) shows the relative change between allaer and nobbaer. All values are the Amazon regional average except the GPP values of (g, h) are regional total. Further analyses on the (c, f, i) diamond locations are given in Figure 7.

We now evaluate BB aerosol impacts on radiation and ecosystem fields over the Amazon during August 2010, when the aerosol has its largest impact. Figure 8 shows the simulated Amazon DRPAR, DFPAR, and GPP fields from the two experiments comprising pair1 (nobbaer and allaer). The distribution of DRPAR shows a clear spatial gradient, with low values in the northwest and high values in the southeast, and the spatial pattern of DFPAR shows the reverse pattern. These features are primarily controlled by the cloud distribution (Figure 3). Comparing the nobbaer and allaer results by calculating field relative change (i.e., (allaer-nobbaer)/allaer), we find that BBaer decreases DRPAR by 16% and increases DFPAR by 10% over the Amazon region, with maximum local changes of up to -50% for DRPAR and 25% for DFPAR. Interestingly, these maxima are not co-located, though the spatial patterns of perturbations do agree with each other. The mismatch in the locations of the maxima in the difference fields implies a nonlinear response of direct and diffuse light to aerosol and cloud particles (see section 3.2). In response to the inclusion of BBaer, the Amazon GPP increases by 10%. That is, the increase in GPP stemming from the increase in the diffuse light fraction overwhelms a potential reduction in GPP from a reduction of total PAR.

We also examine the multi-year (2010-2016) BBaer impacts on net primary production (NPP), that is, the rate at which carbon is accumulated (GPP) in excess of autotrophic respiration. In essence, NPP can be considered a proxy for the net plant sink of atmospheric carbon. Figure 9 shows monthly and long-term averaged NPP over the Amazon Basin from the two experiments comprising pair1. The monthly change of NPP (i.e., dNPP = NPP(allaer) – NPP(nobbaer)) is shown in the figure as a green line. Each year, during the August-September period when BBaer is high and cloudiness is low over the Amazon, BBaer is seen to enhance NPP. The percentage difference of annually-averaged NPP (dNPP/NPP(nobbaer)*100) in % is 4.2, 0.06, 1.9, 0.5, 1.3, 1.9, and 1.0 for the seven studied years. That means the BBaer-induced NPP increases range from 5 TgC yr^{-1} or 0.06% (2011) to 278 TgC yr^{-1} or 4.2% (2010), with a seven-year average of 92 TgC or 1.5%. This is equivalent to storing 92TgC annually within the Amazon ecosystem during the studied period.

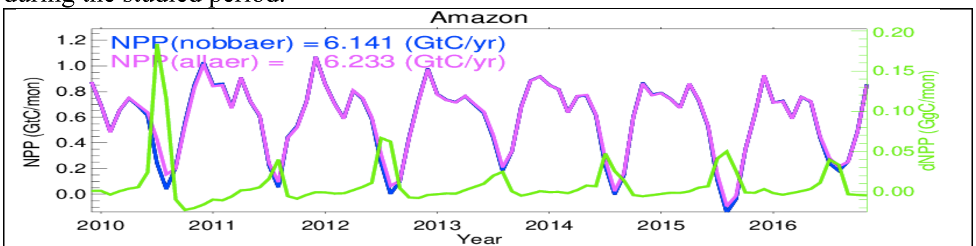

Figure 9. Monthly net primary product (NPP) over the Amazon basin (i.e. the land area of 80W-30W, 25S-5N) for the allaer (magenta-solid) and nobbaer (blue-solid) GEOS simulations with the multiyear mean values indicated in the legend. The monthly difference of NPP (dNPP = NPP(allaer) – NPP(nobbaer)) is shown by the green line and the right y-axis.

The CO_2 fire emission data from the GFED4.1s emission inventory indicate that over this area and time period, fires emit ~250TgCyr^{-1}. The NPP enhancement due to the BBaer-induced diffuse sunlight fertilization thus compensates for about 37% of carbon loss by fires. Our estimates of NPP increases across the Amazon region have a larger interannual range (0.5-4.2%) than that (1.4-2.8%) reported by Rap et al. (2015), although our seven-year averaged NPP increase (1.5%) lies within their range. This is consistent with our study's use of a larger interannual variation of biomass burning emissions into the real atmosphere (e.g., ~ 6x interannual difference in Amazon OC emission during Aug-Sept, 2010-2016, compared to 3x assumed in Rap et al. (2015)).

3.4 How clouds adjust the BBaer sunlight fertilizer effect

Our second objective in this study is to investigate how the presence of clouds affects the ability of BBaer to affect GPP. We highlight the cloud impact because even at the same biomass burning aerosol optical depth (BBAOD), the surface downward DRPAR and DFPAR can be very different between cloudy and cloud-free conditions (see section 3.2). As mentioned above, the Amazon's so-called "dry season" still features a considerable amount of cloud, and the cloudiness levels vary significantly from year to year. This raises some questions: How do clouds affect the aerosol impact on radiation fields during the Amazon biomass burning season? Could different levels of background clouds have different impacts on the efficacy of the BBaer light fertilizer effect? Here, to quantify the cloud influence, we examine BBaer impacts during clear-sky (cloud cover < 0.1), cloudy-sky (cloud cover 0.1-0.3, 0.3-0.6 and >0.6), and all-sky conditions based on gridded daily cloud cover over the Amazon region. Figure 10 provides monthly averaged fields of cloud, aerosol, radiation, and GPP over the Amazon basin during the seven years from the two pair1 experiments, with results for the five cloudiness conditions shown separately. The numbers marked in (a)-(d) are the percentage occurrence frequency of the corresponding cloud cover over the Amazon basin in each month. The differences in the radiation and ecosystem quantities between the two pair1 experiments (shown as dotted lines) are labeled as dDRPAR, dDFPAR, and dGPP.

Generally, the curves for BBAOD (solid black line) and dGPP (dotted light-blue line) are strongly (and positively) correlated, from R = 77.4% for cloud cover > 0.6 (Figure 10d) to R > 94.5% for the four other cloudiness conditions (Figure 10a-c, e). This indicates that interannual changes in dGPP are primarily controlled by interannual fluctuations of biomass burning aerosols. The correlation presumably stems from the fact that biomass burning aerosols increase the diffuse PAR reaching the canopy (dotted pink line) although they decrease the total PAR (dotted purple line) via decreasing direct PAR (Table S1a). This aerosol-radiation-GPP relationship is seen to vary with cloud amount, with clouds acting to reduce the aerosol impact; both the diffuse radiation and the GPP show larger changes with BBAOD under clear sky conditions. The overall (i.e., all-sky) aerosol impact on dGPP is similar to that for a cloud coverage of 0.3-0.6, presumably because the averaged cloud coverage over the Amazon during the studied period is roughly in that range.

Figure 10 and Table S1e show that on an interannual (dry season) basis, the aerosol light fertilizer effect differed the most between 2010 and 2011 (i.e., the dGPP was 8.7% in 2010 and 1.8% in 2011). During these two years, the cloud fraction (CLDFRC) decreased slightly from 42% (2010) to 41% (2011), but BBAOD decreased significantly, by about 80% from 0.198 in 2010 to 0.042 in 2011. Thus, although cloudiness does temper the impact of aerosols on radiation and the ecosystem, the interannual variations of cloudiness in the Amazon (at least during the period we studied) have only a secondary impact on the interannual variations of the aerosol light fertilizer effect. The interannual variation of the aerosol light fertilizer effect is primarily controlled by variations in biomass burning aerosols (e.g., > 6 times variation of biomass burning emissions and BBAOD, table S1e).

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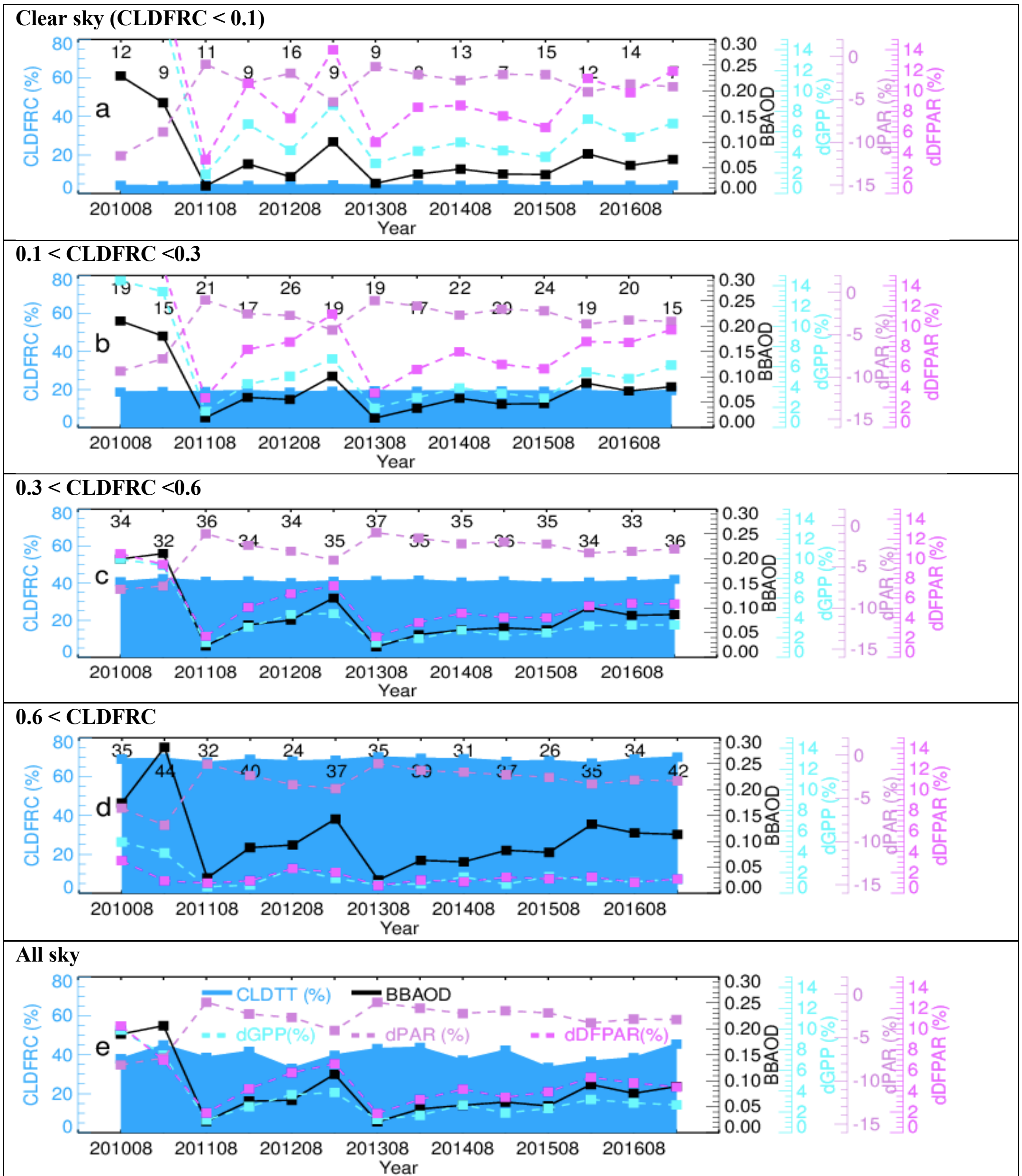

Figure 10. Monthly (August and September) averaged fields during 2010-2016 over Amazon range (80W-30W, 25S-5N) for for different cloudy conditions. The fields shown here are CLDFRC (shaded area), brown carbon aerosol optical depth (BBAOD, black solid line), and the changes of GPP (dGPP), direct (dDRPAR) and diffuse (dDFPAR) fields due to biomass burning aerosol impact on radiative fields for the ecosystem (dot-lines). Note all the changed fields are calculated as dX (%) = (X(aller)-X(nobbaer))/X(nobbaer)*100.0, here X = GPP, DRPAR, or DFPAR.The numbers marked in (a)-(d) are the corresponding occurrence frequency in % over the Amazon basin. Note the dGPP is 119.5% (201008) and 92.6% (201009) in (a). The dDFPAR is 111.1% (201008) and 105.5% (201009) in (a) and 97.1% (201008) in (b).

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Recall, the pair2 experiments are equivalent to the pair1 experiments except for the prescription of 2010 BB emissions for each year during 2011-2016. By jointly analyzing pair1 and pair 2, we can quantify the impacts of two different sets of BB emissions under the same meteorological conditions for every day of every year starting in 2011. Here we study the sensitivity of the aerosol light fertilizer effect to a unit change of BBAOD. That is, on a daily basis, the sensitivity of a variable X to a change in the biomass burning AOD is calculated as: ddX/dBBAOD = $((dX)_1-(dX)_2)/(BBAOD_1-BBAOD_2)$. Here, the X represents GPP, DRPAR, and DFPAR, and the subscripts 1 and 2 represent the pair1 or pair2 experiment, respectively.

ddX/dBBAOD is computed on a gridded daily basis over August-September of 2011-2016. The calculations are then catalogued according to daily cloud cover fraction – we combine the results within each of 10 cloud fraction bins (0-0.1, 0.1-0.2, ..., 0.9-1.0). To examine the maximum impact of interannual cloud change during our study period, the binned ddX/dBBAOD vs. CLDFRC relationship is also computed separately from daily (August-September) values in 2013 and from corresponding daily values in 2015, as these are the years for which monthly cloud cover is around the maximum (0.44) and minimum (0.35), respectively (Figure 10 and table S1e).

Figure 11 shows the results. An almost linear relationship is seen between the ddX/dBBAOD values and cloud cover fraction. BB aerosols increase GPP in clear sky conditions (e.g., 29.6 $kgm^{-2}s^{-1}$) but decrease it under full cloudiness conditions (e.g., -5.8 $kgm^{-2}s^{-1}$). The cloud fraction at which BB aerosol switches from stimulating to inhibiting plant growth occurs at ~0.8. Cloud conditions thus not only affect strongly the strength of the aerosol light fertilizer effect but can also change the fundamental direction of the effect. The lines produced for the three different study periods are fairly similar, indicating that the relationship of ddX/dBBAOD to CLDFRC is fairly stable within the range of cloud cover seen over the Amazon during the period of interest.

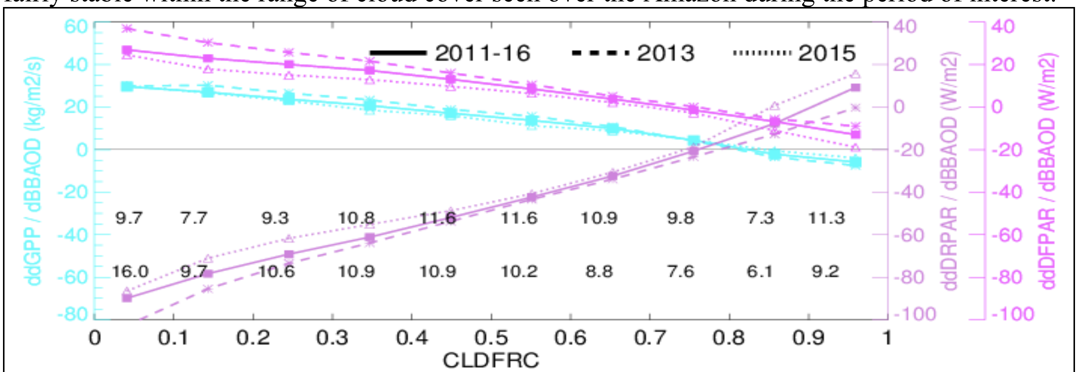

Figure 11. Radiation (DRPAR and DFPAR) and ecosystem (GPP) perturbation on every unit BBAOD change calculated combining the two pairs of experiments, i.e. $(dGPP_1-dGPP_2)/(BBAOD_1-BBAOD_2)$, $(dDRPAR_1-dDRPAR_2)/(BBAOD_1-BBAOD_2)$, and $(dDFPAR_1-dDFPAR_2)/(BBAOD_1-BBAOD_2)$, here subscripts referring to the experiments of pair1 and pari2. These changes are sorted out based on the values of grid box cloud fraction on a daily basis during the reported timeframe (e.g. solid-line for Aug-Sept, 2011-2016, dash-line for Aug-Sept 2013, and dot-line for Aug-Sept 2015). Also shown are the number of the occurrence frequency in % of each cloud fraction bin (0.1 increment) over the Amazon region for 2013 (first row) and 2015 (second row).

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4. Conclusions

We use the NASA GEOS ESM system with coupled aerosol, cloud, radiation, and ecosystem modules to investigate the impact of biomass burning aerosols on plant productivity across the Amazon Basin under the natural background cloud fields experienced during 2010-2016 – a period containing a broad range of cloudiness conditions. We find that the biomass burning aerosol light fertilizer effect does stimulate plant growth and has a notable impact on Amazon ecosystem productivity during the biomass burning season (August-September). In the long-term mean, the aerosol light fertilizer increases DFPAR by 3.8% and decreases DRPAR by 5.4%, allowing it to increase Amazon GPP by 2.6%. On a monthly basis, the light fertilizer effect can increase GPP by up to 9.9%. Consequently, biomass burning aerosols increase Amazonia yearly NPP by 1.5% on average, with yearly increases ranging from 0.06% to 4.2% over the seven years studied. This 1.5% NPP enhancement (or ~92TgC yr^{-1}) is equivalent to ~37% of the carbon loss due to Amazon fires.

The aerosol light fertilizer effect is strongly dependent on the presence of clouds, much stronger in clear sky conditions and decreases with the increase of cloudiness. A fairly robust linear relationship is found between cloud cover fraction and the sensitivity of radiation and GPP change to a change in biomass burning AOD. Curiously, BB aerosols stimulate plant growth under clear-sky conditions but suppress it under full cloudiness conditions. The cloud fraction at which BB aerosol switches from stimulating to inhibiting plant growth occurs at ~0.8. Note, however, that while our results show a clear sensitivity of the aerosol light fertilizer effect to cloudiness, interannual variations in the aerosol light fertilizer's overall effectiveness are controlled primarily by interannual variations in biomass burning aerosols during our studied period because biomass burning AOD can vary by a factor of 6 from year to year. The associated large variations in BBAOD are inevitably propagated to the radiation and ecosystem fields. Overall, our work indicates that feedbacks between aerosols, radiation, and the ecosystem need to be performed in the context of an atmospheric environment with a cloud presence.

This study examines the potential for the biomass burning aerosol light fertilizer effect to stimulate growth in unburned forest over the Amazon basin. The net feedback of Amazon fires on the Amazon biome is still an open question. Some changes, such as increasing atmospheric CO_2 and aerosols, serve as forest fertilizers, whereas others, such as increasing O_3 pollution levels and the deposition of smoke particles on plant leaves, reduce plant photosynthesis. On top of this, fires also induce changes in meteorological fields (e.g., temperature, precipitation, clouds) that can affect plant growth. More efforts are needed to investigate the ecosystem effect of Amazon fires by integrating all these potential factors.

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Data Availability:

All of the observational data used in this study are publicly accessible, e.g., AERONET (https://aeronet.gsfc.nasa.gov), CERES-EBAF (https://ceres.larc.nasa.gov/data/), FluxCom (http://www.fluxcom.org), FluxSat (https://avdc.gsfc.nasa.gov), and GoAmazon (https://www.arm.gov/research/campaigns/amf2014goamazon). The GEOS model results can be provided by contacting with the corresponding author.

Author contributions:

H.B. took an overall responsible for the experiment design, model simulation, and data analysis. E.L., R. D. K., S. P. M., and F. Z. contributed to the ecosystem study, D. O. B. contributed to the cloud study, M. C., P. R. C., A. S. D, M. E. M., and H. Y. contributed to the aerosol study and the model-observation comparison, P. N. contribute to the radiation study, and J. S. provided the GoAmazon results. All authors contributed to the paper writing.

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