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Impact of Amazonian Fires on Atmospheric CO_2

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Key Points:

- CO_2 concentrations are higher over the Amazon than the surrounding region during the fire/dry season
- High concentrations of CO_2 are related to the biomass burning, enhanced sinking air, and surface winds
- Amazon forest changes from a CO_2 sink to a CO_2 source during the fire season

Supporting Information:

- Supporting Information S1

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Abstract Amazon rainforest fires have significant environmental and societal impacts, but the mechanism and impact of the fires on the regional and global carbon cycles have not been fully understood. Over the rainforest, less precipitation, higher surface temperature, and enhanced mid-tropospheric sinking air over the eastern part of the Amazon characterized the fire/dry season. These meteorological conditions will facilitate more fires in the Amazon rainforest. Using the Orbiting Carbon Observatory-2 column CO_2, we notice that there are ~2 ppm more CO_2 over the Amazon compared with the surrounding area during the fire season. The higher concentrations of atmospheric CO_2 are related to the surface biomass burning, enhanced sinking air over the eastern part of the Amazon, and surface winds. Results from this study can help us better understand the carbon sources and sinks over the Amazon during the fire/dry season.

Plain Language Summary In this study, we explore the influence of fires on atmospheric CO_2 over the whole Amazon region using satellite CO_2 data. Our analysis not only reveals an increase in the CO_2 concentration (~2 ppm) over the Amazon during the fire season but also provides a possible mechanism to explain the increase. Our study further suggests that the Amazon forest changes from a CO_2 sink to a CO_2 source during the fire season. The increase in the CO_2 can lead to a warmer climate and produce more fires. It is still a challenge for current models to simulate the impact of fires on atmospheric CO_2 correctly, especially the interannual variability. Results in this study can help us better constrain models in the future.

1. Introduction

The Amazon rainforest is the largest biospheric carbon sink (e.g., Hubau et al., 2020; Pan et al., 2011) and is home to 10%–15% of terrestrial biodiversity (da Silva et al., 2005). However, as of 2018, ~20% of the Brazilian Amazon, which contains ~60% of the Amazon Basin, has been deforested (da Cruz et al., 2020), primarily for subsistence activities, soybean planting, cattle raising, timber logging, and mineral mining. During 2005–2012, the deforestation rate of the Brazilian Amazon significantly dropped by 70% compared to the record in 2004 after a series of national and international efforts, such as satellite monitoring (Diniz et al., 2015), increased state-protected forest areas (Walker et al., 2020), supply chain governance (Nepstad et al., 2014), and intergovernmental agreements (Simonet et al., 2019). However, the trend was first flattened and then reversed after the easing of Brazil's Forest Code in 2012 (Soares-Filho et al., 2014) and 2018 (Abessa et al., 2019); the deforestation in the last two years has been more severe due to the recent increased exports of agricultural products (Fuchs et al., 2019). The deforestation rate of the Brazilian Amazon has now surpassed the level in 2008 and the rate is still accelerating as of the summer of 2020.

Biomass burning, often associated with forest clearing, converts the carbon stored in the vegetative biomass mostly into atmospheric carbon dioxide (CO_2) and carbon monoxide (CO) (Guyon et al., 2005). Thus, deforestation has at least two distinct impacts on climate. The first impact is the increase of radiative forcing resulting from the direct increase of atmospheric CO_2. The second is the indirect influence through a subtle alteration of the hydrological cycle due to the changes in the surface types (e.g., from a forest to bare surface or from trees to savannas) and the atmospheric vertical structure.

The hydrologic cycle over the Amazon Basin is sensitive to the changes in the forest cover and the temperature near the surface. Barkhordarian et al. (2018) showed that as the northern South America becomes

warmer in response to anthropogenic forcing (e.g., greenhouse gases and anthropogenic aerosols), the surface and the atmosphere become drier (Barkhordarian et al., 2019; Berg et al., 2016; Trenberth et al., 2014). The increasingly dry conditions would in turn increase the frequency and extend the lifespan of the wildfires, further reducing forested areas, releasing more CO_2, enhancing greenhouse warming, and eventually risking the very existence of the rainforests (Brando et al., 2020; Khanna et al., 2017; Marengo et al., 2011).

Our knowledge about the CO_2 release from the Amazon rainforest, however, has been limited due to the lack of long-term measurements of CO_2 concentrations and fluxes over the whole Amazon region (Pastorello et al., 2020). Satellite observations of mid-tropospheric CO_2 (Chahine et al., 2008; Crevoisier et al., 2009; Kulawik et al., 2010; Rinsland et al., 2010) and column CO_2 (Crisp et al., 2012; Shiomi et al., 2008) have revealed important natural CO_2 variability over the global domain, such as Madden–Julian Oscillation (Li, 2018; Li et al., 2010), stratospheric sudden warming (Jiang et al., 2013), monsoon (e.g., Wang et al., 2011), El Niño (e.g., Chatterjee et al., 2017), annular mode (Jiang et al., 2010), and volcano eruption (Schwandner et al., 2017). Satellite CO_2 measurements are capable of detecting the enhanced CO_2 emissions from wildfires over Indonesia (Heymann et al., 2017) and southern California (Li et al., 2019). Over the Amazon region, a previous study using aircraft data found that more CO_2 was released to the atmosphere during wildfires (Guyon et al., 2005). Using bi-weekly vertical profiles of CO_2 from the surface to 4.4 km at four locations over the Amazon basin, Gatti et al. (2014) noticed that carbon was lost from the Amazon basin as a response of stalled forest productivity and wildfires during dry years. Previous studies (e.g., Gatti et al., 2014; Guyon et al., 2005) are limited in space and cannot provide a full picture of the impact of fires on atmospheric CO_2 over the whole domain of the Amazon. Satellite CO_2 data are global, so a systematic comparison of atmospheric CO_2 between Amazon and the surrounding areas can be conducted. Below, we utilize the satellite CO_2 observations from National Aeronautics and Space Administration (NASA) Orbiting Carbon Observatory-2 (OCO-2) mission to investigate the impacts of fires on atmospheric CO_2 over the whole Amazon region.

2. Data

2.1. Precipitation Data

Global Precipitation Climatology Project (GPCP) Version 2.3 precipitation (Adler et al., 2018), National Centers for Environmental Prediction Reanalysis 2 (NCEP2) surface temperature, NCEP2 500 hPa vertical pressure velocity, NCEP2 surface pressure, and NCEP2 surface winds (Kanamitsu et al., 2002) are used in this paper to study the meteorological conditions for fires in the Amazon. Monthly mean GPCP Version 2.3 precipitation data and NCEP2 data are available from January 1979 to present. The spatial resolution of GPCP Version 2.3 precipitation data and NCEP2 data are 2.5° × 2.5° in latitude and longitude.

2.2. OCO-2 and AIRS Data

To explore the impact of Amazon fires on atmospheric CO_2, we have utilized Version 9 OCO-2 column CO_2 (Crisp et al., 2017; Eldering et al., 2017) in this paper. We also use Version 6 column CO data from Atmospheric Infrared Sounder (AIRS) (Warner et al., 2013; Yurganov et al., 2008), because CO data can be used to track biomass burning events (Yurganov et al., 2008). OCO-2 column CO_2 data are retrieved using CO_2 spectra at 1.61 and 2.06 μm (Connor et al., 2008; Crisp et al., 2017). Comparisons between OCO-2 column CO_2 and in-situ measurements from Total Carbon Column Observing Network (TCCON) suggest that the precision of OCO-2 column CO_2 is about 0.5 ± 1.5 ppm (Wunch et al., 2017). OCO-2 column CO_2 data are available from September 2014 to present. AIRS column CO has a maximum sensitivity at 500 hPa. AIRS column CO data are available from September 2002 to present. In this paper, we have regridded OCO-2 column CO_2 and AIRS column CO to 2° × 2° in latitude and longitude.

2.3. Fire Emission Database

To better understand the impact of CO_2 surface emissions on atmospheric CO_2 during the fire season in the Amazon, we have utilized CO_2 biomass burning emissions from Global Fire Emissions Database Version 4.1 (GFEDv4.1) (Giglio et al., 2013) and biosphere CO_2 emissions from the Carnegie-Ames Stanford Approach

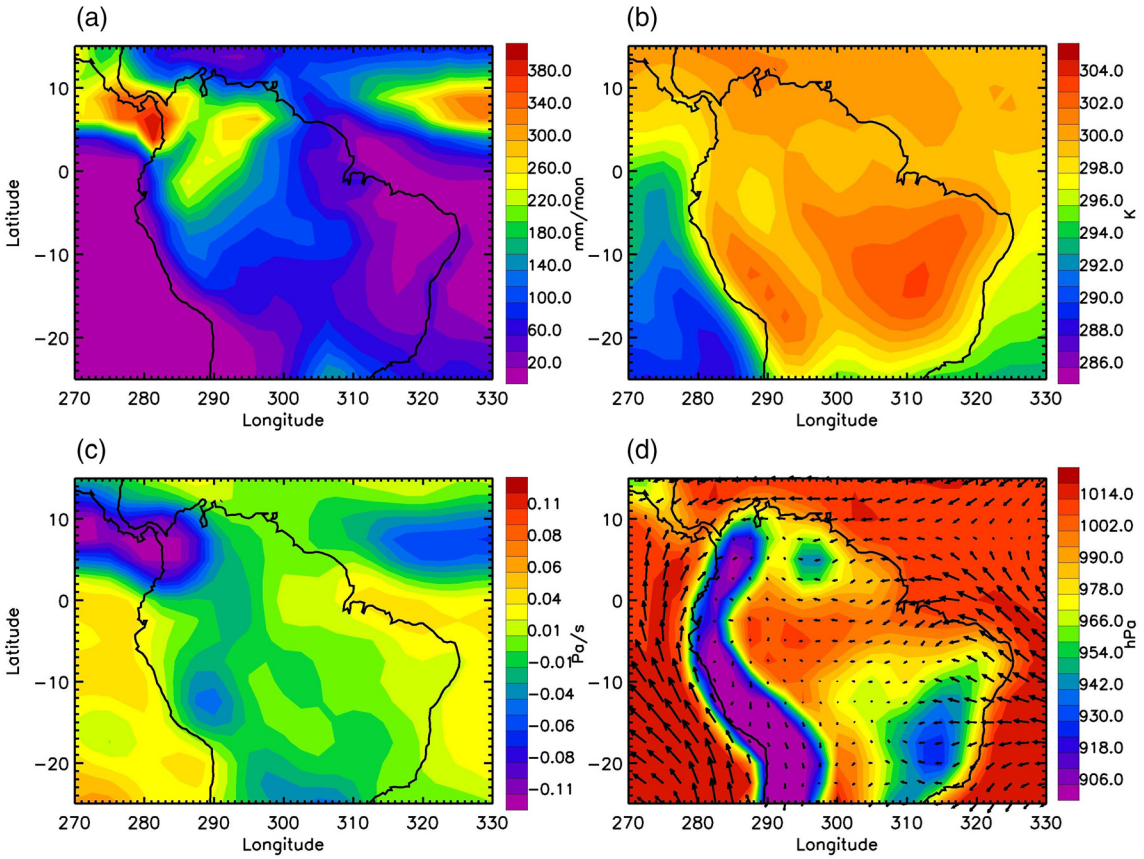

Figure 1. (a) Global Precipitation Climatology Project (GPCP) precipitation averaged for August–October, 2015–2019. Units are mm/mon. (b) NCEP2 surface temperature averaged for August–October, 2015–2019. Units are K. (c) NCEP2 500 hPa vertical pressure velocity averaged for August–October, 2015–2019. Units are Pa/s. (d) NCEP2 surface pressure and horizontal winds averaged for August–October, 2015–2019. Units for surface pressure are hPa.

(CASA) biogeochemical model (Randerson et al., 1996). Monthly mean GFEDv4.1 CO_2 biomass burning emissions and CASA biosphere-atmosphere CO_2 exchange data are available from January 1997 to December 2016. The spatial resolution of GFEDv4.1 biomass burning CO_2 emissions and CASA biosphere-atmosphere CO_2 exchange data are 0.25° × 0.25° in latitude and longitude. GFEDv4.1 CO_2 biomass burning data and CASA biosphere-atmosphere CO_2 exchange data are not available in later years (2017–2019) due to the inconsistency of upgraded burned area data (Randerson et al., 2018). We will revisit the CO_2 emission in the future when surface emission data are available in later years (2017–2019).

2.4. Burned Area Data

Burned area data from Moderate Resolution Imaging Spectrometer (MODIS) (Giglio et al., 2018) are also used in this paper. MODIS burned area data are available from November 2000 to December 2019. The spatial resolution of the monthly mean MODIS burned area are 0.25° × 0.25° in latitude and longitude.

3. Results

We focus on the period from August to October, the dry months of the Amazon, when the Amazon fires mostly occur. To investigate the meteorological conditions in the fire/dry season in the Amazon, we calculate mean values of Global Precipitation Climatology Project (GPCP) Version 2.3 precipitation, the National Centers for Environmental Prediction's Reanalysis 2 (NCEP2) surface temperature, NCEP2 500-hPa vertical pressure velocity, NCEP2 surface pressure, and NCEP2 surface horizontal winds over the fire/dry season from 2015 to 2019. Figure 1a shows that the amount of precipitation is low over the Amazon during the fire/dry season (August–October, 2015–2019). Surface temperature is high over the Amazon (see Figure 1b).

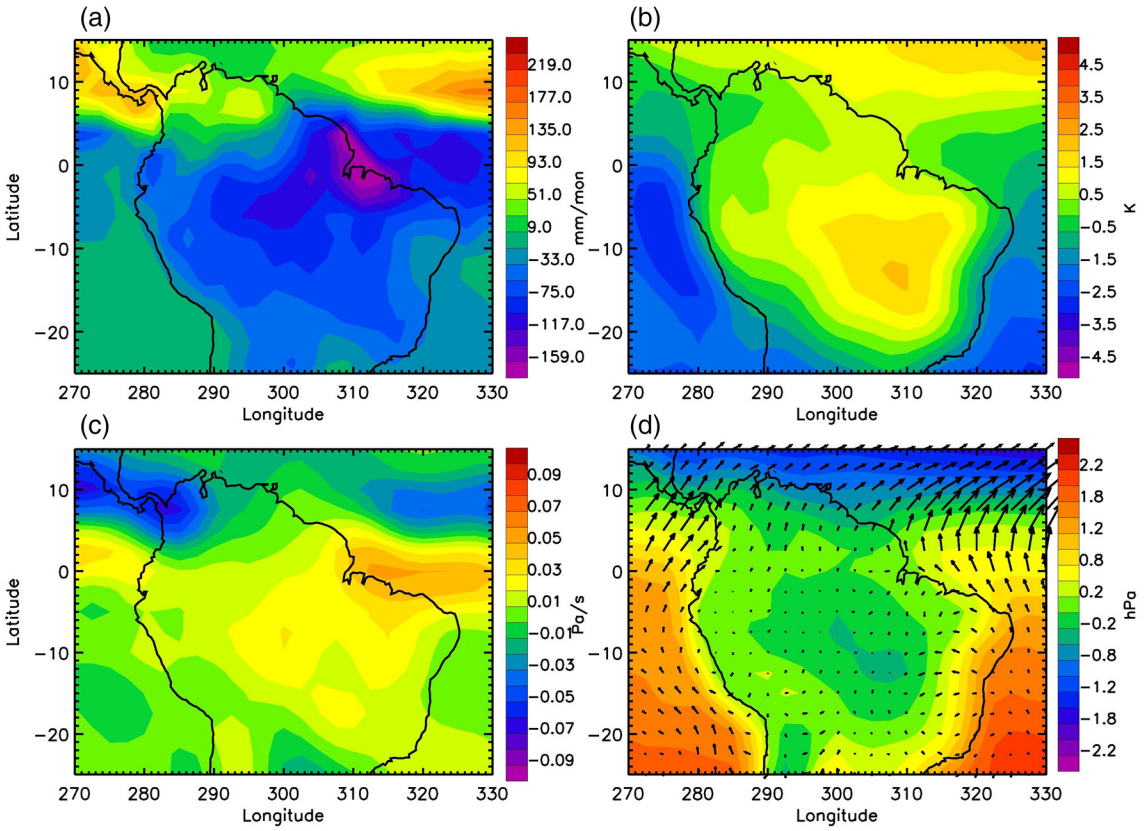

Figure 2. (a) GPCP precipitation anomaly for August–October, 2015–2019. Units are mm/mon. (b) NCEP2 surface temperature anomaly for August–October, 2015–2019. Units are K. (c) NCEP2 500 hPa vertical pressure velocity anomaly for August–October, 2015–2019. Units are Pa/s. (d) NCEP2 surface pressure anomaly and horizontal wind anomaly for August–October, 2015–2019. Units for surface pressure are hPa.

Figure 1c shows 500 hPa vertical pressure velocity averaged for the fire/dry season. Negative (positive) value of 500 hPa vertical pressure velocity refers to rising (sinking) air. There is rising air over the western part of South America and sinking air over the eastern part of South America. There is a low-pressure system in the western part of South America and a high-pressure system in the eastern part of South America (See Figure 1d). Surface winds move toward the Amazon basin from the east coast. With Andes Mountains along the west coast of South America, the westward winds from the east coast tend to trap pollutants released from the fires in the Amazon basin. Figure 2 shows the anomalies of GPCP precipitation, NCEP2 surface temperature, NCEP2 500-hPa vertical pressure velocity, and NCEP2 surface pressure and horizontal winds. Anomalies are calculated by subtracting the climatological averages (January 2015–December 2019) from original data at each grid point. The precipitation is anomalously less during the fire/dry season compared with climatology over the Amazon (Figure 2a), and is accompanied by a higher surface temperature and enhanced sinking air over the eastern Amazon. These meteorological anomalies would further enhance the fire frequency and intensity during the dry season. There is a small surface pressure anomaly (~0.5 hPa) as shown in Figure 2d, which is very small compared with the surface pressure (~950–1,000 hPa) in Figure 1d. There is also stronger converging air from west, east, and south directions, moving pollutants from the southern Amazon to the northern Amazon.

To investigate the impact of fires on atmospheric CO_2, we calculate the mean value of detrended OCO-2 column CO_2 in August–October, 2015–2019. Since we are not interested in the positive trend in column CO_2 in this study, a linear trend estimated by the least squares method (Bevington & Robinson, 2003) has been removed from OCO-2 column CO_2 data at each grid point. As shown in Figure 3a, CO_2 concentrations are about 2 ppm higher over the Amazon region than the surrounding areas. Since CO, produced by incomplete combustion, can track the biomass burning well (Yurganov et al., 2008), we also calculate the mean

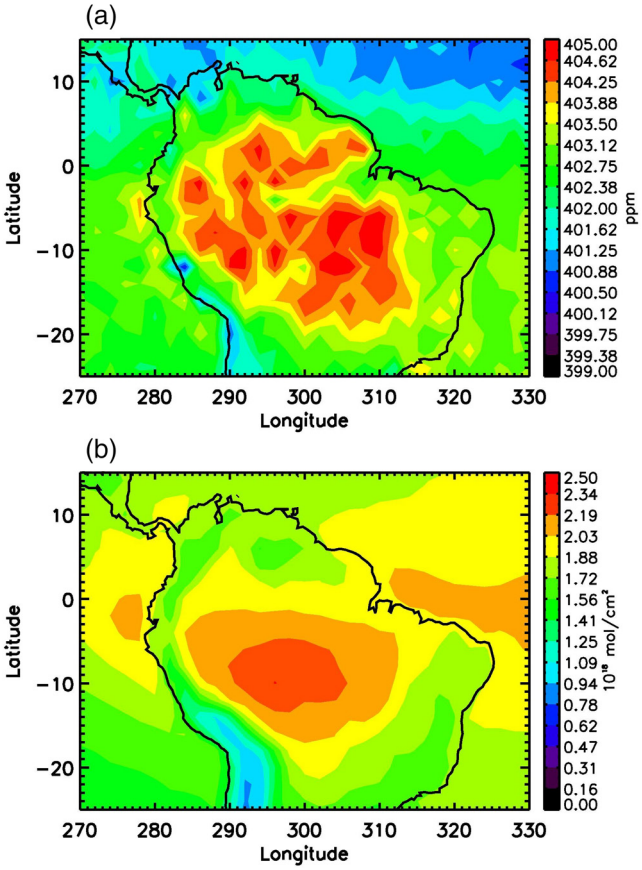

Figure 3. (a) OCO-2 CO_2 averaged for August–October, 2015–2019. Units are ppm. (b) Atmospheric Infrared Sounder (AIRS) column CO averaged for August–October, 2015–2019. Units are 10^{18} mol/cm^2.

value of AIRS column CO in August–October, 2015–2019. As shown in Figure 3b, CO concentrations are higher over the Amazon region than the surrounding areas.

To investigate possible explanations for the high atmospheric CO_2 concentrations over the Amazon during the fire/dry season, we examine surface CO_2 emissions over the Amazon using the global CO_2 biomass burning emission from the Global Fire Emissions Database, Version 4.1 (GFEDv4) and the net ecosystem CO_2 exchange (NEE), defined as the difference between respiration and gross primary production (photosynthesis), from the Carnegie-Ames-Stanford Approach (CASA) model. CO_2 surface emissions averaged in August–October, 2015–2016 are shown in Figure 4. For a direct comparison, we also calculate mean values of detrended OCO-2 column CO_2 and AIRS column CO during August–October, 2015–2016 in Figure S1. Figure 4a shows an enhanced CO_2 emission from biomass burning during the fire/dry season over the Amazon region, consistent with the OCO-2 observations. CO_2 biomass burning emissions are particularly high over the southern part of the Amazon. There are also elevated CO_2 biomass-burning emissions over the central and northern parts of the Amazon, which contributes to the high CO_2 concentration in the atmosphere as shown in Figure 3a. The positive values of NEE in Figure 4b suggest that CO_2 are released from the biosphere to the atmosphere; negative values of NEE suggest that CO_2 is removed from the atmosphere by the biosphere. Thus CO_2 is released from the biosphere to the atmosphere over the southern and northern parts of the Amazon during the fire/dry season while CO_2 is taken up in the northeastern and northwestern parts of the Amazon. Ecosystem respiration (ER) and gross primary production (GPP) averaged in the fire/dry season are shown in Figures 4c and 4d, respectively. The spatial distribution of CO_2 released from respiration is more uniform over the Amazon region than that of CO_2 uptake by photosynthesis. There is less CO_2 uptake by photosynthesis over the southern Amazon, where most fires occur. The combination of respiration and photosynthesis contributes to the enhanced CO_2 release in the southern and northern parts of the Amazon as shown in Figure 4b.

Figure S2 shows the anomalies of GFEDv4.1 biomass burning, NEE, ER, and GPP for August−October, 2015–2016. CO_2 biomass burning emissions are anomalously high over the southern and central Amazon during the fire/dry season compared with climatology (Figure S2a). NEE anomalies are higher over southern and northern parts of the Amazon during the fire/dry season compared with climatology as shown in Figure S2b. Figure S3 shows the MODIS burned area and anomalies for August−October, 2015–2019. A lot of areas were burned over the southern and central Amazon. The burned areas during the fire/dry season (August−October, 2015–2019) are much higher than the climatology (Figure S3b), implying more CO_2 emission due to biomass burning during August−October, 2015–2019.

To explore the temporal variations of different variables over the Amazon, we calculate GPCP Version 2.3 precipitation and NCEP2 500 hPa vertical pressure velocity for the wet season (January−March) and the dry season (August–October) over 288°E-314°E, 20°S-0°S. The region (288°E-314°E, 20°S-0°S) is chosen, since this is the area with high concentrations of CO_2 and CO. Time series of GPCP precipitation (green line) and NCEP2 500 hPa vertical pressure velocity (blue line) are shown in Figure 5a. The average amount of precipitation is above 250 mm during the wet season (January–March) and is below 100 mm during the dry season (August−October). The values of 500 hPa vertical pressure velocity are higher during dry season than the wet season. There is more sinking air (or, equivalently, less rising air) during the dry season than the wet season, which can help trap trace gases in the Amazon region during the dry season (August–October). The same averaging algorithms as GPCP precipitation data are applied to OCO-2 column CO_2, AIRS

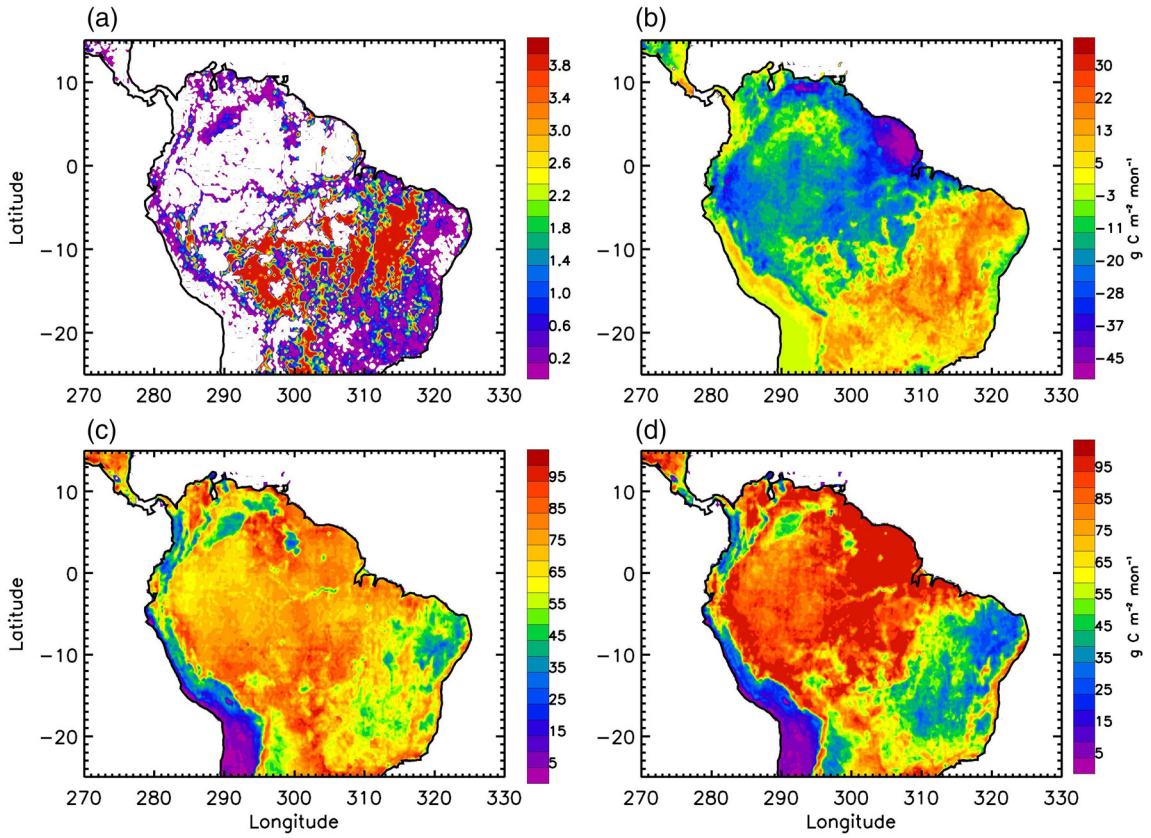

Figure 4. (a) GFEDv4.1 biomass burning averaged for August–October, 2015–2016. (b) Net ecosystem CO_2 exchange (NEE) averaged for August–October, 2015–2016. (c) Ecosystem respiration (ER) averaged for August–October, 2015–2016. (d) Gross primary production (GPP) averaged for August–October, 2015–2016. Units are g C m^{-2} mon^{-1}.

column CO, and NEE. The black line is OCO-2 column CO_2 averaged over the region; the red line is AIRS column CO averaged over the region. Both CO and CO_2 released from the fire reflect the intensity of the fire. Figure 5b shows that the magnitudes of CO_2 and CO are comparable (high CO_2 coincides with high CO) except in 2016, where the CO_2 is influenced primarily by the biosphere's response to the strong El Niño event (Chatterjee et al., 2017; Levin et al., 2019; Liu et al., 2017). The correlation coefficient between OCO-2 column CO_2 and AIRS column CO is 0.74 with a significance level of 4%. The significance level is calculated using a Monte Carlo method (Jiang et al., 2004). Details for correlation coefficients and significance levels are summarized in Table S1 in supplementary materials. The correlation coefficients of GPCP precipitation with OCO-2 column CO_2 and AIRS CO are −0.65 (7%) and −0.95 (5%), respectively. Both OCO-2 column CO_2 and AIRS column CO concentrations are high during dry seasons (August–October) and low during wet seasons (January–March). The correlation coefficients of vertical pressure velocity with OCO-2 column CO_2 and AIRS CO are 0.64 (7%) and 0.95 (4%), respectively. More sinking air can contribute to more CO_2 and CO in the atmosphere during the dry season than the wet season. High concentrations of OCO-2 CO_2 during dry seasons (August–October) are also related to biomass burning and burned area as shown in Figures S4a and S4b, respectively. The anomalous signal in the wet season of 2016 is related to the strong 2015–2016 El Niño event (e.g., Chatterjee et al., 2017; Levine et al., 2019; Liu et al., 2017). The 2015–2016 El Niño event peaked in the late 2015 with severe droughts (Liu et al., 2017). Conditions of high surface temperature and low soil moisture lead to a reduction in the photosynthesis and an increase in the soil and plant respiration (Chatterjee et al., 2017; Levine et al., 2019; Liu et al., 2017), resulting in more CO_2 in the atmosphere. As shown as pink line in Figure 5b, the average value of NEE over the region (288°E-314°E, 20°S-0°S) is positive for January–March, 2016 which means more CO_2 is released from biosphere to the atmosphere as a response to the El Niño event. The average value of NEE over this region (pink line) is complex as a result of cancellation of positive and negative values over different regions (Figure 4b). The average value of

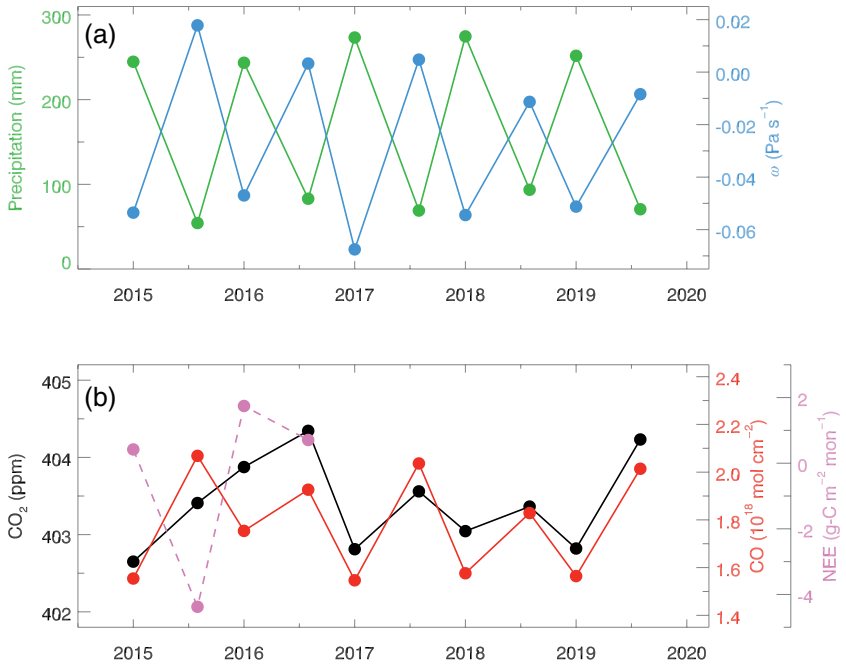

Figure 5. (a) Time series of GPCP precipitation and NCEP2 500 hPa vertical pressure velocity averaged over 288°E-314°E, 20°S-0°S for wet seasons (January–March) and dry seasons (August–October). Green line is precipitation and blue line is 500 hPa vertical pressure velocity. (b) Time series of detrended OCO-2 CO_2, AIRS column CO, and NEE averaged over 288°E-314°E, 20°S-0°S for wet seasons (January–March) and dry seasons (August–October). Black line is the detrended OCO-2 CO_2. Red line is AIRS column CO. Pink dashed line is NEE.

NEE is relatively small in the wet season (January–March) of 2015 and the dry season (August–October) of 2016. The average value of NEE is negative in the dry season (August–October) of 2015 which will be offset by the CO_2 biomass burning emission in the dry season of 2015 (Figure S4a in supplementary materials). The relatively high NEE during the wet season (January–March) of 2016 can help to explain the relatively high CO_2 concentration during the wet season (January–March) of 2016 as a response to the El Niño event.

4. Conclusions

In this paper, we have examined the impact of fires on atmospheric CO_2 over the Amazon region. To investigate the meteorological conditions during the fire/dry season, we calculate mean values and anomalies of precipitation, surface temperature, 500 hPa vertical pressure velocity, surface pressure, and surface winds during August–October, 2015–2019. There is less precipitation, higher surface temperature, and enhanced mid-tropospheric sinking air over the eastern part of the Amazon during the fire/dry season. All these meteorological conditions favor the formation of fires over the Amazon during the fire/dry season (August–October). To investigate the impacts of fires on atmospheric CO_2, we estimate concentrations of OCO-2 column CO_2 during the fire/dry season. Column CO_2 concentrations are about 2 ppm higher over the Amazon basin than the surrounding area during the fire/dry season, which coincides with a high column CO in the same region due to the incomplete combustion of the biomass, as observed by NASA's AIRS instrument. High concentrations of OCO-2 column CO_2 are related to the surface biomass burning, enhanced sinking air over the eastern part of the Amazon, and surface winds. Although the Amazon is the biggest land CO_2 sink, CO_2 released from fires make this region a CO_2 source during the fire/dry season (see Figure 4b), which will have a large impact on the carbon budget, leading to a warmer climate and more fires in the future.

Temporal variations of precipitation, vertical pressure velocity, OCO-2 column CO_2, AIRS CO, and MODIS burned area are also investigated. The time series of OCO-2 column CO_2 have a negative correlation with precipitation ($R = -0.65$) and positive correlations with vertical pressure velocity ($R = 0.64$), AIRS column CO ($R = 0.75$), and MODIS burned area ($R = 0.68$). It suggests that there is less precipitation, enhanced sinking air, and more burned area over the Amazon during the fire/dry season, which will contribute to

higher CO_2 concentrations. It remains challenging for biogeochemistry-transport models to simulate the impact of fires on atmospheric CO_2 correctly over the Amazon, especially the interannual variability. Results revealed from this study can help us better understand the carbon budget over the Amazon and constrain the numerical models. In the future, we plan to improve the aerosol retrievals and increase the yield of CO_2 retrievals over biomass-burning regions. With more yields over the biomass burning region and improved spatial coverage, we can explore the temporal variation of CO_2 during a biomass-burning event on a daily basis.

Data Availability Statement

GPCP Version 2.3 precipitation data are available at https://psl.noaa.gov/data/gridded/data.gpcp.html. NCEP2 Reanalysis data are available at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html. OCO-2 Version 9 column CO_2 data are available at https://co2.jpl.nasa.gov/#mission=OCO-2. AIRS Version 6 column CO data are available at https://airs.jpl.nasa.gov/data/get-data/standard-data/. GFED Version 4.1 data are available at https://www.geo.vu.nl/~gwerf/GFED/GFED4/. MODIS burned area data are available at http://modis-fire.umd.edu/.

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