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Co-variability of smoke and fire in the Amazon basin

Amit Kumar Mishra, Yoav Lehahn, Yinon Rudich*, Ilan Koren*

Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot 76100, Israel

HIGHLIGHTS

- Joint statistical analysis of fire and smoke is conducted in the Amazon basin.
- Analysis shows strong inter-annual correlation between smoke (AOD) and fire (FC).
- Spatial homogenization of smoke are found over the basin on a seasonal time scale.
- MODIS-AODs have a stronger correlation with fire properties than AERONET-AODs.
- Provided optimal spatial-temporal scales for AOD data for different applications.

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ABSTRACT

The Amazon basin is a hot spot of anthropogenically-driven biomass burning, accounting for approximately 15% of total global fire emissions. It is essential to accurately measure these fires for robust regional and global modeling of key environmental processes. Here we have explored the link between spatio-temporal variability patterns in the Amazon basin's fires and the resulting smoke loading using 11 years (2002–2012) of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Aerosol Robotic Network (AERONET) observations. Focusing on the peak burning season (July–October), our analysis shows strong inter-annual correlation between aerosol optical depth (AOD) and two MODIS fire products: fire radiative power (FRP) and fire pixel counts (FC). Among these two fire products, the FC better indicates the amount of smoke in the basin, as represented in remotely sensed AOD data. This fire product is significantly correlated both with regional AOD retrievals from MODIS and with point AOD measurements from the AERONET stations, pointing to spatial homogenization of the smoke over the basin on a seasonal time scale. However, MODIS AODs are found better than AERONET AODs observation for linking between smoke and fire. Furthermore, MODIS AOD measurements are strongly correlated with number of fires ~1^0–2^0 to the east, most likely due to westward advection of smoke by the wind. These results can be rationalized by the regional topography and the wind regimes. Our analysis can improve data assimilation of satellite and ground-based observations into regional and global model studies, thus improving the assessment of the environmental and climatic impacts of frequency and distribution variability of the Amazon basin's fires. We also provide the optimal spatial and temporal scales for ground-based observations, which could be used for such applications.

1. Introduction

Smoke aerosols from natural and anthropogenic fire are significant modulator of climate (Turco et al., 1990; Kaufman and Fraser, 1997; Schultz et al., 2003; van der Werf et al., 2008; Boucher et al., 2013) through their direct interaction with incoming and outgoing radiation (Davidi et al., 2009; Leibensperger et al., 2012 and references therein) and their ability to affect cloud microphysics and therefore hydrological processes (Andreae et al., 2004; Koren et al., 2004; 2008; Stevens and Feingold, 2009; Tao et al., 2013; Altaratz et al., 2014; Rosenfeld et al., 2014). The spatial and temporal variations in the properties of smoke aerosol particles lead to high uncertainties in global and regional climate radiative forcing calculations (Boucher et al., 2013). This is also true for smoke in the Amazon basin, which is a hot spot of anthropogenically-driven biomass burning (Cochrane, 2003; Aragao et al., 2007). Biomass burning is a large source of particulate matter during the burning

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* Corresponding authors.
E-mail addresses: Yinon.Rudich@weizmann.ac.il (Y. Rudich), ilan.koren@weizmann.ac.il (I. Koren).

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season (June–November) in the Amazon Basin (Martin et al., 2010), which accounts for 15% of total global fire emissions on average (van der Werf et al., 2010). The major part of the emissions originates from agriculture crop residue burning (Reinhardt et al., 2001; Ribeiro, 2008; Uriarte et al., 2009) and deforestation fires along the borders of the Amazon forest, known as the arc of deforestation (Morton et al., 2008). However, atmospheric transport patterns lead to smoke spatial distribution that can be very different than the distribution of the actual fire sources (Freitas et al., 2005).

The availability of fire products from satellites [e.g. the Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Very High Resolution Radiometer, and Along Track Scanning Radiometer etc.] enable new dimensions of research, that include long term global and regional quantitative studies of biomass-burning (Wooster et al., 2003; Ichoku and Kaufman, 2005; Ichoku et al., 2008; Kaiser et al., 2012; Schroeder et al., 2014), emission estimates of organic and black carbon (Vermote et al., 2009), elucidating biomass burning patterns and trends (Duncan et al., 2003; Giglio et al., 2006a, 2006b; Koren et al., 2007; Ichoku et al., 2008; Hoeve et al., 2012; Hyer et al., 2013), and quantifying the potential of smoke injection heights using sub-pixel information of fire properties (Peterson et al., 2013, 2014). Satellite-derived fire pixel counts (FC) or fire radiative powers (FRP) with different parameterizations are generally used to synthesize a variety of smoke emissions inventories. These include the Global Fire Assimilation System, which estimates emissions by converting MODIS-derived FRP into dry matter burnt and fire constituents using land-cover dependent conversion factors (Kaiser et al., 2012; Remy and Kaiser, 2014). The Brazilian Biomass Burning Emission Model uses satellite derived-FC with a different emission parameterization to synthesize emission inventories of biomass burning species (Freitas et al., 2009; Longo et al., 2010). These smoke emission inventories are needed for simulating smoke transport and for accurately representing radiative impacts in global climate models (GCM) and regional chemical transport models (CTM). Although making best use of available datasets, there are large uncertainties associated with the output of these atmospheric models due to uncertainties in absolute emission fluxes and other unknown or not yet fully understood processes.

One way to reduce these uncertainties may be the assimilation of satellite-derived aerosol optical depth (AOD, derived from smoke) in conjugation with FC or FRP data into established GCMs and CTMs. An alternative method could be provided to validate these model products regarding their prescribed fires and estimated biomass burning fluxes. However, for such applications, one must know the link between fire (FC, FRP) and smoke loading.

In this study, a joint statistical analysis of fire and smoke loading was conducted for the burning seasons for 2002–2012 using MODIS and Aerosol Robotic Network (AERONET) observations. Specifically, this study addresses the following questions (1) How does smoke loading scale with FC and FRP? (2) How does this association vary as a function of spatial and temporal scale? (3) How do the basin-wide atmospheric dynamics affect the observed co-variability?

2. Study region and data analysis

Combined statistics of fire and smoke loading are analyzed for the Amazon basin during the fire season (June–November) between 2002 and 2012. A large domain over the deforestation arc (4^0S–18^0S, 70^0W–44^0W) is used as a primary region of interest (ROI) in this study (Fig. 1). The ROI mainly constitute deforestation-fire, Savana (Cerrado)-fire and crop-residue burning during the Amazonian dry season (Castellanos et al., 2013).

Monthly (MYD14CMH, $0.5^0 \times 0.5^0$ spatial resolution) and eight-day mean (MYD14C8H, $0.25^0 \times 0.25^0$ spatial resolution) of MODIS (Aqua) Collection 5 level 3 climate modeling grid (CMG) fire products are used to retrieve overpass-corrected fire pixel counts, mean cloud fraction, cloud-and-overpass-corrected fire pixel counts and mean fire radiative power (Justice et al., 2002; Kaufman et al., 1998, 2003; Giglio et al., 2006a; 2006b; Giglio, 2013). The CMG fire products are planned to facilitate the MODIS fire information into GCMs and CTMs. These fire products are obtained from http://modis-fire.umd.edu/pages/ActiveFire/ActiveFire.html & ftp://fuoco.geog.umd.edu/modis/C5/cmg/. The traditional 'gridded fire counts' are corrected for multiple satellite overpass and missing values, which are termed as 'overpass-corrected fire pixel counts' for each grid cell (Giglio et al., 2006b). In general, high cloud cover during the burning season hinders the detection of small fires and hence the observed FC may be smaller than the actual FC. Therefore, 'cloud-and-overpass-corrected fire pixel counts' are computed for each grid cell, which is the ratio of 'overpass-corrected fire pixel counts' to '1 − mean cloud fraction' (Giglio et al., 2006b). The cloud-and-overpass-corrected fire pixel counts for those grid cells where 'mean cloud fraction = 1' are denoted zero. The 'cloud-and-overpass-corrected fire pixel counts' will be used in this study as FC. The calculation of FRP requires the information about brightness temperature of fire pixels and background (non-fire) brightness temperature in the immediate vicinity of the fire, using the 4 μm channel (Kaufman et al., 2003; Giglio, 2013). However, the information about background brightness temperature is sometimes unavailable in the neighborhood of high cloud cover and very large fires. The fire pixels which fall in above mentioned cases and those that are detected at scan angle above 40^0 are not included in mean FRP calculation. Detailed information on CMG fire products and their estimation methodology could be found in Kaufman et al. (2003), Giglio et al. (2006b) and Giglio (2013).

Apart from high cloud cover, other limitations to the fire detection process from the MODIS observations also exist (Giglio et al., 2003; 2006b; Philip, 2007). Many small agricultural fires are missed in the detection process because they are too small to raise the brightness temperature of the pixel. Therefore, it is difficult to distinguish it from the background brightness temperature. The number of missed detections increases away from nadir, as the pixel size increases from 1 km to 8–10 km. In addition, there are gaps between the MODIS swaths in the equatorial regions, which also contribute to the number of missed detections. More details on fire detection limitations from MODIS observations can be found elsewhere (Giglio et al., 2003; Philip, 2007; Giglio, 2013). In addition, the level 3 CMG products provide mean FRP at coarse spatial resolutions ($0.5^0 \times 0.5^0$ & $0.25^0 \times 0.25^0$) as compared to level 2 products (1 km × 1 km), which could reduce the signal from the largest and most intense fires. Ichoku et al. (2008) have shown that the decrease in spatial resolution of the sensors tends to underestimate the relative FRP. However, the mutual high correlations between these sensors indicate that the general variation in FRP is well captured, irrespective of the spatial resolution.

AOD at 550 nm is retrieved from MODIS (Aqua) Collection 5.1 level 3 global aerosol products (monthly mean, eight-day mean and daily) (Remer et al., 2008; Levy et al., 2007). MODIS AOD products are retrieved on $1^0 \times 1^0$ spatial resolutions. In order to compare with AOD product, the spatial resolution of MODIS fire product is reduced to $1^0 \times 1^0$ using the methodology given in Giglio (2013), i.e. FCs are sum of individual pixels and FRPs are average of individual pixels, weighted by their individual FC.

Due to discontinuity in availability of AERONET-derived daily level 2 data for longer time period (2002–2012), AERONET level 1.5 (cloud corrected) AOD_{500} from 4 sites, Abracos_Hill (AH), Alta_Floresta (AF), Ji_Parana_SE (JPSE) and Rio_Branco (RB) are used in this study (Holben et al., 1998). Due to limited availability of data