Modeled Effects of Biomass Burning Aerosols on Photosynthesis

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Introduction

Previous studies have shown that clouds and aerosols may enhance forest net primary production by increasing diffuse photosynthetically-active radiation (PAR), and hence illuminating leaves more evenly (e.g., Gu et al., 2002). Oliveira et al. (2007) showed that moderate loading of biomass burning smoke enhances net ecosystem exchange (NEE) in the Amazon, but heavy loading decreases it. With thick smoke, the decrease in total PAR outweighs the beneficial effect of increased diffuse fraction of PAR. To elucidate the relative importance of these competing effects, and to assess the combined influence of clouds and smoke on gross primary production (GPP), we develop and apply a Canopy-Atmosphere Radiation and Photosynthesis model (CARP).

Methods

The CARP Model couples 10 canopy layers to the DISORT SWIR atmospheric radiative transfer model (Zender et al., 1997), to solve for fluxes throughout the atmosphere-canopy column in >400 spectral bands within the PAR region. The vertical coordinate in our canopy model is cumulative (layer to top-of-canopy) leaf-stem area index. We consider any statistical distribution of leaf orientation, solve for layer optical depth, and quantify incident direct and diffuse radiation on each pool of leaf angles within each layer. We then estimate photosynthesis at the leaf level and derive GPP by integrating leaf-level fluxes over the full canopy. In the sensitivity experiments presented, we consider different combinations of smoke, cloud, and canopy thickness, assuming an even distribution of 3600 leaf angles. Smoke optical properties are from Reid et al. (2002). We estimate leaf-level photosynthesis using a standard rectangular hyperbola function, assuming a quantum yield of 0.06 moles CO$_2$ per mole of absorbed PAR. We assume diffuse PAR is isotropic and absorption is evenly distributed amongst leaves within a layer. Future work will incorporate temperature dependencies and observations of elevated quantum yield, but lower maximum yield, from canopy vegetation that is shaded most of the time.

3. GPP Dependence on Optical Depth

In a canopy with LAI=5, daily-mean GPP is enhanced, relative to clear-sky, with aerosol optical depth (AOD) up to 2.5 (black curve). This agrees well with Oliveira et al. (2006), who report NEE enhancement for loadings up to 2.7. The AOD of 0.5 enhancement is 0.75 (25% enhancement), lower than values reported by Oliveira et al. (2006).

A cloud (blue curve), however, can increase GPP by up to 45%, and the cloud optical depth range of enhancement extends well beyond that of smoke aerosol. This is because liquid drops have a much higher scattering ratio than smoke (also see box 2). This tells us that the diffuse-PAR enhancement effect is sensitive to aerosol single-scatter albedo.

When we introduce smoke in combination with a cloud of moderate thickness (optical depth=10), GPP decreases for any aerosol burden. Hence, the diffuse-PAR enhancement effect is also highly sensitive to cloud cover.

2. Daily Cycle of GPP

Here, we show the daily cycle of GPP in a canopy with LAI=5.0 m$^2$ m$^{-2}$ at latitude -10º on August 20 (peak burning season in the Amazon) with different smoke aerosol and cloud optical depths (also see box 2). Relative to clear-sky conditions, both low cloud and aerosol loadings (optical depth=1) increase GPP throughout the day. With heavier aerosol loading (AOD=3.0), production rates decrease during early morning and evening, when the system is light-limited, but increase at mid-day because of more even distribution of PAR amongst leaves. Clouds have a greater enhancement effect on GPP because they are highly-scattering, and hence reduce canopy-top insolation by a smaller amount than smoke, while still increasing diffuse radiation.

1. GPP Rates Within the Canopy

Under clear skies (zenith angle of 60º), production is efficient at the canopy top, but decays quickly with depth (black curve). With smoke aerosol loading, GPP rates are lower at the top, but decay more slowly with canopy depth. Thus, even with relatively high zenith angle, total canopy GPP can be greater with smoke present in the atmosphere.

4. Effects of Variability in Cloud Cover

The Amazon, even during the dry season of burning, is characterized by frequent, and frequently-varying, cloud cover. Here, we examine the sensitivity of GPP to aerosol loading with varying duration of cloud cover. We estimate GPP at 15-minute resolution with cloud cover (optical depth=10) during 25%, 50%, and 75% of the day. We find GPP enhancement for AOD<1.8 with 25% cloud cover, slight enhancement for AOD=1.2 with 50% cloud cover, and negligible enhancement when 75% or more of the day is cloud-covered.

5. Influence of Canopy Thickness

In this experiment, we assess the sensitivity of smoke-induced GPP enhancement to canopy thickness. With small LAI (1.0), the enhancement is minute. This is because the majority of leaf surface is sunlit, so any decrease in insolation decreases GPP. The decrease is only small, though, because the exposed leaves are near light saturation – the slight insolation reduction from smoke reduces photosynthesis rates only slightly. With LAI > 3 (typical of Amazonia), there is a substantial GPP enhancement during cloudless conditions, because of the increase in PAR reaching shaded leaves. The enhancement increases with increasing LAI, but asymptotes above an LAI of 5.

References


Conclusions

- Smoke with optical depth less than ~2.5 enhances daily-mean GPP for typical cloudless Amazon conditions. Both the AOD of maximum GPP enhancement and the magnitude of enhancement depend on the aerosol absorptivity – smoke with lower single-scatter albedo enhances GPP less.
- When clouds of moderate thickness are present, smoke of any optical thickness decreases GPP, regardless of whether the smoke layer is above or below the cloud.
- The NPP-enhancement effect of smoke is greater in thicker canopies.
- Considering only light-related effects, we find it unlikely that smoke enhances GPP in regions with cloud cover greater than 50% of the time (box 4).