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Authors

Doughty, Russell
Köhler, Philipp
Frankenberg, Christian
et al.

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TROPOMI reveals dry-season increase of solar-induced chlorophyll fluorescence in the Amazon forest

Russell Doughty^a, Philipp Köhler^b, Christian Frankenberg^{b,c}, Troy S. Magney^b, Xiangming Xiao^{a,1}, Yuanwei Qin^a, Xiaocui Wu^a, and Berrien Moore III^d

^aDepartment of Microbiology and Plant Biology, University of Oklahoma, Norman, OK 73019; ^bDivision of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125; ^cJet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; and ^dCollege of Atmospheric and Geographic Sciences, University of Oklahoma, Norman, OK 73019

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Photosynthesis of the Amazon rainforest plays an important role in the regional and global carbon cycles, but, despite considerable in situ and space-based observations, it has been intensely debated whether there is a dry-season increase in greenness and photosynthesis of the moist tropical Amazonian forests. Solar-induced chlorophyll fluorescence (SIF), which is emitted by chlorophyll, has a strong positive linear relationship with photosynthesis at the canopy scale. Recent advancements have allowed us to observe SIF globally with Earth observation satellites. Here we show that forest SIF did not decrease in the early dry season and increased substantially in the late dry season and early part of wet season, using SIF data from the Tropospheric Monitoring Instrument (TROPOMI), which has unprecedented spatial resolution and near-daily global coverage. Using in situ CO₂ eddy flux data, we also show that cloud cover rarely affects photosynthesis at TROPOMI's midday overpass, a time when the forest canopy is most often light-saturated. The observed dry-season increases of forest SIF are not strongly affected by sun-sensor geometry, which was attributed as creating a pseudo dry-season green-up in the surface reflectance data. Our results provide strong evidence that greenness, SIF, and photosynthesis of the tropical Amazonian forest increase during the dry season.

photosynthesis | productivity | MODIS | EVI | geometry

It has been heavily debated among the remote sensing and ecological research communities whether there is a dry-season green-up and increase in photosynthesis of the moist tropical Amazon forest (1–5). The answer to this question has important implications for understanding Earth's carbon fluxes and the impact of climate variability and climate change on those fluxes. However, a resolution to this debate has been delayed due to arguments that the geometry between the satellite sensors and the sun causes a pseudoseasonality in the reflectance data (4, 6).

Traditionally, spaceborne Earth surface reflectance data over the terrestrial biosphere have been used to calculate vegetation indices, which are useful for observing changes in canopy “greenness” and estimating chlorophyll content at large spatial scales (1, 7). However, vegetation indices do not provide direct information on the fate of sunlight absorbed by chlorophyll (absorbed photosynthetically active radiation [APAR_{chl}]), whose individual photons take one of 3 pathways: photosynthesis, heat dissipation, and chlorophyll fluorescence (8). Under favorable conditions, most APAR_{chl} is used for photosynthesis, and a small amount ($\leq \sim 2\%$) is emitted by chlorophyll as fluorescence in the red and far-red portion of the electromagnetic spectrum (~ 650 nm to 800 nm), which is created by the deexcitation of absorbed photons in all living plants (9).

Recently, quantification of the emission of solar-induced chlorophyll fluorescence (SIF) has become feasible from space, providing ample new opportunities to investigate the functioning of the photosynthetic machinery from remote sensing platforms (10–12). SIF retrievals require high spectral resolution and signal-to-noise ratio, and the only satellite instruments that have met these requirements were designed for atmospheric remote sensing, such as the Greenhouse Gases Observing Satellite, Global

Ozone Monitoring Experiment 2, and Orbiting Carbon Observatory 2 (13–16). Although the global SIF datasets developed from these satellite observations have provided valuable insight into vegetation dynamics on Earth's surface, their coarse spatial and temporal resolutions have not sufficiently resolved some important questions about the spatial distribution and temporal variability of SIF and photosynthesis on Earth. SIF is not a direct measure of photosynthesis, but satellite- and in situ-observed SIF has been shown to have a strong positive linear relationship with photosynthesis at the canopy scale (13, 15, 17), implying that changes in canopy SIF indicate changes in photosynthesis in the same direction (18, 19). The Tropospheric Monitoring Instrument (TROPOMI), a spectrometer onboard the Sentinel-5 Precursor satellite launched in October 2017 by the European Space Agency, enables a step change in SIF research, providing unprecedented high spatial and temporal resolution SIF observations that can address many of these important questions (20).

Here we report and analyze TROPOMI SIF data from March 2018 to June 2019 over the Amazon. TROPOMI's high spatial and temporal resolution reveals previously unknown details on the spatial distribution of SIF in the Amazon (Fig. 1A–C) and enables us to track SIF for forests and nonforests over time (Fig. 2A and *SI Appendix*, Figs. S1–S4). We show evidence that there is an overall dry-season increase in photosynthesis by Amazonian forests (Fig. 2A), where there was relatively little change in SIF in the early dry season (June through July), but a substantial increase in SIF in the late dry season (September through October) (Figs. 1A–C and 2A). Middle dry-season TROPOMI SIF in Fig. 1B, a point in time when the difference between forest and

Significance

The Amazon is the largest terrestrial contributor to global atmospheric carbon fluxes, but it has been debated whether photosynthesis in the Amazonian forest increases during the dry season. We now report new evidence that there is a dry-season increase in photosynthesis in the Amazon rainforest, using observations of solar-induced chlorophyll fluorescence from the Tropospheric Monitoring Instrument (TROPOMI), which has been shown to be a promising proxy of photosynthesis. The new findings point the way toward future research that addresses the implications of Amazonian seasonality on the global carbon cycle.

Author contributions: R.D., X.X., and B.M. designed research; R.D., P.K., C.F., T.S.M., X.X., Y.Q., X.W., and B.M. performed research; R.D., P.K., and C.F. contributed new reagents/analytic tools; R.D. and P.K. analyzed data; and R.D., P.K., C.F., T.S.M., X.X., Y.Q., and X.W. wrote the paper.

The authors declare no competing interest.

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¹To whom correspondence may be addressed. Email: xiangming.xiao@ou.edu.

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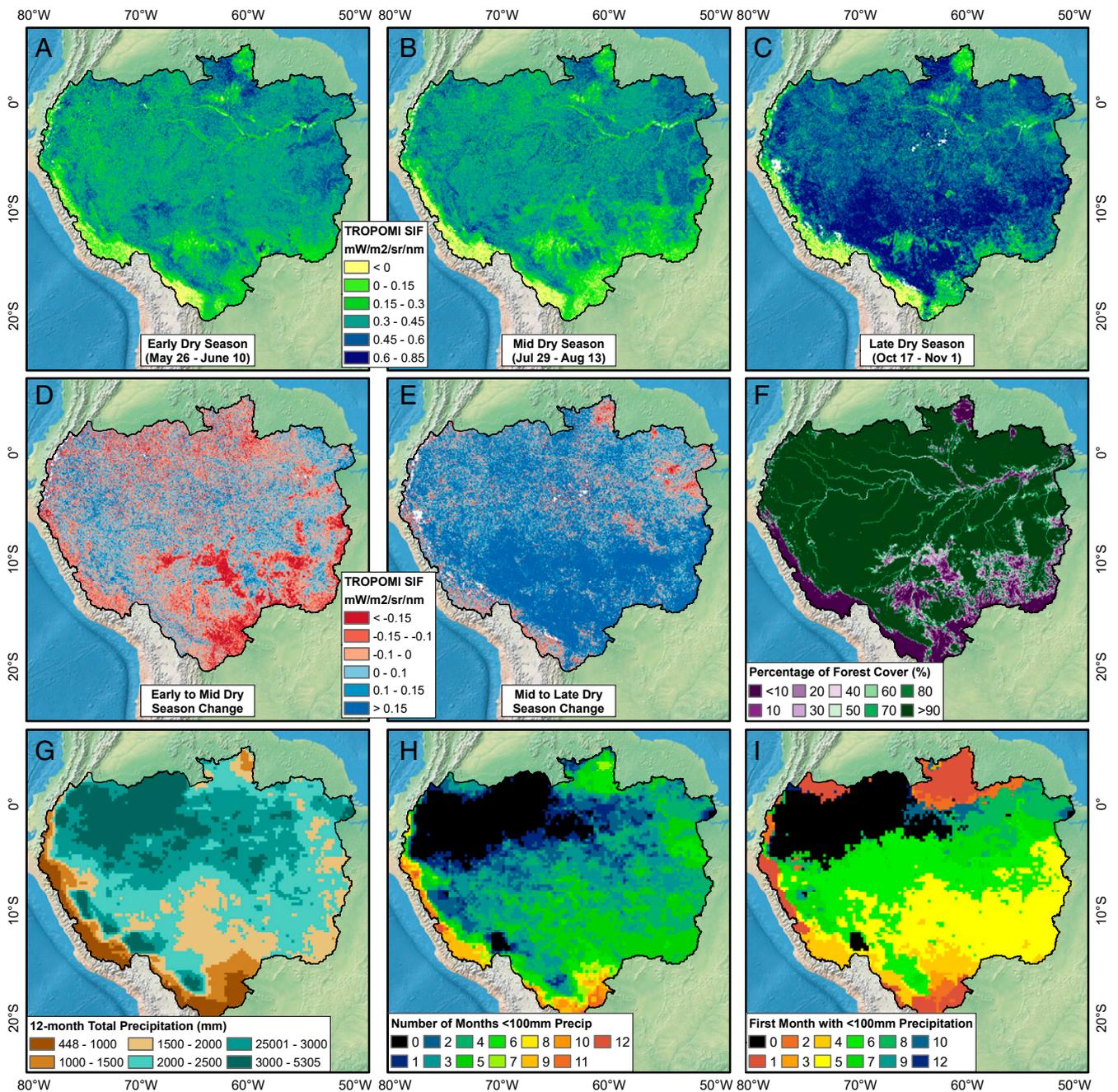


Fig. 1. SIF, forest cover, and precipitation in the Amazon Basin. SIF during the (A) early, (B) middle, and (C) late dry season. (D) Middle minus early dry-season SIF. (E) Late minus middle dry-season SIF. (F) Percentage forest cover in each TROPOMI 0.05° pixel. (G) Total precipitation March 2018 to February 2019. (H) Number of months with <100 mm of precipitation. (I) First month with <100 mm precipitation.

nonforest SIF is greatest, mimics the percentage of forest cover in each TROPOMI grid cell shown in Fig. 1F. The Amazon River and its tributaries in the northern part of the basin are also evident in Fig. 1A–C where surface water induces low SIF values. Wet-season SIF for seasonally moist forests (<2,000 mm mean annual precipitation [MAP]) was higher than SIF for moist forests (>2,000 mm MAP), which indicated that perhaps the productivity of seasonally moist forests was water-limited (Fig. 2). The ~2,000-mm MAP threshold has previously been found to determine whether water is a factor limiting photosynthesis in tropical forests (21).

For nonforest in the Amazon, SIF declined considerably in the early dry season (*SI Appendix, Figs. S1 and S4*), especially in the

cropland region of central Bolivia and in the arc of deforestation in the Brazilian states of Acre, Rondônia, and Mato Grosso (Fig. 1D). In the late dry season, nonforest SIF continually increased. There were some hotspots where SIF decreased during the late dry season, notably in the Serra do Cachimbo Mountain region, the plains of the Brazilian state of Roraima, and the deforested areas in the vicinity of Santarém and Altamira (Fig. 1E).

In forests, the dry-season increase in SIF can be attributed to the loss of old leaves, the flushing of new leaves, and an increase in canopy chlorophyll content, which has been observed using in situ litterfall traps, tower-based time lapse photography, and satellite-based vegetation indices (1, 22, 23). For nonforest lands in the arc of deforestation, the decrease in SIF can be attributed to the

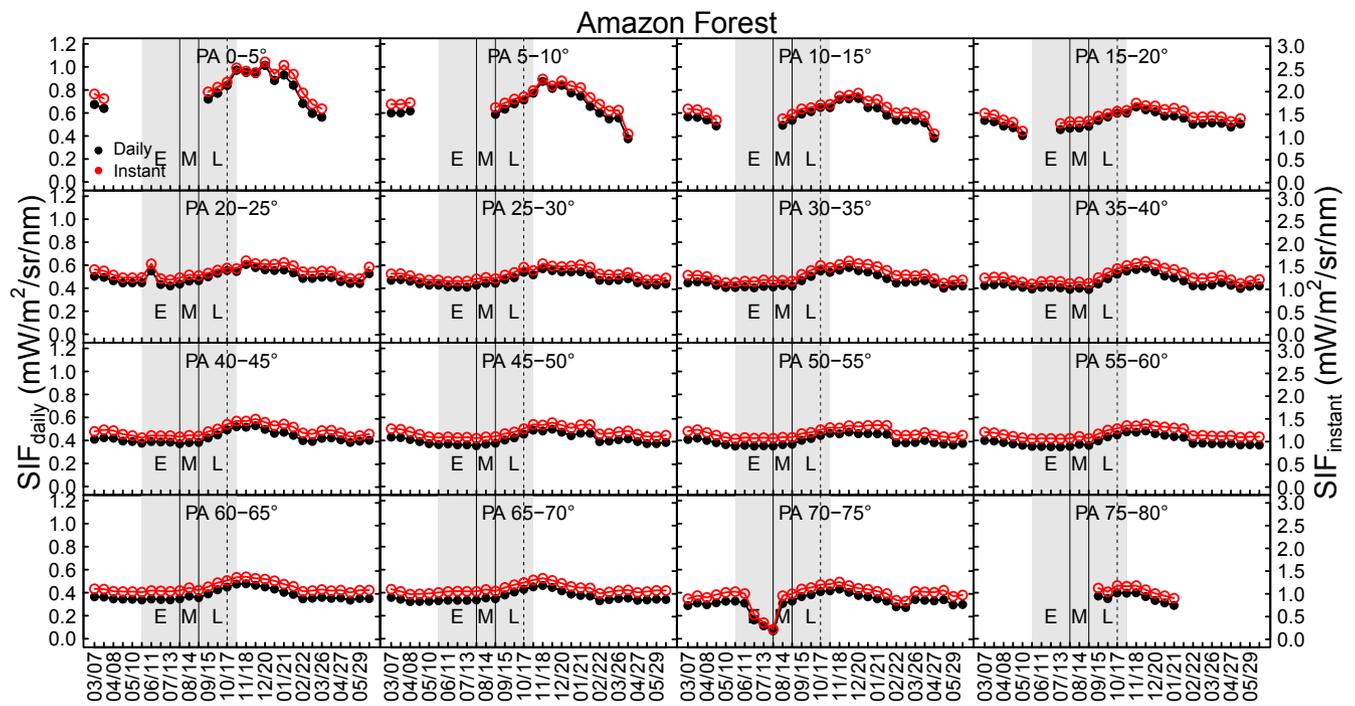


Fig. 4. TROPOMI SIF_{daily} and SIF_{instant} at different phase angles for the Amazon forest. Areas shaded in gray represent the early (E), middle (M), and late (L) dry seasons. The dashed line approximates when TROPOMI's phase angles are lowest. These trends were also illustrated for moist and seasonally moist forest with greater than and less than 2,000-mm MAP and for nonforest in *SI Appendix, Figs. S6–S8*. Dates represent the first day of TROPOMI's 16-d revisit cycle. Tick marks are every 16 d, and labels are every 32 d. The complete date range represented is 7 March 2018 to 29 June 2019.

to decrease after the phase angles of the TROPOMI soundings reached their minimum. However, SIF increased for several weeks after TROPOMI phase angles began increasing and despite increased cloud cover (Fig. 2). We also found a significant and strong relationship between TROPOMI SIF and bidirectional reflectance distribution function (BRDF)-corrected enhanced vegetation index (EVI) from Moderate Resolution Imaging Spectroradiometer (MODIS) MCD43A4 for moist and seasonally moist forest ($R^2 = 0.82$ and 0.93 , respectively), and between TROPOMI SIF for moist forest and the K83 tower site ($R^2 = 0.66$) (*SI Appendix, Fig. S9*).

The seasonality of TROPOMI SIF agrees with in situ seasonality of photosynthesis and MODIS EVI (Fig. 2*A* and *B*), but to what extent do incoming solar radiation and cloud cover affect canopy photosynthesis and spaceborne observations of SIF in the Amazon? The amount of photosynthetically active radiation reaching the top of the canopy (PAR_{TOC}) is determined by the difference between the amount of incoming PAR at the top of the atmosphere (PAR_{TOA}) from the sun and the amount of PAR reflected into space and absorbed by clouds, trace gases, aerosols, and particulate matter (ΔPAR). Thus, seasonality in PAR_{TOA} (length of day and solar angle) and ΔPAR (mostly cloud cover/thickness) determine the amount and timing of instantaneous and daily PAR_{TOC} ($PAR_{TOC} = PAR_{TOA} - \Delta PAR$), which drives photosynthesis and serves as a phenological queue for tropical tree species (26).

Diurnally, there is a tight relationship between PAR_{TOC} and photosynthesis in the morning and evening, as they rise and fall in tandem (27). At midday, the relationship between PAR_{TOC} and photosynthesis decouples as the canopy becomes light-saturated (*SI Appendix, Fig. S10*). Using in situ data, we found that, during TROPOMI's early afternoon overpass time of 12:45 PM to 2:30 PM local solar time (LST) over the Amazon (*SI Appendix, Fig. S11*), photosynthesis is nearly always light-saturated (Fig. 5*A–C*) and ΔPAR rarely impacts photosynthesis (Fig. 5*D–F*). Dense clouds can block the emission of SIF into space, and TROPOMI soundings

are prefiltered to remove soundings that are affected by high radiance levels due to cloud albedo and that have $>80\%$ cloud fraction. However, in situ data indicate that cloud cover rarely blocks enough solar irradiance at TROPOMI's overpass time to induce light limitation of photosynthesis (Fig. 5). We cannot completely rule out that seasonal changes in cloud cover and optical thickness may affect SIF dynamics in the Amazon, but we did observe that the strongest increase in SIF occurred during the middle to late dry season despite reduced PAR_{TOC} and increased ΔPAR and cloud fraction (*SI Appendix, Fig. S12*), which suggests that changes in cloud properties during the dry season have an insignificant effect on SIF retrievals. The seasonality of forest SIF was most similar to PAR_{TOA} , indicating that perhaps the timing of leaf flush in the forest is photosensitive to the length of the day and/or responsive to herbivory, which are not necessarily mutually exclusive (1, 28, 29).

In summary, the dry-season increase of TROPOMI SIF in the Amazon mimics the dry-season increase of photosynthesis as estimated from eddy flux data (23), in situ observations by phenological cameras of seasonal canopy senescence and leaf flush (22, 30), and BRDF-corrected, reflectance-based satellite observations (3, 11, 21, 31). Our results not only help resolve the debate over whether there is a dry-season increase in photosynthesis in moist tropical Amazon forest but also indicate that changes in photosynthesis during the dry season are largely driven by land cover type and changes in the forest canopy.

Materials and Methods

TROPOMI Observations. We used daily corrected ungridded TROPOMI SIF data for all data analysis (Fig. 1 and *SI Appendix, Figs. S1–S4*) and daily corrected gridded TROPOMI SIF data in 0.05° spatial resolution for visualization in Fig. 1 (20). Gridded (0.20°) and ungridded data are available at <http://fluio.gps.caltech.edu/data/tropomi/>. It is also important to note that aerosols and clouds have different effects on SIF and reflected radiance at top-of-atmosphere (decreasing SIF, increasing reflectance), and cloud shadows reduce reflectance but not necessarily photosynthesis (Fig. 5), so any reflectance-based correction may introduce an

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