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A Comprehensive Assessment of the Climatic Impact of the 2015 Indonesian Fire Peak Period: From Emissions to Radiative Forcing

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Abstract. The 2015 wildfire season in Indonesia, fueled by an extremely strong El Niño, ranked as the most severe wildfire season of the 21st century, with profound implications for global greenhouse gas budgets and the broader climate system. This study first precisely quantified the extremity of the 2015 Indonesian fire, revealing that key metrics (fire count, radiative power, estimated burned area) surged to levels substantially exceeding the 2010–2020 baseline—with September's fire count Z-score peaking at 7.1. A high-resolution greenhouse gas emission inventory was also constructed, whose detectable contribution to atmospheric greenhouse gas concentrations was quantified; this further corroborated a strong lagged correlation (r=0.97, p=0.006) between fire emissions and atmospheric CO_2 concentrations. Ultimately, the direct climate impact of the fires was quantified: the emission pulse exerted an average instantaneous radiative forcing of ~0.011 W/m^2 over the peak burning period, a quantifiable perturbation equivalent to ~0.5% of the total radiative forcing from anthropogenic CO_2 accumulated since 1750. This case highlights the significant, pulse-like role of extreme fire events in the global carbon-climate system.

Keywords: 2015 Indonesian fire, Climatic impact, Greenhouse gas emissions, Radiative forcing, Climate feedback mechanism

1. Introduction

Indonesian tropical peatlands constitute one of the world's largest terrestrial carbon sinks. During the 2015 extreme El Niño, prolonged drought rendered these ecosystems highly flammable, triggering the most severe fire season of the 21st century [1,2]. While existing studies have qualitatively characterized the "extremity" of the 2015 fires and offered preliminary estimates of total emissions, substantial research gaps persist. Firstly, there is a paucity of systematic, multi-dimensional, and precise quantification of the fire's "extreme magnitude" based on long-term historical datasets. Secondly, high uncertainties in peatland burning emission factors result in insufficient precision in current assessments of the greenhouse gas composition of this event—particularly CH_4, a gas with high global warming potential [3]. Thirdly, while most studies have focused on bottom-up emission source estimations, research employing top-down atmospheric

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concentration observations to directly identify, isolate, and quantify the net contribution of this fire event to elevated atmospheric CO_2 and CH_4 concentrations remains limited. Finally, the complete chain from emissions to climate effects, specifically radiative forcing, has not been fully quantified, constraining our capacity to evaluate the short-term impacts of such extreme events on the global energy balance. Therefore, this study seeks to address these research gaps through two core objectives: first, to precisely quantify the extreme magnitude of the event using multi-source satellite data; second, to develop a high-resolution greenhouse gas emission inventory. Employing a top-down approach, this study utilizes GOSAT concentration data to detect distinct atmospheric greenhouse gas pulses. It further isolates fire-induced CO_2 and CH_4 signals by computing differences between regional and global concentration anomalies. This work ultimately delivers a novel and comprehensive case study, advancing our understanding of the climate feedback mechanisms associated with extreme fire events under global warming.

2. Extremity and drivers of the 2015 Indonesia fire

During the peak fire period of 2015, all measured metrics—including fire count, total Fire Radiative Power (FRP), and estimated burned area—surged to levels substantially exceeding those of historical reference periods.

A detailed monthly analysis of fire count anomalies further emphasizes the severity of the 2015 wildfire season (Figure 1). The extreme intensity of this event is particularly pronounced in the peak monthly values: in October 2015, FRP increased by 841% relative to the 2010–2020 historical average, while fire count rose by 609% and estimated burned area surged by 841%. While August exhibited a significant positive anomaly, the months of September, October, and December were marked by extreme anomalies. September's Z-score peaked at a remarkable 7.1—a statistical metric indicating an event well outside the normal distribution and underscoring the intense concentration of fire activity during late summer and autumn. The convergence of these record-breaking metrics in October—with FRP and estimated area both exceeding 800% of historical levels—attests to an unprecedented scale of fire intensity and spatial extent. Collectively, these findings offer multifaceted evidence that the 2015 wildfire season was not only severe but also temporally concentrated, with its most intense phase occurring in the latter half of the year, culminating in the extreme October anomalies.

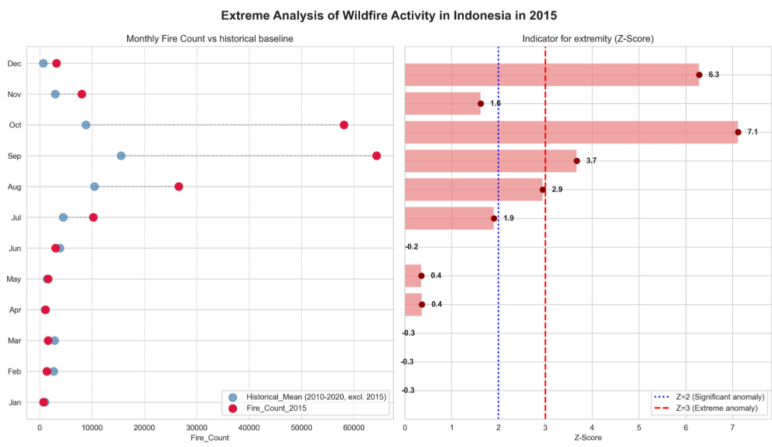

Figure 1. (left) Monthly fire count of 2015 vs the historical average value from 2010-2020 except 2015.(right) value of Z-score in each month

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A consistently nonlinear relationship has been documented between dry-season precipitation and various indicators of fire and pollution [2]. Employing the piecewise linear regression approach outlined by Robert D. Field, this study established a piecewise linear relationship between Self-Calibrating Palmer Drought Severity Index (scPDSI) data—sourced from the Climatic Research Unit (CRU) at the University of East Anglia's School of Environmental Sciences—and fire count data acquired from the Fire Information for Resource Management System (FIRMS) during the 2015 fire season [4]. The analysis identified an scPDSI threshold of -1.8602. When the scPDSI falls below this threshold, indicating escalating drought severity, the fire count increases rapidly. Conversely, when conditions exceed this threshold (less dry), the fire count increases only slowly and marginally [2]. The application of this model to the 2015 data yields valuable insights. During the peak of the 2015 Southeast Asian fire season, scPDSI values dropped below this threshold, coinciding with a sharp rise in fire counts.(Figure 2) This finding, from the perspective of drought indicators, cross-validates the causal inference that during the 2015 El Niño event, peatlands dried sufficiently to ignite, thereby triggering widespread fires [5-7].

It is crucial to emphasize, however, that the impacts of El Niño-induced drought were substantially amplified by pre-existing anthropogenic activities [8,9]. Extensive drainage for agricultural and plantation purposes had already lowered the water table across vast peatland areas, rendering them highly susceptible to ignition during dry periods [7]. Furthermore, land-use change has fundamentally altered the fire regime itself, with both fire ignition probability and peat combustion depth increasing significantly in degraded non-forest shrublands and in areas proximal to drainage canals [8].

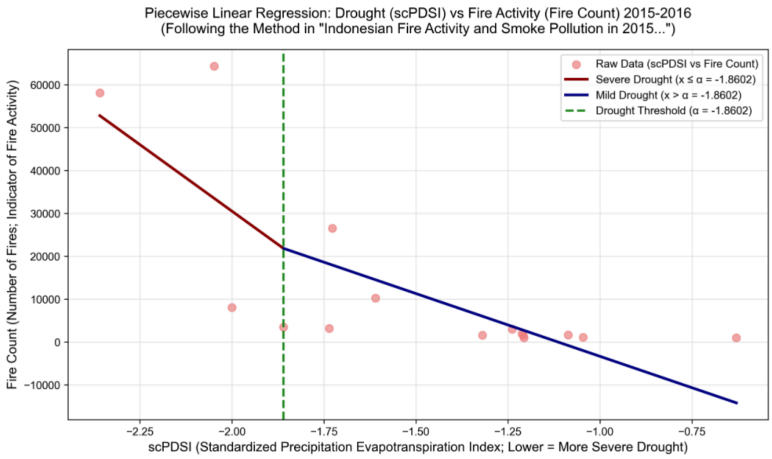

Figure 2. Piecewise linear regression of drought (scPDSI) and fire count in Indonesia, 2015-2016

3. Quantification of greenhouse gas emissions (CO_2, CH_4)

To quantify the emissions of the 2015 fire season, the study calculated the "bottom-up" data, which is the emission of the primary emitted gases (CO_2 and CH_4), verified by the "top-bottom" data, which is the concentration of these two types of gases in the atmosphere. For the emission data, we employed data from the Global Fire Emissions Database (GFED), specifically Version 5.1 (GFED5.1; Global Fire Emissions Database, 2024). This comprehensive database integrates multi-source satellite observations (primarily from MODIS) and biogeochemical modeling to quantify fire emissions. Key parameters—including burned area—are derived from the MODIS MCD64A1 Collection 6 product. The emission calculations are based on a bi-directional modeling approach that considers fuel type, fuel load, combustion completeness, and species-specific emission factors. The

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dataset provides gridded estimates for a wide range of trace gases and aerosols, including carbon (C), CO_2, CO, CH_4, and PM2.5, which are critical for assessing the atmospheric impact of wildfires.

Regional CO_2 and CH_4 emissions were calculated by multiplying grid-specific emission factors with burned area data, enabling a subsequent quantification of the emission anomaly for the 2015 fire season. The result of the Z-score analysis verified that the 2015 Indonesian wildfire season was an extreme greenhouse gas emission event, with both CO_2 and CH_4 emissions far exceeding historical baselines (2002–2020, excluding 2015). In terms of data, for CO_2, emissions in September 2015 reached approximately 393.94 Tg/month, greatly surpassing the historical average of approximately 84.58 Tg/month, and the Z-scores for CO_2 emissions in September, October, and December all exceeded the threshold for an extreme anomaly ($Z > 3$). For CH_4, the Z-scores in September, October, and December also exceeded the threshold for an extreme anomaly ($Z > 3$). This extreme emission event is closely linked to intensified fire activity driven by the 2015 El Niño-induced drought, highlighting the close connection between climate anomalies in Southeast Asia and wildfire greenhouse gas emissions [2].

This study employed the monthly GOSAT Level 3 (L3) gridded products, which provides global column-averaged CO_2 and CH_4 dry air mole fraction (XCO_2) data at a monthly temporal resolution on a 2.5°× 2.5°spatial grid. Monthly mean XCO_2 and XCH_4 values for the Southeast Asian region (11°S–6°N, 70°E–150°E) during 2011 were extracted to analyze the lagged response relationship between wildfire emissions and atmospheric concentrations. To isolate the regional fire signal, the difference between Indonesian and global concentration anomalies was computed.

A correlation analysis was performed between emission and concentration data during the 2015 fire season (July–December). For CO_2, the primary analysis showed that the correlation between emissions and concentrations in the current month is not significant ($r=0.484$, $p=0.3306$). However, considering the time lag of the atmospheric transport and response, the analysis revealed that when emissions were lagged by one month, a stronger correlation with concentration signals was observed ($r=0.971$, $p=0.006$). As shown in Figure 3, the high-emission period of fire in July and August corresponds to the peak of atmospheric concentration in August and September. This phase shift further confirms the existence of a hysteresis effect. In particular, the concentration peak in September (1.32 ppm) was highly consistent with the emission peak in August in terms of time, demonstrating the identifiable signal transmission from emission to observation.

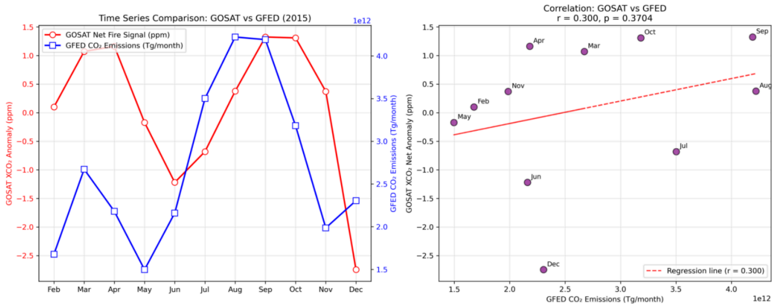

Figure 3. Time series comparison between emissions and concentrations of CO_2

For CH_4, the correlation with emissions is significantly stronger when analyzed across the entire 2015 calendar year with a one-month lag ($r = 0.775$, $p = 0.041$) compared to the fire season alone (July-December; $r = 0.537$, $p = 0.351$). This discrepancy can be attributed to several interrelated factors. Primarily, the limited six-month sample size during the fire season reduces statistical power. Furthermore, non-fire sources—i.e., biogenic and thermogenic methane (excluding pyrogenic

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methane as defined by the Global Methane Budget framework of Saunois et al. (2025))—such as waterlogged soils, swamps, rice paddies, and peatlands, which are significant in Indonesia [10-12], contribute a substantial background signal. Lower agreement (>66% discrepancy) in biomass combustion estimates derived from top-down approaches has been discussed in other methane emission-related literature [10]. This result highlights the significant uncertainty that still exists in our understanding of CH_4 emissions.

The one-month lag between emission and concentration peaks reflects monsoon-driven transport: fires inject CO_2/CH_4 into the lower-mid troposphere in July–October, and southeasterly winds plus deep vertical mixing require ~4 weeks to homogenise the plume regionally before GOSAT detection. Consequently, despite the distinct temporal patterns between CO_2 and CH_4, the identified time-lagged correlations for both gases correspond to the fundamental physical process of atmospheric transport and mixing, thereby providing a robust top-down validation of fire emissions.

4. Climatic impact: radiative forcing and temperature response

To quantify the direct climatic impacts of the pulse-like GHG emissions from the 2015 Indonesian fires, instantaneous radiative forcing (RF) was first estimated. The calculation was based on the net increase in atmospheric concentrations of CO_2 and CH_4 primarily attributable to the fires—i.e., the cleaned regional anomaly signals derived from GOSAT data, which represent the net contribution of the fire season after subtracting global background anomalies. Formulas recommended by the IPCC Third Assessment Report (TAR) were adopted [13].

For CO_2, the RF was calculated using the expression: $\Delta RF = \alpha \cdot \ln(C / C_0)$, where α is 5.35W/m^2 based on radiative transfer calculations incorporating three-dimensional climatological meteorological input data (Myhre et al., 1998b), C is the perturbed concentration (background + fire-induced anomaly), and C_0 is the reference pre-industrial concentration [14]. This calculation utilized an initial background CO_2 concentration of 393.60 ppm at the onset of the fire season (August 2015). For CH4, the radiative forcing was calculated using the following formula from the same IPCC report:

$$\Delta F = \alpha\left(\sqrt{M} - \sqrt{M_0}\right) - \left[f\left(M, N_0\right) - f\left(M_0, N_0\right)\right] \quad (1)$$

$$f\left(M, N\right) = 0.47 \times \ln[1 + 2.01 \times 10^{-5} \times \left(MN\right)^{0.75} + 5.31 \times 10^{-15} \times M\left(MN\right)^{1.52}] \quad (2)$$

and the constant α equals 0.036. M is the perturbed concentration (background + fire-induced anomaly), M_0 is the reference pre-industrial concentration, and N_0 is the background concentration of the N_2O. The 2015 global annual mean CH_4 concentration of 328 ppb, reported by the World Meteorological Organization (WMO), was adopted as the baseline value (N_0) [14].

The monthly net radiative forcing derived from fire-induced XCO_2 and XCH_4 anomalies exhibited significant temporal variability across 2015, CO_2 anomaly-related RF peaked prominently at +17.95 mW/m² in September 2015 (coinciding with the period of most intense fire activity), while XCH_4-related RF reached 3.007 mW/m² in October. The average radiative forcing during the peak of the fire season of CO_2 is 11.46mW/m², and that of CH_4 is 1.66. This reflects the sustained climatic impacts of the pulse-like CO_2 and CH_4 emissions during the most intense burning phase.

This study quantifies that CO_2 emissions from the 2015 extreme Indonesian fire event (August–November) produced an instantaneous radiative forcing of approximately 0.01146 W/m². To evaluate the climatic relevance of this forcing, the potential global temperature response was

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estimated using the IPCC-established climate sensitivity parameter (λ ≈ 0.8 °C/(W·m-2)) established by the IPCC [15]. The result indicates that this forcing corresponds to an equilibrium global mean temperature increase of approximately 0.01°C.

While this absolute temperature change appears modest, its climatic significance becomes apparent when considered in context: this single, regional fire event, occurring over only four months, contributed a radiative forcing equivalent to about 0.53% of the total CO_2-induced forcing accumulated from all global anthropogenic activities since the Industrial Revolution (2.16 W/m²). Stated alternatively, the event perturbed the Earth's energy balance by an amount equivalent to roughly 0.5% of the forcing accumulated over more than two centuries of industrial activity.

This comparison underscores that the 2015 Indonesian fires constituted a sharp, pulse-like perturbation to the climate system. Such discrete extreme events are not merely regional environmental crises; they represent globally quantifiable, physically meaningful injections of RF that can temporarily accelerate the trajectory of climate change. It is important to note that the estimated 0.01°C warming reflects an idealized equilibrium response; the actual transient temperature evolution would be modulated by the atmospheric residence time of GHGs and oceanic thermal inertia.

5. Conclusion

This study demonstrates that the 2015 El Niño event served as a critical climatic trigger, inducing severe drought conditions that precipitated an extreme fire season in Indonesia. Our findings indicate that the emission pulse from these fires not only produced a detectable signal in atmospheric GHG concentrations—exhibiting a distinct one-month lagged correlation—but also generated a quantifiable radiative forcing of approximately 0.011 W/m^2 during the peak burning period. This forcing, while transient, represents a meaningful perturbation to the Earth's energy balance, highlighting the role of episodic extreme fires in the global carbon-climate system. Nevertheless, this study has certain limitations. Uncertainties in emission factors—particularly for peatland combustion—persist as a challenge for bottom-up emission quantification. Furthermore, the spatial resolution of the GOSAT satellite data, though valuable for regional-scale analysis, may not fully resolve fine-scale concentration plumes from intense yet localized fires. Future research should prioritize refining peatland carbon stock maps, integrating machine learning techniques to enhance emission quantification, and employing Earth system models to better simulate the long-term feedbacks between climate-driven fire events and the global carbon cycle.

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