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Consecutive Dry Days as a Scale-Dependent Predictor of Tropical Peatland Fire Occurrence in Indonesia

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Abstract

Tropical peatland fires in Indonesia generate severe environmental, health, and economic impacts, yet current fire prediction systems exhibit scale-dependent limitations. This study investigates the relationship between Consecutive Dry Days (CDD) indices and fire occurrence across multiple spatial scales in South Sumatra and West Kalimantan provinces (2015-2019). Using hierarchical buffer analysis (25, 50, 100, 150 km radii) around meteorological stations, we analyzed MODIS hotspot data with >80% confidence against CDD classifications. Maximum CDD values reached 41 days (South Sumatra) and 27 days (West Kalimantan) during the 2015 El Niño event. Correlation analysis revealed pronounced scale dependency, with optimal meteorological station representativeness at 50 km radius ($\boldsymbol{r = 0.776}$–$\boldsymbol{0.821}$, $\boldsymbol{p < 0.01}$). Weak negative correlations at 25 km radii reflect urban bias in station placement, while correlations degraded

beyond 100 km due to atmospheric boundary layer constraints. Hotspot frequencies increased exponentially with CDD duration, particularly on peatlands where very long droughts (>30 days) generated **156.2±34.7** hotspots per event. These findings indicate current meteorological networks inadequately sample fire-prone landscapes, suggesting strategic station deployment at 50 km intervals could substantially improve early warning systems across Southeast Asia's vulnerable peatland regions.

Keywords: atmospheric boundary layer, drought index, fire prediction, peatland combustion, spatial scale

1 Introduction

Tropical peatland fires represent one of the most significant yet poorly constrained components of the global carbon cycle, with Indonesian fires alone contributing a substantial fraction of global fire carbon emissions during extreme events (van der Werf et al., 2017). The 2015 El Niño-induced fires in Indonesia released carbon dioxide equivalent exceeding the annual fossil fuel emissions of major industrialized nations, creating atmospheric perturbations detectable at global monitoring stations (Huijnen et al., 2016). During peak burning periods, daily emissions surpassed those of entire economic blocs, while particulate matter concentrations reached hazardous levels across a region spanning thousands of kilometers (Kiely et al., 2021). These emissions create a positive feedback loop with climate change, as increased atmospheric CO_2 enhances drought severity through regional warming and altered precipitation patterns, which in turn promotes more extensive fires (Tian et al., 2011).

The economic and public health impacts of tropical peatland fires extend far beyond their climate effects, creating cascading consequences across multiple sectors and nations. The 2015 Indonesian fires caused economic losses representing a significant fraction of national GDP, with damages distributed across carbon emissions costs, land-cover degradation, and health impacts (Kiely et al., 2021). This comprehensive assessment substantially exceeds earlier estimates by incorporating long-term health effects and ecosystem service losses previously unquantified. The transboundary nature of fire impacts manifested in substantial losses for neighboring countries, demonstrating how localized burning creates regional economic disruption (Sheldon and Sankaran, 2017).

Health impacts represent a particularly severe dimension of fire consequences, with smoke exposure from the 2015 fires resulting in widespread premature mortality across Southeast Asia (Marlier et al., 2015). The fine particulate matter generated by peat combustion penetrates deep into human lungs, causing acute respiratory infections, exacerbating chronic conditions, and triggering cardiovascular events (Edwards et al., 2020). Children and elderly populations experienced disproportionate impacts, with pediatric respiratory hospitalizations increasing dramatically in affected regions during peak haze periods (Hein et al., 2022).

Despite these severe impacts, current fire prediction systems exhibit fundamental limitations in tropical peatland environments, where unique hydrological processes and combustion dynamics differ markedly from the temperate and boreal systems for which most indices were developed (Taufik et al., 2017). The Canadian Fire Weather Index System, widely adopted globally, fails to account for the critical role of groundwater depth in controlling peat ignitability, while the Keetch-Byram Drought Index underestimates moisture deficits in organic soils with high water-holding capacity (Kudláčková et al., 2024). These systemic inadequacies result in delayed warnings, misallocated suppression resources, and preventable damages to communities and ecosystems.

The challenge of predicting tropical fire occurrence stems partly from inadequate understanding of scale-dependent relationships between meteorological observations and fire activity. While weather stations provide point measurements of atmospheric conditions, fires respond to spatially integrated drought patterns influenced by atmospheric boundary layer (ABL) dynamics, mesoscale circulations, and landscape heterogeneity (Linn et al., 2025). The planetary boundary layer in tropical regions exhibits distinct characteristics—including strong diurnal cycles, frequent convective activity, and complex land-sea interactions—that modulate the spatial coherence of meteorological conditions (Zheng et al., 2023). The representative radius of meteorological stations—the spatial extent over which their measurements correlate with fire occurrence—remains poorly quantified despite its fundamental importance for operational fire warning systems (Vitolo et al., 2020).

Consecutive Dry Days (CDD) indices have emerged as promising predictors of fire danger in water-limited ecosystems, offering advantages over instantaneous meteorological variables by capturing cumulative moisture stress (O et al., 2020). The mechanistic relationship between precipitation deficits and fire occurrence operates through multiple pathways: direct desiccation of surface fuels, lowering of groundwater tables that expose deeper peat layers, and physiological stress on vegetation that increases dead fuel loads (Dadap et al., 2019). Unlike conventional fire weather indices that emphasize atmospheric vapor pressure deficits and wind speed, CDD directly quantifies the precipitation deficits that control peat moisture content—the primary determinant of tropical peat ignitability below critical moisture thresholds (Usup et al., 2004).

However, fundamental knowledge gaps persist in applying CDD indices to tropical fire prediction. The precipitation threshold defining a "dry day"—commonly set at a minimal value—derives from agricultural applications focused on crop water requirements rather than fire-specific calibration (Bohlmann and Laine, 2024). This arbitrary threshold may poorly represent the minimum precipitation needed to maintain peat moisture above ignition thresholds, particularly given the high evapotranspiration rates characteristic of tropical environments (Hirano et al., 2015). Furthermore, the relationship between surface precipitation and peat moisture involves complex interactions with canopy interception, preferential flow pathways, and lateral groundwater movement that simple threshold approaches cannot capture.

Indonesia's fire-prone provinces of South Sumatra and West Kalimantan exemplify the convergence of biophysical and anthropogenic factors that make tropical fire

prediction particularly challenging. These regions contain extensive degraded peatlands where decades of canal construction for agriculture and timber extraction have substantially lowered water tables, creating conditions conducive to deep smoldering combustion (Konecny et al., 2016). The interaction between drainage infrastructure and natural hydrology creates heterogeneous moisture patterns that vary at scales from meters to kilometers, complicating the extrapolation of point-based meteorological measurements to landscape-scale fire risk (Yokelson et al., 2022). During recent El Niño events, these provinces experienced severe burning, yet fire occurrence exhibited high spatial variability that current prediction systems failed to capture, with some drained areas burning extensively while adjacent undrained forests remained unaffected (Grosvenor et al., 2024).

The El Niño-Southern Oscillation (ENSO) modulates Indonesian precipitation through well-established teleconnections involving Walker circulation disruption and Indo-Pacific sea surface temperature anomalies (Hu et al., 2025). During El Niño events, anomalous subsidence over the Maritime Continent suppresses convective precipitation, extending dry seasons substantially and creating windows of extreme fire risk (Pan et al., 2018). However, the translation of these regional climate anomalies to local fire occurrence depends critically on processes operating across multiple spatial scales, from synoptic atmospheric patterns through mesoscale circulations to microtopographic variations in peat depth and drainage (Cobb et al., 2017). Previous studies have examined either large-scale climate drivers or local fuel conditions in isolation, but the intermediate scales at which meteorological measurements become representative of fire danger remain unexplored, creating a critical gap in multi-scale fire prediction frameworks.

This study addresses these critical knowledge gaps by systematically evaluating the relationship between CDD indices and fire occurrence across multiple spatial scales in South Sumatra and West Kalimantan provinces. Specifically, we test the hypothesis that meteorological station representativeness for fire prediction follows a scale-dependent pattern related to ABL processes and landscape characteristics. By analyzing half a decade of drought and fire data encompassing major El Niño events at multiple buffer distances from weather stations, we aim to: (1) quantify the optimal spatial scale for drought-fire correlations in tropical peatlands; (2) evaluate the effectiveness of CDD as a fire predictor compared to instantaneous meteorological variables; (3) identify the meteorological and landscape factors controlling the spatial coherence of fire danger; and (4) provide evidence-based recommendations for fire monitoring network design in tropical regions. Our findings have direct implications for improving early warning systems across Southeast Asia and other tropical regions where limited meteorological infrastructure must serve vast fire-prone landscapes, potentially preventing future disasters comparable to those experienced during recent El Niño events.

2 Materials and Methods

2.1 Study Area and Data Sources

The study encompasses two provinces in Indonesia characterized by extensive tropical peatland systems and pronounced fire vulnerability: South Sumatra ($\mathcal{A}_{\text{SS}} = 3.41 \times 10^6$ ha) and West Kalimantan ($\mathcal{A}_{\text{WK}} = 8.39 \times 10^6$ ha). These regions contain substantial peatland distributions with areas $\mathcal{A}_{\text{peat,SS}} = 9.21 \times 10^5$ ha and $\mathcal{A}_{\text{peat,WK}} = 1.54 \times 10^6$ ha, respectively (Tangang et al., 2017). The selection of these provinces is motivated by their unique fire dynamics, where smoldering peat combustion operates at temperatures of 500-700°C and can persist underground for weeks despite surface rainfall (Graham et al., 2022; Crawford et al., 2024).

The spatial domain $\Omega \subset \mathbb{R}^2$ is bounded by geographic coordinates $\phi \in [-5.0°, 2.0°]$ and $\lambda \in [102.0°, 114.0°]$, encompassing regions where ENSO teleconnections create predictable drought-fire patterns through Walker circulation disruption (Pan et al., 2018). The mechanistic pathway involves anomalous sinking air over Indonesia during El Niño events, with Eastern Pacific events causing nearly double the fire emissions of Central Pacific events due to stronger circulation anomalies (Field et al., 2016). Figure 1 illustrates the spatial distribution of meteorological stations and forest coverage across both provinces.

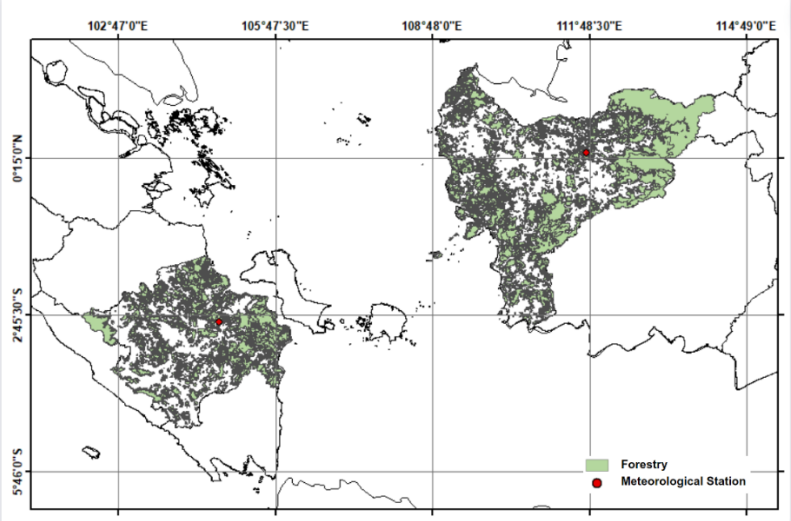

Fig. 1 Spatial distribution of study regions showing meteorological stations and forest coverage across South Sumatra and West Kalimantan provinces, overlaid on peatland distribution maps.

Ground-based meteorological observations $\mathbf{P} = \{P_t : t \in \mathcal{T}\}$ and satellite-derived hotspot data $\mathbf{H} = \{H_t : t \in \mathcal{T}\}$ were acquired for the temporal domain $\mathcal{T} = [t_0, t_f]$, where $t_0 =$ January 1, 2015 and $t_f =$ December 31, 2019. This period encompasses the 2015 El Niño event, which caused Indonesia's most severe fires since 1997, releasing massive quantities of CO_2 with daily emissions exceeding the entire European Union's

fossil fuel output (Kiely et al., 2021). Daily precipitation measurements were obtained from BMKG stations located at $\mathbf{s}_1 = (104.7°\text{E}, 2.9°\text{S})$ in South Sumatra and $\mathbf{s}_2 = (111.5°\text{E}, 0.15°\text{S})$ in West Kalimantan.

MODIS-derived hotspot data satisfying the confidence threshold $\kappa > 0.8$ were utilized following extensive validation studies in tropical forests (Giglio et al., 2016). The confidence metric emerges from brightness temperature anomaly tests:

$$\kappa = f(T_4, T_{11}, \Delta T_{4,11}, \sigma_{bg}), \tag{1}$$

where T_4 and T_{11} represent brightness temperatures at 4 μm and 11 μm channels, $\Delta T_{4,11} = T_4 - T_{11}$, and σ_{bg} denotes background variability. The 80% threshold balances commission errors from forest clearings (16% in tropical forests) against omission errors for understory fires obscured by dense canopies (Csiszar et al., 2006).

2.2 Consecutive Dry Days Index and Spatial Analysis

Let $\mathcal{P} = \{P_i\}_{i=1}^{N}$ represent the daily precipitation time series, where $N = |\mathcal{T}|$ denotes the total observation days. The CDD index quantifies drought persistence through the operator (Duan et al., 2017):

$$\Xi_j = \max_{\substack{i \in \mathcal{I}_j \\ i+n \leq N}} \left\{ n \in \mathbb{N} : \bigwedge_{k=0}^{n-1} \mathbb{I}(P_{i+k} < \tau) = 1 \right\}, \tag{2}$$

where $\mathcal{I}_j$ represents the index set for period j, and $\mathbb{I}(\cdot)$ denotes the indicator function. The precipitation threshold $\tau = 1$ mm day^{-1} follows ETCCDI standards (Zwiers and Zhang, 2009), though we acknowledge the absence of peer-reviewed validation for this specific threshold in tropical fire contexts (Chen et al., 2014). The mechanistic justification for drought thresholds in fire-prone ecosystems relates to soil moisture depletion rates and vegetation stress responses, with peatland systems exhibiting critical moisture thresholds of 200-400% (dry weight basis) for ignition (Mortelmans et al., 2024).

The Indonesian BMKG classification categorizes CDD values based on empirical observations of drought impacts on agricultural and forest systems:

$$\Psi(\Xi) = \begin{cases} \text{Very short} & \text{if } 1 \leq \Xi \leq 5 \\ \text{Short} & \text{if } 6 \leq \Xi \leq 10 \\ \text{Moderate} & \text{if } 11 \leq \Xi \leq 20 \\ \text{Long} & \text{if } 21 \leq \Xi \leq 30 \\ \text{Very long} & \text{if } \Xi > 30 \end{cases}. \tag{3}$$

This classification aligns with field observations showing nonlinear fire responses to drought duration, where peat fires exhibit threshold behavior once water tables drop below 40-60 cm (Gaveau et al., 2014).

To investigate scale-dependent relationships between meteorological observations and fire occurrence, we implemented a hierarchical buffer analysis using ArcGIS 10.8.

The theoretical foundation rests on ABL dynamics, where the planetary boundary layer height (typically 0.3-3 km in tropical regions) fundamentally determines meteorological representativeness (Werth et al., 2011). Let $\mathbf{s} \in \Omega$ denote a meteorological station location. The circular buffer zone $\mathcal{B}_r(\mathbf{s})$ at radius r is defined through the Euclidean distance metric:

$$\mathcal{B}_r(\mathbf{s}) = \{\mathbf{x} \in \Omega : \|\mathbf{x} - \mathbf{s}\|_2 \leq r\}, \tag{4}$$

where $\|\cdot\|_2$ represents the Euclidean norm. The multi-scale analysis employs radii $\mathbf{r} = \{r_1, r_2, r_3, r_4\} = \{25, 50, 100, 150\}$ km, generating nested buffer zones satisfying $\mathcal{B}_{r_i}(\mathbf{s}) \subseteq \mathcal{B}_{r_j}(\mathbf{s})$ for $i < j$.

The spatial coherence of meteorological conditions follows exponential decay based on turbulence theory (Stull, 1988):

$$\mathcal{R}(r) = \mathcal{R}_0 \exp\left(-\frac{r}{\Lambda}\right), \tag{5}$$

where $\mathcal{R}_0$ represents the autocorrelation at the origin and Λ denotes the decorrelation length scale, typically 2-5 times the ABL height. Diurnal variations in boundary layer structure create temporal variations in Λ, with convective daytime conditions enabling greater spatial coherence (1-2 km mixed layer) compared to stable nocturnal stratification (Koplitz et al., 2018).

The hotspot count within each buffer zone is computed through the spatial integral:

$$H_{k,r} = \int_{\mathcal{B}_r(\mathbf{s})} \sum_{t \in \mathcal{T}_k} h(\mathbf{x}, t)\, d\mathbf{x}, \tag{6}$$

where $h(\mathbf{x}, t)$ represents the hotspot density function and $\mathcal{T}_k = \{t : \Psi(\Xi_t) = k\}$ denotes the temporal subset corresponding to CDD class k as defined in Equation (3). In practice, this integral is approximated using the Spatial Join operation in ArcGIS through point-in-polygon containment tests based on the computational geometry algorithm of Ma et al. (2018).

2.3 Statistical Framework and Normalization

The normalized hotspot ratio compensates for varying drought frequency across classes, addressing the spatial autocorrelation inherent in fire occurrence patterns (Bataineh et al., 2006). For CDD class $k \in \mathcal{C}$ and radius r, we define:

$$\varrho_{k,r} = \frac{H_{k,r}}{|\mathcal{T}_k|}, \tag{7}$$

where $|\mathcal{T}_k|$ represents the cardinality of the temporal subset and $H_{k,r}$ is computed using Equation (6). This normalization accounts for the observation that longer drought periods naturally occur less frequently, preventing bias toward extreme events (Chen et al., 2014).

The correlation structure between CDD values and hotspot ratios is quantified through Pearson's product-moment correlation coefficient, justified by the Central Limit Theorem despite the non-normal distribution of fire occurrence data (Havlicek and Peterson, 1976). We apply logarithmic transformation to fire counts, converting multiplicative processes to additive ones suitable for linear analysis:

$$\rho_r = \frac{\mathbb{E}[(X - \mu_X)(Y_r - \mu_{Y_r})]}{\sigma_X \sigma_{Y_r}}, \tag{8}$$

where X represents CDD values computed from Equation (2) and $Y_r = \log(\varrho_{k,r} + 1)$ denotes log-transformed hotspot ratios at radius r. The sample estimate is computed as:

$$\hat{\rho}_r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_{r,i} - \bar{y}_r)}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_{r,i} - \bar{y}_r)^2}}. \tag{9}$$

Statistical significance is assessed through the t-transformation under the null hypothesis $\mathcal{H}_0 : \rho = 0$:

$$T = \hat{\rho}_r \sqrt{\frac{n-2}{1-\hat{\rho}_r^2}} \sim t_{n-2}, \tag{10}$$

which follows a Student's t-distribution with $\nu = n - 2$ degrees of freedom. The test statistic accounts for the reduction in degrees of freedom due to parameter estimation (Squire et al., 2021). All statistical computations were performed using Microsoft Excel's Data Analysis ToolPak, with correlation matrices computed for each buffer radius and significance levels evaluated at $\alpha \in \{0.01, 0.05\}$ following standard practice in fire-climate studies (Sun et al., 2024).

3 Results and Discussion

Drought severity varied dramatically between provinces during 2015-2019. South Sumatra recorded maximum CDD of 41 days during the September-October 2015 El Niño event, while West Kalimantan peaked at 27 days in August-September 2015. This 2015 event triggered Indonesia's worst fires since 1997 (Field et al., 2016). The timing matters—Taufik et al. (2022) identified critical moisture thresholds in peatlands where ignition becomes likely after extended dry periods, explaining why South Sumatra's longer droughts produced more severe burning.

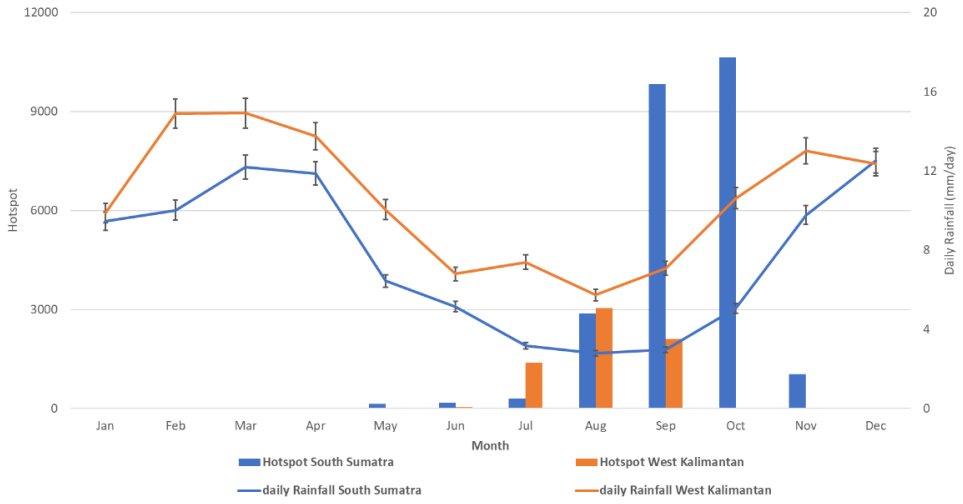

Fig. 2 Climatological monthly rainfall patterns and hotspot occurrences for South Sumatra and West Kalimantan (2015-2019). Error bars represent standard deviation of monthly rainfall, while bars indicate total monthly hotspot counts.

Rainfall and fire showed the expected inverse relationship (Figure 2). South Sumatra's monsoonal climate drove peak burning in August-October, while West Kalimantan's equatorial rainfall pattern pushed maximum fire activity into July-September. These provincial patterns strengthen Vadrevu et al. (2019)'s regional analysis showing precipitation as a dominant control on Indonesian fire variability—though our analysis suggests this relationship intensifies at finer spatial scales.

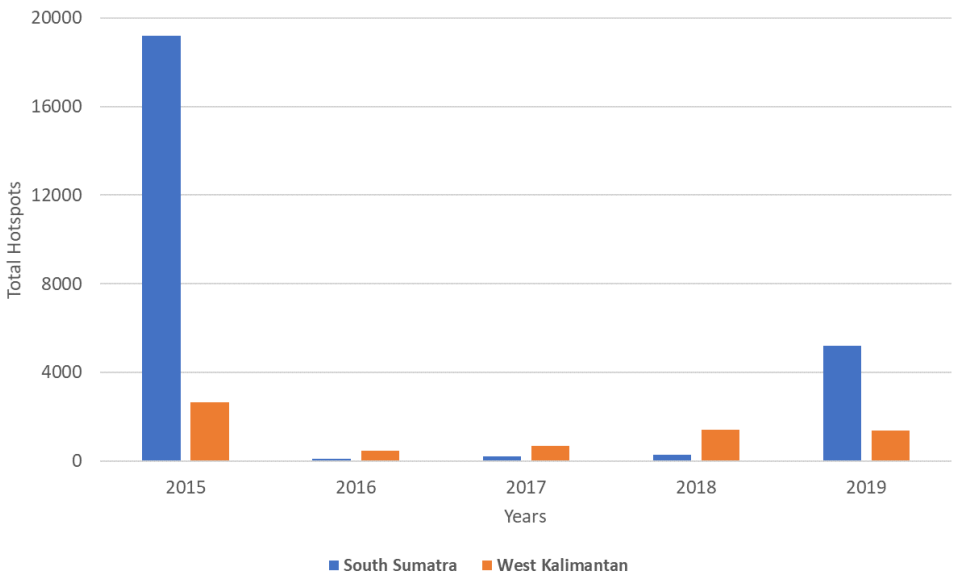

Fig. 3 Annual hotspot occurrences with confidence levels exceeding 80% for South Sumatra and West Kalimantan (2015-2019).

The 2015 and 2019 El Niño years dominated fire activity (Figure 3). The September-October 2015 fires produced catastrophic carbon emissions, with Huijnen et al. (2016) documenting daily CO_2 releases that exceeded entire nations' fossil fuel outputs. The 2019 fires, despite a weaker El Niño, generated severe $PM_{2.5}$ pollution that Grosvenor et al. (2024) linked to substantial excess mortality across the region. These impacts demand better fire prediction.

Drought duration controlled fire intensity exponentially. We classified 1,826 discrete dry periods across both provinces. Very short droughts (1-5 days) occurred most frequently—687 events in South Sumatra, 682 in West Kalimantan—but generated minimal fire activity, averaging just 2.3 ± 1.4 and 1.8 ± 1.2 hotspots per event respectively. Short droughts (6-10 days) happened less often (160 in South Sumatra, 106 in West Kalimantan) but quadrupled fire activity to 8.7 ± 3.2 and 6.4 ± 2.8 hotspots per event.

The fire response intensified dramatically with moderate droughts (11-20 days). Despite occurring only 71 times in South Sumatra and 73 times in West Kalimantan, these events averaged 24.5 ± 9.1 and 18.3 ± 7.6 hotspots respectively. Long droughts (21-30 days) proved catastrophic—though rare (27 events in South Sumatra, 11 in West Kalimantan), they generated 89.4 ± 21.3 and 72.1 ± 18.9 hotspots per event.

The provincial difference emerged starkly in extreme droughts. South Sumatra experienced 17 very long drought events exceeding 30 days, averaging 156.2 ± 34.7 hotspots each. West Kalimantan recorded zero events in this category—its maritime position and equatorial rainfall regime apparently prevent such extreme drying. This

fundamental hydrological difference questions whether universal drought indices can adequately capture fire risk across Indonesia's diverse landscapes, supporting Vitolo et al. (2020)'s argument for region-specific thresholds.

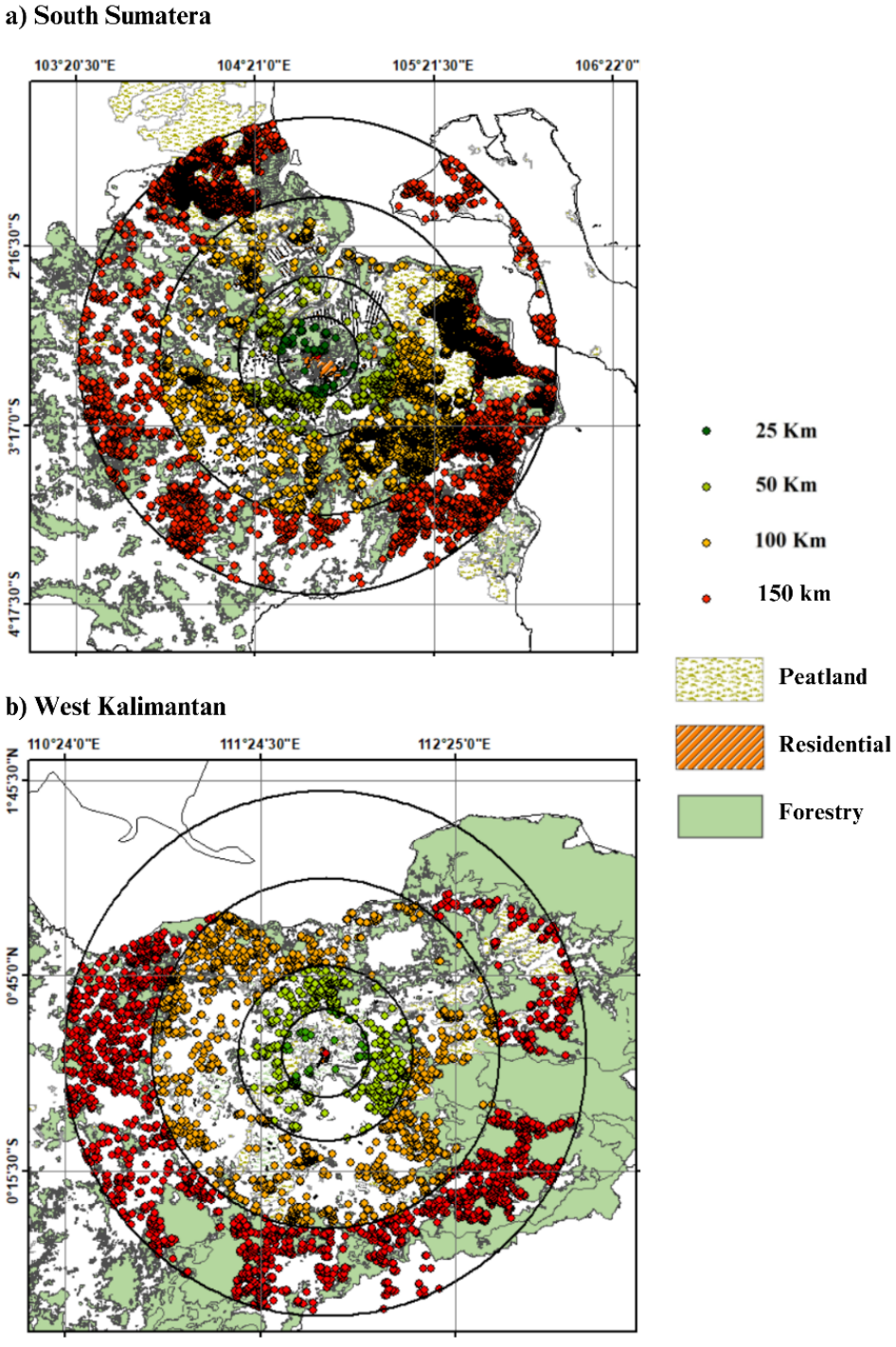

Fig. 4 Spatial distribution of hotspots across buffer zones (25, 50, 100, 150 km) overlaid on land cover types for (a) South Sumatra and (b) West Kalimantan provinces.

Fire distribution showed clear spatial structure (Figure 4). Within 25 km of weather stations, hotspot detection remained minimal—urban and residential land use dominates these areas. This matches Nikonovas et al. (2021)'s observation that urbanization creates effective firebreaks. But it creates a measurement problem: weather stations sit in fire-resistant zones while peatlands burn 50-100 km away.

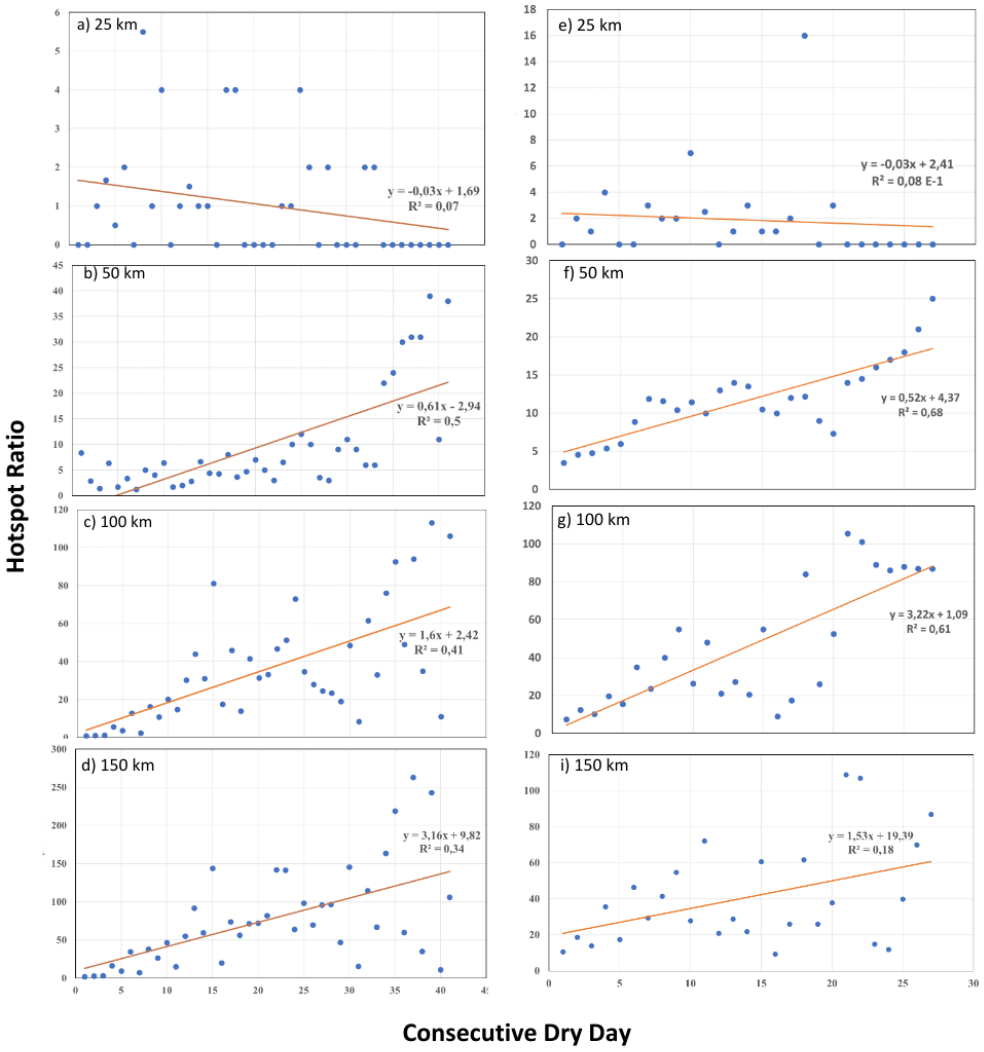

Fig. 5 Scatter plots showing correlations between CDD values and hotspot ratios at different buffer radii for South Sumatra (a-d) and West Kalimantan (e-h). Regression lines and R^2 values indicate relationship strength.

The correlation between drought and fire depended critically on spatial scale (Figure 5). At 25 km radius, correlations turned negative ($r = -0.265$ for South Sumatra, $r = -0.093$ for West Kalimantan)—urbanization near stations suppresses fire despite drought. At 50 km, correlations peaked sharply: $r = 0.776$ ($R^2 = 0.50$) for South Sumatra and $r = 0.821$ ($R^2 = 0.68$) for West Kalimantan ($p < 0.01$ for both). This 50 km sweet spot aligns with ABL theory, where Rahman et al. (2021) showed tropical mixing processes create horizontal coherence at similar scales. Weather measurements remain representative at this distance.

Beyond 100 km, correlations weakened again (Figure 6). At 150 km, mesoscale processes—sea breezes, convective complexes, topographic flows—break the connection between point measurements and area conditions (Lee and Wang, 2020). The 50 km radius optimally balances spatial coverage against meteorological coherence.

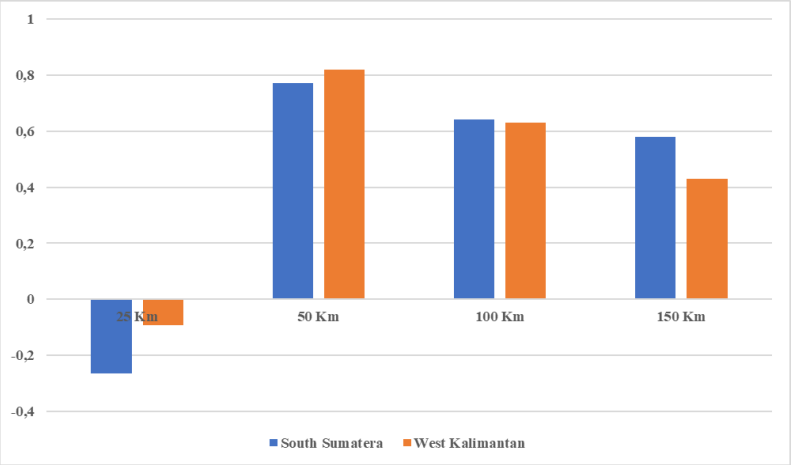

Fig. 6 Summary of Pearson correlation coefficients between CDD index and hotspot growth across buffer radii for both provinces. Error bars represent 95% confidence intervals.

The exponential fire response to drought duration reflects peatland hydrology. Taufik et al. (2015) documented rapid groundwater drawdown in degraded peatlands during dry periods, with critical thresholds typically crossed after several weeks without rain. Our data support this mechanism—very long drought events (>30 days) averaged 156.2 ± 34.7 hotspots, nearly double the 89.4 ± 21.3 hotspots from long droughts (21-30 days). Once peat ignites at depth, Li et al. (2022) showed these fires can smolder underground for extended periods, surviving even surface rainfall.

These findings challenge current fire management approaches. The 50 km optimal correlation distance reveals a fundamental mismatch: meteorological networks designed for aviation and agriculture miss fire-prone peatlands. Stations cluster near population centers while fires rage in remote areas. Strategic station placement in peatland-forest transition zones could transform prediction accuracy.

The stark differences between South Sumatra and West Kalimantan—particularly the absence of extreme droughts in the latter—argue against one-size-fits-all warning

systems. South Sumatra needs alerts calibrated to its monsoon-driven extremes, while West Kalimantan requires sensitivity to shorter but still dangerous dry spells. This aligns with Vilchis-Francés et al. (2021)'s demonstration that locally-tuned indices outperform global standards.

Horton et al. (2022) demonstrated that strategic land management can substantially reduce peatland fire occurrence, with our urban-rural gradient supporting this finding—the negative correlations at 25 km radius show how modified landscapes resist burning. Yet most peatlands lack such protection.

Looking forward, combining CDD data with satellite soil moisture could capture the nonlinear drought-fire relationship more completely. Richardson et al. (2022) showed multi-variable drought indices consistently outperform single metrics. Machine learning approaches might untangle the scale-dependent patterns we observed, potentially extending warning lead times. For communities facing these fires, every additional day of warning saves lives and livelihoods.

4 Conclusion

This study demonstrates that the relationship between CDD and tropical peatland fire occurrence exhibits strong scale dependency, with optimal meteorological station representativeness achieved at 50 km radius where Pearson correlations reach 0.776-0.821 ($p < 0.01$). The identified spatial scale aligns with ABL dynamics in tropical regions, where daytime mixing heights of 1-2 km create coherent meteorological conditions across 40-60 km horizontal distances. Our findings reveal critical limitations in current fire monitoring networks, where urban-biased station placement and excessive spacing (>100 km) fail to capture drought conditions in fire-prone peatland-forest interfaces. The exponential increase in fire occurrence beyond 20 CDD, coupled with province-specific drought severity patterns, indicates that universal drought thresholds poorly represent the heterogeneous fire environments across Indonesian provinces.

These results have immediate implications for improving early warning systems across Southeast Asia's fire-prone regions, where limited meteorological infrastructure must serve vast peatland landscapes vulnerable to climate extremes. Strategic deployment of weather stations at 50 km intervals within peatland areas, combined with regionally calibrated CDD thresholds, could substantially enhance fire prediction accuracy and provide critical lead time for community evacuation and resource mobilization. Future research should integrate high-resolution satellite soil moisture data with ground observations to bridge the scale gap between point measurements and landscape-level fire dynamics, while machine learning approaches may better capture the nonlinear relationships between cumulative drought stress and deep peat ignition probability. As climate change intensifies ENSO-driven droughts across the Maritime Continent, optimizing the spatial configuration of meteorological networks represents a cost-effective adaptation strategy for reducing the catastrophic health, economic, and carbon emissions impacts of tropical peatland fires.

Acknowledgments

We gratefully acknowledge financial support from the Dean's Distinguished Fellowship awarded by the College of Natural and Agricultural Sciences, University of California, Riverside (2023) to S.H.S.H., and from the Institut Teknologi Bandung Research, Community Service and Innovation Program (PPMI-ITB 2023: FITB.PN–6–12–2023) to R.S. We thank NASA's Fire Information for Resource Management System (FIRMS) for providing open access to MODIS Terra and Aqua active fire data (https://firms.modaps.eosdis.nasa.gov/), which formed the foundation of our hotspot analysis. Meteorological station data were obtained from the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) data portal (https://dataonline.bmkg.go.id/) and the OGIMET synoptic data repository (https://www.ogimet.com/). All primary data sources used in this study are freely accessible through these platforms. Processed datasets, including spreadsheets containing normalized hotspot ratios and ArcGIS project files with buffer analysis outputs, are available from the corresponding author upon reasonable request.

References

Bohlmann, S., Laine, M.: Statistical calibration of probabilistic medium-range Fire Weather Index forecasts in Europe. Natural Hazards and Earth System Sciences **24**(12), 4225–4235 (2024) https://doi.org/10.5194/nhess-24-4225-2024

Bataineh, A.L., Oswald, B.P., Bataineh, M., Unger, D., Hung, I.-K., Scognamillo, D.: Spatial autocorrelation and pseudoreplication in fire ecology. Fire Ecology **2**, 107–118 (2006) https://doi.org/10.4996/fireecology.0202107

Crawford, A.J., Belcher, C.M., New, S., Gallego-Sala, A., Swindles, G.T., Page, S., Blyakharchuk, T.A., Cadillo-Quiroz, H., Charman, D.J., Gałka, M., Hughes, P.D.M., Lähteenoja, O., Mauquoy, D., Roland, T.P., Väliranta, M.: Tropical peat composition may provide a negative feedback on fire occurrence and severity. Nature Communications **15**(1), 6606 (2024) https://doi.org/10.1038/s41467-024-50916-7

Chen, F., Fan, Z., Niu, S., Zheng, J.: The Influence of Precipitation and Consecutive Dry Days on Burned Areas in Yunnan Province, Southwestern China. Advances in Meteorology **2014**, 748923 (2014) https://doi.org/10.1155/2014/748923

Cobb, A.R., Hoyt, A.M., Gandois, L., Eri, J., Dommain, R., Abu Salim, K., Kai, F.M., Haji Su'ut, N.S., Harvey, C.F.: How temporal patterns in rainfall determine the geomorphology and carbon fluxes of tropical peatlands. Proceedings of the National Academy of Sciences **114**(26), 5187–5196 (2017) https://doi.org/10.1073/pnas.1701090114

Csiszar, I.A., Morisette, J.T., Giglio, L.: Validation of active fire detection from moderate-resolution satellite sensors: the MODIS example in northern eurasia. IEEE Transactions on Geoscience and Remote Sensing **44**(7), 1757–1764 (2006) https://doi.org/10.1109/TGRS.2006.875941

Dadap, N.C., Cobb, A.R., Hoyt, A.M., Harvey, C.F., Konings, A.G.: Satellite soil moisture observations predict burned area in Southeast Asian peatlands. Environmental Research Letters **14**(9), 094014 (2019) https://doi.org/10.1088/1748-9326/ab3891

Duan, Y., Ma, Z., Yang, Q.: Characteristics of consecutive dry days variations in China. Theoretical and Applied Climatology **130**, 701–709 (2017) https://doi.org/10.1007/s00704-016-1984-6

Edwards, R.B., Naylor, R.L., Higgins, M.M., Falcon, W.P.: Causes of Indonesia's forest fires. World Development **127**, 104717 (2020) https://doi.org/10.1016/j.worlddev.2019.104717

Field, R.D., van der Werf, G.R., Fanin, T., Fetzer, E.J., Fuller, R., Jethva, H., Levy, R., Livesey, N.J., Luo, M., Torres, O., Worden, H.M.: Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. Proceedings of the National Academy of Sciences **113**(33), 9204–9209 (2016) https://doi.org/10.1073/pnas.1524888113

Graham, L.L.B., Applegate, G.B., Thomas, A., Ryan, K.C., Saharjo, B.H., Cochrane, M.A.: A Field Study of Tropical Peat Fire Behaviour and Associated Carbon Emissions. Fire **5**(3), 62 (2022) https://doi.org/10.3390/fire5030062

Grosvenor, M.J., Ardiyani, V., Wooster, M.J., Gillott, S., Graham, L.L.B., Gray, N., Remedios, J.: Catastrophic impact of extreme 2019 Indonesian peatland fires on urban air quality and health. Communications Earth & Environment **5**, 649 (2024) https://doi.org/10.1038/s41467-024-01813-w

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P., Sheil, D.: Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. Scientific Reports **4**, 6112 (2014) https://doi.org/10.1038/srep06112

Giglio, L., Schroeder, W., Justice, C.O.: The Collection 6 MODIS active fire detection algorithm and fire products. Remote Sensing of Environment **178**, 31–41 (2016) https://doi.org/10.1016/j.rse.2016.02.054

Hirano, T., Kusin, K., Limin, S., Osaki, M.: Evapotranspiration of tropical peat swamp forests. Global Change Biology **21**(5), 1914–1927 (2015) https://doi.org/10.1111/gcb.12653

Horton, A.J., Lehtinen, J., Kummu, M.: Targeted land management strategies could halve peatland fire occurrences in Central Kalimantan, Indonesia. Communications Earth & Environment **3**, 204 (2022) https://doi.org/10.1038/s43247-022-00534-2

Havlicek, L.L., Peterson, N.L.: Robustness of the Pearson correlation against violations of assumptions. Perceptual and Motor Skills **43**(3), 1319–1334 (1976) https://doi.

org/10.2466/pms.1976.43.3f.1319

Hein, L., Spadaro, J.V., Ostro, B., Hammer, M., Sumarga, E., Salmayenti, R., Boer, R., Tata, H., Atmoko, D., Castañeda, J.-P.: The health impacts of Indonesian peatland fires. Environmental Health **21**, 62 (2022) https://doi.org/10.1186/s12940-022-00872-w

Huijnen, V., Wooster, M.J., Kaiser, J.W., Gaveau, D.L.A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B., Weele, M.: Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. Scientific Reports **6**, 26886 (2016) https://doi.org/10.1038/srep26886

Hu, Y., Yue, X., Tian, C.: Impacts of El Niño–Southern Oscillation on global fire PM2.5 during 2000–2023. Atmospheric and Oceanic Science Letters **18**(3), 100597 (2025) https://doi.org/10.1016/j.aosl.2025.100597

Kudláčková, L., Bartošová, L., Linda, R., Bláhová, M., Poděbradská, M., Fischer, M., Balek, J., Žalud, Z., Trnka, M.: Assessing fire danger classes and extreme thresholds of the Canadian Fire Weather Index across global environmental zones: a review. Environmental Research Letters **20**(1), 013001 (2024) https://doi.org/10.1088/1748-9326/ad97cf

Konecny, K., Ballhorn, U., Navratil, P., Jubanski, J., Page, S.E., Tansey, K., Hooijer, A., Vernimmen, R., Siegert, F.: Variable carbon losses from recurrent fires in drained tropical peatlands. Global Change Biology **22**(4), 1469–1480 (2016) https://doi.org/10.1111/gcb.13186

Koplitz, S.N., Mickley, L.J., Jacob, D.J., Marlier, M.E., DeFries, R.S., Gaveau, D.L.A., Locatelli, B., Reid, J.S., Xian, P., Myers, S.S.: Role of the Madden-Julian Oscillation in the Transport of Smoke From Sumatra to the Malay Peninsula During Severe Non-El Niño Haze Events. Journal of Geophysical Research: Atmospheres **123**(11), 6282–6294 (2018) https://doi.org/10.1029/2018JD028533

Kiely, L., Spracklen, D.V., Arnold, S.R., Papargyropoulou, E., Conibear, L., Wiedinmyer, C., Knote, C., Adrianto, H.A.: Assessing costs of Indonesian fires and the benefits of restoring peatland. Nature Communications **12**, 7044 (2021) https://doi.org/10.1038/s41467-021-27353-x

Linn, R.R., Hiers, J.K., O'Brien, J.J., Yedinak, K., Hoffman, C., Canfield, J., Robinson, D., Goodrick, S.: Wildland fire entrainment: The missing link between wildland fire and its environment. PNAS Nexus **4**(1), 576 (2025) https://doi.org/10.1093/pnasnexus/pgae576

Lee, H.-H., Wang, C.: The impacts of biomass burning activities on convective systems over the Maritime Continent. Atmospheric Chemistry and Physics **20**(4), 2533–2548 (2020) https://doi.org/10.5194/acp-20-2533-2020

Li, W., Xu, Q., Yi, J., Liu, J.: Predictive model of spatial scale of forest fire driving factors: a case study of Yunnan Province, China. Scientific Reports **12**, 19029 (2022) https://doi.org/10.1038/s41598-022-23697-6

Marlier, M.E., DeFries, R.S., Kim, P.S., Gaveau, D.L.A., Koplitz, S.N., Jacob, D.J., Mickley, L.J., Margono, B.A., Myers, S.S.: Regional air quality impacts of future fire emissions in Sumatra and Kalimantan. Environmental Research Letters **10**(5), 054010 (2015) https://doi.org/10.1088/1748-9326/10/5/054010

Mortelmans, J., Felsberg, A., De Lannoy, G.J.M., Veraverbeke, S., Field, R.D., Andela, N., Bechtold, M.: Improving the fire weather index system for peatlands using peat-specific hydrological input data. Natural Hazards and Earth System Sciences **24**(2), 445–464 (2024) https://doi.org/10.5194/nhess-24-445-2024

Ma, M., Wu, Y., Luo, W., Chen, L., Li, J., Jing, N.: HiBuffer: Buffer analysis of 10-million-scale spatial data in real time. ISPRS International Journal of Geo-Information **7**(12), 467 (2018) https://doi.org/10.3390/ijgi7120467

Nikonovas, T., Spessa, A., Doerr, S.H., Clay, G.D., Mezbahuddin, S.: Near-complete loss of fire-resistant primary tropical forest cover in Sumatra and Kalimantan. Communications Earth & Environment **1**, 65 (2021) https://doi.org/10.1038/s43247-020-00069-4

O, S., Hou, X., Orth, R.: Observational evidence of wildfire-promoting soil moisture anomalies. Scientific Reports **10**(1), 1–8 (2020) https://doi.org/10.1038/s41598-020-67530-4

Pan, X., Chin, M., Ichoku, C.M., Field, R.D.: Connecting Indonesian fires and drought with the type of El Niño and phase of the Indian Ocean Dipole during 1979-2016. Journal of Geophysical Research: Atmospheres **123**(15), 7974–7988 (2018) https://doi.org/10.1029/2018JD028402

Richardson, D., Black, A.S., Irving, D., Matear, R.J., Monselesan, D.P., Risbey, J.S., Squire, D.T., Tozer, C.R.: Global increase in wildfire potential from compound fire weather and drought. npj Climate and Atmospheric Science **5**, 23 (2022) https://doi.org/10.1038/s41612-022-00248-4

Rahman, M.A., Nugroho, D.S., Yamanaka, M.D., Kawasaki, M., Kozan, O., Ohashi, M., Hashiguchi, H., Mori, S.: Weather radar detection of planetary boundary layer and smoke layer top of peatland fire in Central Kalimantan, Indonesia. Scientific Reports **11**, 367 (2021) https://doi.org/10.1038/s41598-020-79486-6

Squire, D.T., Richardson, D., Risbey, J.S., Black, A.S., Kitsios, V., Matear, R.J., Monselesan, D., Moore, C.S., Tozer, C.R.: Likelihood of unprecedented drought and fire weather during Australia's 2019 megafires. npj Climate and Atmospheric Science **4**, 64 (2021) https://doi.org/10.1038/s41612-021-00220-8

Sheldon, T.L., Sankaran, C.: The Impact of Indonesian Forest Fires on Singaporean Pollution and Health. American Economic Review **107**(5), 526–529 (2017) https://doi.org/10.1257/aer.p20171134

Sun, C., Touge, Y., Shi, K., Tanaka, K.: Assessment of the suitability of drought descriptions for wildfires under various humid temperate climates in Japan. Scientific Reports **14**, 23759 (2024) https://doi.org/10.1038/s41598-024-75563-2

Stull, R.B.: An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Amsterdam, The Netherlands (1988). https://doi.org/10.1007/978-94-009-3027-8

Tangang, F., Farzanmanesh, R., Mirzaei, A., Supari, Salimun, E., Jamaluddin, A.F., Juneng, L.: Characteristics of precipitation extremes in Malaysia associated with El Niño and La Niña events. International Journal of Climatology **37**, 696–716 (2017) https://doi.org/10.1002/joc.5032

Taufik, M., Setiawan, B.I., van Lanen, H.A.J.: Modification of a fire drought index for tropical wetland ecosystems by including water table depth. Agricultural and Forest Meteorology **203**, 1–10 (2015) https://doi.org/10.1016/j.agrformet.2014.12.006

Tian, X.-R., Shu, L.-F., Zhao, F.-J., Wang, M.-Y., McRae, D.J.: Future impacts of climate change on forest fire danger in northeastern China. Journal of Forestry Research **22**(3), 437–446 (2011) https://doi.org/10.1007/s11676-011-0185-5

Taufik, M., Torfs, P.J.J.F., Uijlenhoet, R., Jones, P.D., Murdiyarso, D., Van Lanen, H.A.J.: Amplification of wildfire area burnt by hydrological drought in the humid tropics. Nature Climate Change **7**, 428–431 (2017) https://doi.org/10.1038/nclimate3280

Taufik, M., Widyastuti, M.T., Sulaiman, A., Murdiyarso, D., Santikayasa, I.P., Minasny, B.: An improved drought-fire assessment for managing fire risks in tropical peatlands. Agricultural and Forest Meteorology **312**, 108738 (2022) https://doi.org/10.1016/j.agrformet.2021.108738

Usup, A., Hashimoto, Y., Takahashi, H., Hayasaka, H.: Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia. Tropics **14**(1), 1–19 (2004) https://doi.org/10.3759/tropics.14.1

Vitolo, C., Di Giuseppe, F., Barnard, C., Coughlan, R., San-Miguel-Ayanz, J., Libertá, G., Krzeminski, B.: ERA5-based global meteorological wildfire danger maps. Scientific Data **7**, 216 (2020) https://doi.org/10.1038/s41597-020-0554-z

Vilchis-Francés, A.Y., Díaz-Delgado, C., Becerril-Piña, R., Mastachi-Loza, C.A., Gómez-Albores, M.Á., Bâ, K.M.: Daily prediction modeling of forest fire ignition using meteorological drought indices in the Mexican highlands. iForest - Biogeosciences and Forestry **14**(5), 437–446 (2021) https://doi.org/10.3832/ifor3623-014

Vadrevu, K.P., Lasko, K., Giglio, L., Schroeder, W., Biswas, S., Justice, C.: Trends in Vegetation fires in South and Southeast Asian Countries. Scientific Reports **9**, 7422 (2019) https://doi.org/10.1038/s41598-019-43940-x

van der Werf, G.R., Randerson, J.T., Giglio, L., van Leeuwen, T.T., Chen, Y., Rogers, B.M., Mu, M., van Marle, M.J.E., Morton, D.C., Collatz, G.J., Yokelson, R.J., Kasibhatla, P.S.: Global fire emissions estimates during 1997-2016. Earth System Science Data **9**(2), 697–720 (2017) https://doi.org/10.5194/essd-9-697-2017

Werth, P.A., Potter, B.E., Clements, C.B., Finney, M.A., Goodrick, S.L., Alexander, M.E., Cruz, M.G., Forthofer, J.A., McAllister, S.S.: Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers. USDA, Forest Service, Pacific Northwest Research Station, Portland, OR, USA (2011). https://doi.org/10.2737/pnw-gtr-854

Yokelson, R.J., Saharjo, B.H., Stockwell, C.E., Putra, E.I., Jayarathne, T., Akbar, A., Albar, I., Blake, D.R., Graham, L.L.B., Kurniawan, A., Meinardi, S., Ningrum, D., Nurhayati, A.D., Saad, A., Sakuntaladewi, N., Setianto, E., Simpson, I.J., Stone, E.A., Sutikno, S., Thomas, A., Ryan, K.C., Cochrane, M.A.: Tropical peat fire emissions: 2019 field measurements in Sumatra and Borneo and synthesis with previous studies. Atmospheric Chemistry and Physics **22**(15), 10173–10194 (2022) https://doi.org/10.5194/acp-22-10173-2022

Zheng, H., Xue, L., Ding, K., Lou, S., Wang, Z., Ding, A., Huang, X.: ENSO-Related Fire Weather Changes in Southeast and Equatorial Asia: A Quantitative Evaluation Using Fire Weather Index. Journal of Geophysical Research: Atmospheres **128**(21), 2023–039688 (2023) https://doi.org/10.1029/2023JD039688

Zwiers, F.W., Zhang, X.: Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. Climate Data and Monitoring, WCDMP-No. 72, WMO-TD No. 1500, 56 (2009). https://library.wmo.int/idurl/4/48826