

Analysis of Pollutant Distribution Due to Forest Fires in Ketapang Regency in 2015 Using The WRF-Chem Model

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Manuscript received: 14 January 2025; Received in revised form: 28 May 2025; Accepted: 2 June 2025

Abstract

A forest fire occurred on September 9, 2015, resulting in 616 hotspots distributed across several regencies in West Kalimantan, 442 of which were in Ketapang Regency. This study aims to analyze the spatial and temporal distribution of pollutants caused by forest fires in Ketapang Regency in 2015 using the Weather Research and Forecasting with Chemistry (WRF-Chem) model. The data used to run the model includes the Final Global Data Assimilation System (FNL) dataset, the Emission Database for Global Atmospheric Research (EDGAR), and The Fire Inventory from NCAR (FINN), which serve as input and emission source data. The highest concentrations of pollutants, which are PM_{2.5} and PM₁₀ at 30 µg/m³ each and CO at 342.9 µg/m³, were observed in the southern part of Kalimantan, which is the main source of the forest fires. These pollutants subsequently dispersed toward the northern part of Kalimantan. During the fire events, pollutants were transported to the upper atmosphere from morning to noon but accumulated near the surface at night. This pattern was influenced by meteorological conditions, including wind speed and direction, surface pressure, and air temperature. During forest fires, pollutants are emitted into the atmosphere from morning to afternoon, and accumulate near the surface during the night. This pattern was influenced by meteorological factors, including wind speed and direction, surface pressure, and air temperature.

Keywords: CO; forest fire; PM_{2.5}; PM₁₀; WRF-Chem.

Citation: Yani, E., Ihwan, A., Ardianto, R., Adriat, R., & Jumarang, M. I. (2025). Analysis of Pollutant Distribution Due to Forest Fires in Ketapang Regency in 2015 Using The WRF-Chem Model. *Jurnal Geocelebes*, 9(2):113–125, doi: 10.70561/geocelebes.v9i2.42903

Introduction

Indonesia has experienced significant deforestation due to forest fires, with forest loss reaching 1.1 million hectares annually (2% of the total area), out of a total forested area of 130 million hectares (Darmawan, 2020). One of the major consequences of forest fires in Indonesia is air pollution. Air pollution predominantly arises from human activities, including transportation, forest fires, industrial processes, waste decomposition and burning, as well as other household activities (Manisalidis et al., 2020; Siddiqua et al., 2022). Substances contributing to air pollution include carbon

monoxide (CO) and particulate matter (PM) (Siegmund et al., 2024; Tang et al., 2022). PM refers to a type of air pollutant composed of a mixture of various elements such as sulfates, ammonia, organic matter, nitrates, sea salt, dust, water, and other compounds (Dahari et al., 2021).

The 2015 forest fires were the largest in the past 20 years in Sumatra and Kalimantan. That year witnessed a significant increase in hotspots compared to the previous year, resulting in widespread haze (Nurhayati et al., 2021, Yin et al., 2020; Ihwan et al., 2024). These fires burned approximately 2.6 million hectares of land and garnered

international attention due to severe smoke impacts, which disrupted public health and daily activities. According to Terra Aqua satellite imagery, around 70,000 hotspots were recorded in 2015. Ketapang District, located in the southern part of West Kalimantan Province, was among the areas most affected by the fires that year (Miettinen et al., 2017). Forest and land fires in Ketapang Regency in 2013, 2015, and 2017 affected an area of 368.28 hectares, with 141 hotspots predominantly located in mixed dryland agriculture, swamp scrub, and scrubland areas (Jusman et al., 2023; Yananto et al., 2017). Based on MODIS satellite monitoring by BMKG (Indonesian Agency for Meteorological, Climatological and Geophysics), on Wednesday, September 9, 2015, at 05:00 WIB (West Indonesia Time), 616 hotspots were recorded across several districts in West Kalimantan. Ketapang Regency recorded the highest number, with 442 hotspots—a sharp increase from 73 hotspots reported in the previous update at 16:00 WIB on September 8, 2015.

One approach to predicting and analyzing pollution emissions during forest fires is the use of the Weather Research and Forecasting with Chemistry (WRF-Chem) model. WRF-Chem is a weather research and forecasting model integrated with chemical processes. Developed by NOAA/ESRL and DOE/PNNL, this model is designed to assess air quality at relatively small scales. WRF-Chem provides detailed descriptions of the emission, mixing, transport, and chemical transformation of gases and aerosols influenced by meteorological factors (NOAA, 2022). It is also capable of analyzing the distribution of air pollutants such as carbon monoxide and particulate matter (Tampubolon & Boedisantoso, 2016). Several previous studies have employed the WRF-Chem model, including those by (Darmanto & Sofyan, 2012; Sicard et al., 2021; Ghude et al., 2020).

The phenomenon of pollutant distribution caused by forest fires in West Kalimantan in 2015 presents an interesting subject for study. Due to the scarcity of air quality data in Indonesia and limitations in direct observation. To address this gap, we employ the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) to simulate the emission, transport, and deposition of CO, PM₁₀, and PM_{2.5} during the peak fire period in September 2015. The WRF-Chem model is well-suited for such applications as it integrates meteorological and chemical processes in a fully coupled framework, allowing for the dynamic interaction between atmospheric conditions and chemical constituents (Grell et al., 2005; Spiridonov et al., 2019; Georgiou et al., 2022; Agarwal et al., 2024). This study provides a high-resolution analysis of CO, PM₁₀, and PM_{2.5} distributions during the 2015 Ketapang fires, emphasizing of pollutant dispersion and accumulation processes. By focusing on regional-scale impacts and transboundary transport, which are crucial for air quality management during future forest fire crises.

Materials and Methods

Conducting Data Collection

Data collection was carried out in 2015. The required data includes the Final Global Data Assimilation System (FNL) data for the period from September 7, 2015 at 00:00 UTC to September 11, 2015 at 00:00 UTC, with a spatial resolution of 0.25° x 0.25°, which can be downloaded from <https://rda.ucar.edu/datasets/ds083.3/dataaccess/>. Additionally, global air emission concentration data from the Emission Database for Global Atmospheric Research (EDGAR) for 2015, with a resolution of 0.1° x 0.1°, can be obtained from https://edgar.jrc.ec.europa.eu/emissions_data_and_maps. The Fire Inventory from NCAR (FINN) version 2 provides annual global daily emission estimates for major gases and aerosols, with a spatial resolution

of $0.1^\circ \times 0.1^\circ$, available for download at <https://rda.ucar.edu/datasets/ds312.9/dataaccess/>.

Running the WRF-Chem Model

1. Pre-processing

The simulation focused on the western region of Kalimantan (Figure 1). The simulation period was set based on the peak of forest fire events occurring from 8 to 10 September 2015.

Meteorological data were obtained from FNL provided by NCEP and processed using the WRF Preprocessing System (WPS) through three stages: geogrid, ungrib, and metgrid, to generate meteorological input data consistent with the simulation domain.

The emission data used included anthropogenic emissions of CO, PM₁₀, and PM_{2.5} from EDGAR, as well as biomass

burning emissions from FINN (Callewaert et al., 2023). These datasets were first converted to NetCDF format and adjusted both vertically (injection height) and spatially. Subsequently, both datasets were integrated into the WRF-Chem simulation domain.

2. Processing

The WRF-Chem simulation was conducted using the following physical parameterization schemes: microphysics using WRF Single-Moment 3, and cumulus parameterization using the Grell-Dévényi ensemble (Grell & Dévényi, 2002). The chemical schemes included MOZCART for gas-phase chemistry and GOCART for aerosols.

3. Post-processing

The model output is visualized using the NCAR Command Language (NCL) software.

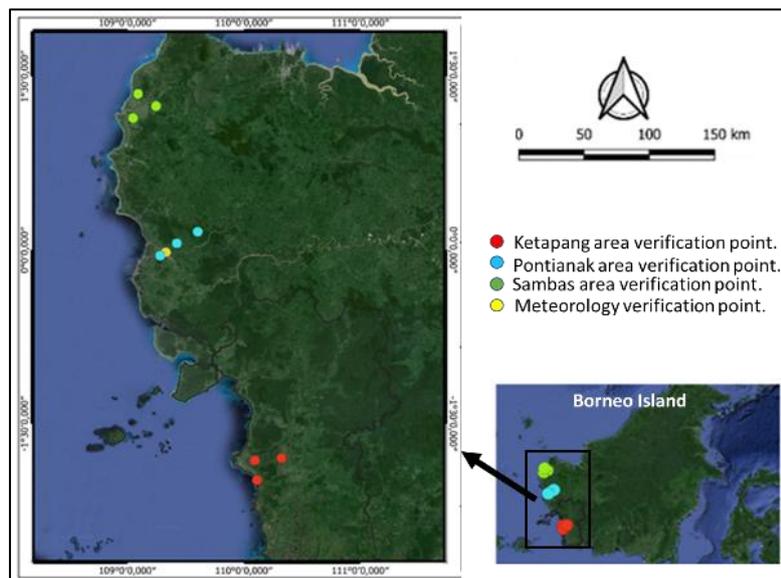


Figure 1. Research location.

Data Analysis

At this stage, various parameters, including wind speed and direction, PM_{2.5}, PM₁₀, and CO, are analyzed to understand how weather parameters influenced the spatial and temporal distribution of pollutants during the forest and land fires in Ketapang Regency in 2015.

The sampling method in this study involved selecting three representative regions: Ketapang, Pontianak, and Sambas for the WRF-Chem model simulation results. In each region, three observation points were evenly distributed to collect data on air pollution distribution. The average value from the three observation points was used to represent the air quality data for each

respective region (Figure 1). These results were used to examine the temporal dynamics during the simulation period.

The average concentrations of CO, PM₁₀, and PM_{2.5} were then compared to the

classification of the Air Pollutant Standard Index (ISPU) as stated in the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number P.14/MENLHK/SETJEN/KUM.1/7/2020 (Table 1).

Table 1. The classification of the Air Pollutant Standard Index (Minister of Environment and Forestry of the Republic of Indonesia, 2020).

ISPU Category	PM _{2.5} concentration (µg/m ³)	PM ₁₀ concentration (µg/m ³)	CO concentration (µg/m ³)
Good	15.5	50	4000
Moderate	55.4	150	8000
Unhealthy	150.4	350	15000
Very unhealthy	250.4	420	30000
Dangerous	500	500	45000

Results and Discussion

Wind Speed and Direction

The WRF-Chem model output illustrates wind direction conditions from September 8 to September 10, 2015, predominantly blowing from the southeast toward the north. Figure 2 shows wind speed in the West Kalimantan region, with the highest speeds occurring between 07:00 WIB and

13:00 WIB, ranging from 5 m/s to 10 m/s. The increase in particulate matter was closely linked to meteorological factors, including the dispersion and diffusion of pollutants caused by changes in meteorological conditions (Yang et al., 2020a). Wind plays a key role in spreading pollutants out of areas with high concentrations and reducing pollutant levels in other regions (Yang et al., 2020b).

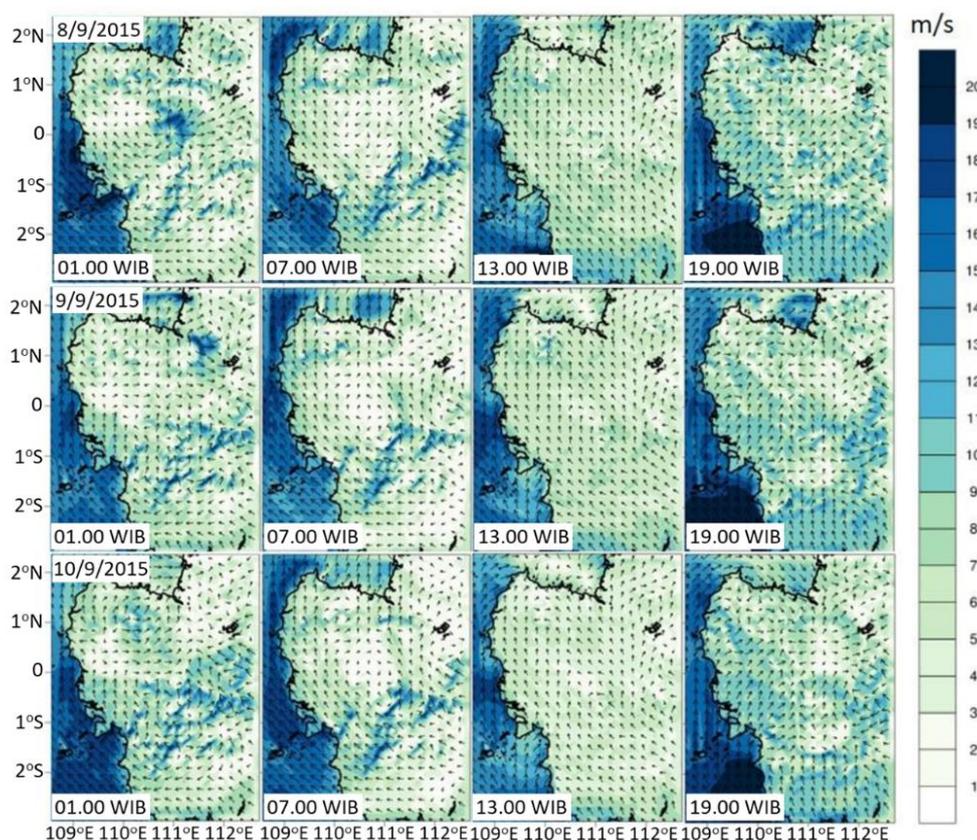


Figure 2. Map of Wind speed and direction in West Kalimantan on 08-10 September 2015.

Figure 3 shows the wind direction and speed at coordinates 0.02° S – 109.33° E from September 7, 2015, to September 11, 2015. The dominant wind direction from the model output (Figure 3a) is from the south-southeast toward the north,

consistent with the wind direction from the observation data (Figure 3b), which predominantly moves northward. This indicates that during the forest fire event, the air mass carrying pollutants was transported toward the northern region.

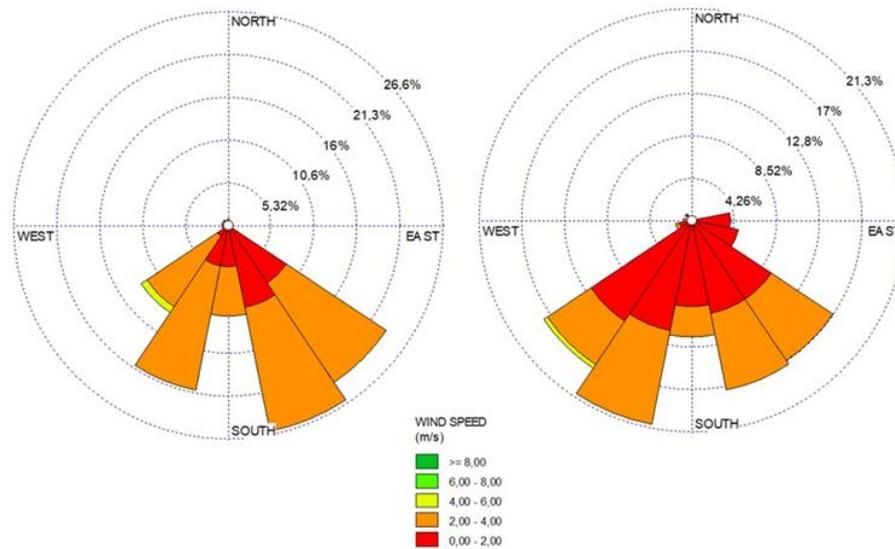


Figure 3. Wind speed and direction at coordinates 0.02° S – 109.33° E (a) wind-rose from model output (b) wind-rose from observation data.

Particulate Matter ($PM_{2.5}$)

The model output shows the distribution of $PM_{2.5}$ pollutants in West Kalimantan, with Ketapang Regency having the highest number of hotspots. $PM_{2.5}$ spread northward, following the southeast wind direction. Figure 4 shows $PM_{2.5}$ concentrations from September 8 to September 10, 2015. In the southern part of West Kalimantan, particularly Ketapang Regency, $PM_{2.5}$ concentrations increased due to forest fires.

$PM_{2.5}$ concentrations ranged from $10 \mu\text{g}/\text{m}^3$ to $15 \mu\text{g}/\text{m}^3$ between 19:00 WIB and 01:00 WIB. At 07:00 WIB, $PM_{2.5}$ concentrations began to disperse, following the wind toward Pontianak City and Sambas Regency. By 13:00 WIB, pollutants spread rapidly toward the northern border of neighboring countries. Figure 10 shows that from 01:00 WIB on September 8 to 23:00

WIB on September 10, 2015, Ketapang Regency, Pontianak City, and Sambas Regency were key sampling points for $PM_{2.5}$ concentrations. The highest concentrations, recorded at 19:00 WIB, ranged from $10 \mu\text{g}/\text{m}^3$ to $12 \mu\text{g}/\text{m}^3$. $PM_{2.5}$ concentrations consistently decreased between 07:00 WIB and 16:00 WIB, with values ranging from $1 \mu\text{g}/\text{m}^3$ to $2 \mu\text{g}/\text{m}^3$.

The meteorological pattern for $PM_{2.5}$ is similar to that for CO and PM_{10} . Wind from the southeast caused pollutants to spread northward. Strong winds facilitated wider dispersion, while weak winds led to localized buildup. Low-pressure systems, occurring between 12:00 WIB and 16:00 WIB, helped reduce $PM_{2.5}$ concentrations near the surface by promoting air mixing and rising. In contrast, low temperatures between 19:00 WIB and 07:00 WIB trapped $PM_{2.5}$ near the surface, resulting in higher concentrations.

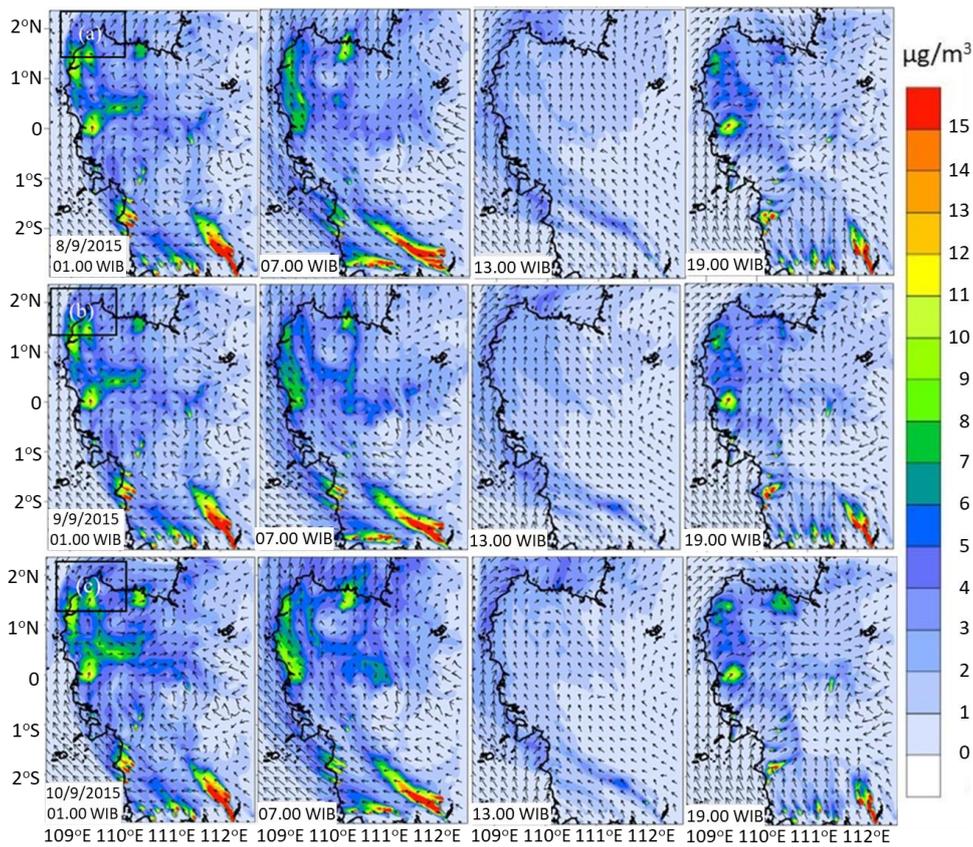


Figure 4. Map of PM_{2.5} distribution in West Kalimantan on 08-10 September 2015.

Figure 5 illustrates a graph showing PM_{2.5} concentrations recorded between September 8, 2015, at 01:00 WIB, and September 10, 2015, at 23:00 WIB in Ketapang Regency, Pontianak City, and Sambas Regency. Ketapang Regency is recognized as the main source of PM_{2.5} emissions. Figure 5 indicates that PM_{2.5} levels in these three regions reached their highest point at 19:00 WIB, with

concentrations between 10 µg/m³ and 12 µg/m³. In contrast, concentrations dropped during the period from 07:00 WIB to 16:00 WIB, ranging from 1 µg/m³ to 2 µg/m³. This decline in PM_{2.5} concentration during the morning and midday hours is linked to meteorological conditions, including increased wind speed and rising temperatures due to solar radiation.

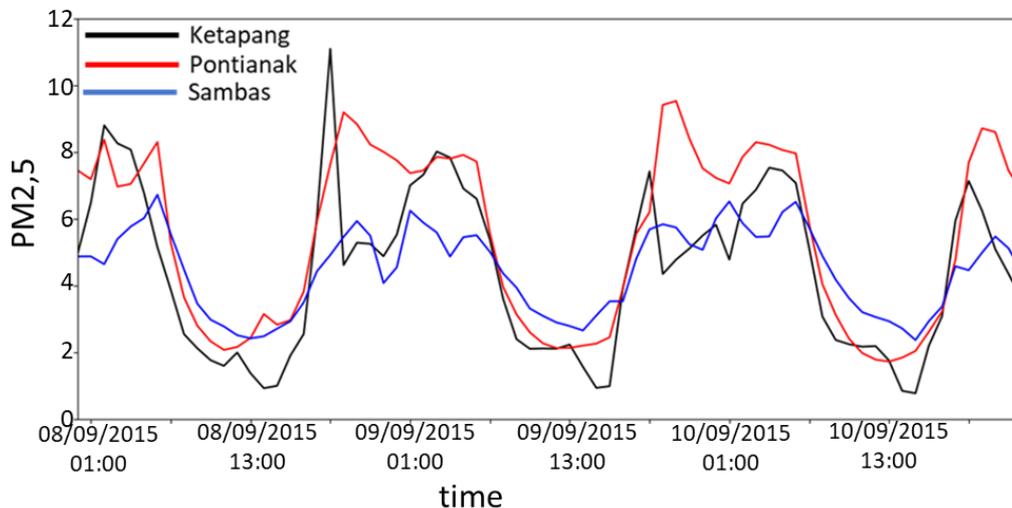


Figure 5. Time series graph of PM_{2.5} per 3 hours in Ketapang Regency, Pontianak City, and Sambas Regency from September 8, 2015 at 01.00 WIB to September 10, 2015 at 23.00 WIB.

Particulate Matter (PM₁₀)

The model output shows the distribution of PM₁₀ pollutants in West Kalimantan, with the largest number of hotspots located in Ketapang Regency. PM₁₀ spread northward, following the wind direction from the southeast. Figure 6 shows that the highest PM₁₀ concentrations ranged from 10 µg/m³ to 15 µg/m³, indicating significant air pollution caused by forest fires between September 8 and September 10, 2015. Over the three-day period, a consistent pattern emerged, where PM₁₀ concentrations were highest between 19:00 WIB and 01:00 WIB. At 07:00 WIB, PM₁₀ concentrations began to disperse as pollutants were carried away by wind toward northern areas, such as Sambas Regency and the neighboring country border. By 13:00 WIB, pollutants spread significantly, reducing concentrations at the source due to rising air temperatures. High temperatures made PM₁₀ particles less dense, facilitating their

dispersion and lowering pollutant concentrations.

Figure 7. presents a graph illustrating PM₁₀ concentrations from September 8, 2015, at 01:00 WIB to September 10, 2015, at 23:00 WIB in Ketapang Regency, Pontianak City, and Sambas Regency. PM₁₀ concentrations in these three areas varied over time. The levels peaked at 19:00 WIB, reaching a maximum of 14 µg/m³. Conversely, they decreased between 07:00 WIB and 16:00 WIB, ranging from 1 µg/m³ to 3 µg/m³.

The findings indicate that pollutant concentrations in Pontianak are higher than those in Ketapang and Sambas (Figure 7). The elevated levels of pollutants in Pontianak are attributed to a combination of emission sources, including anthropogenic activities such as transportation and industry (characteristic of a developing urban area) and transboundary pollution originating from forest and land fires in the Ketapang region.

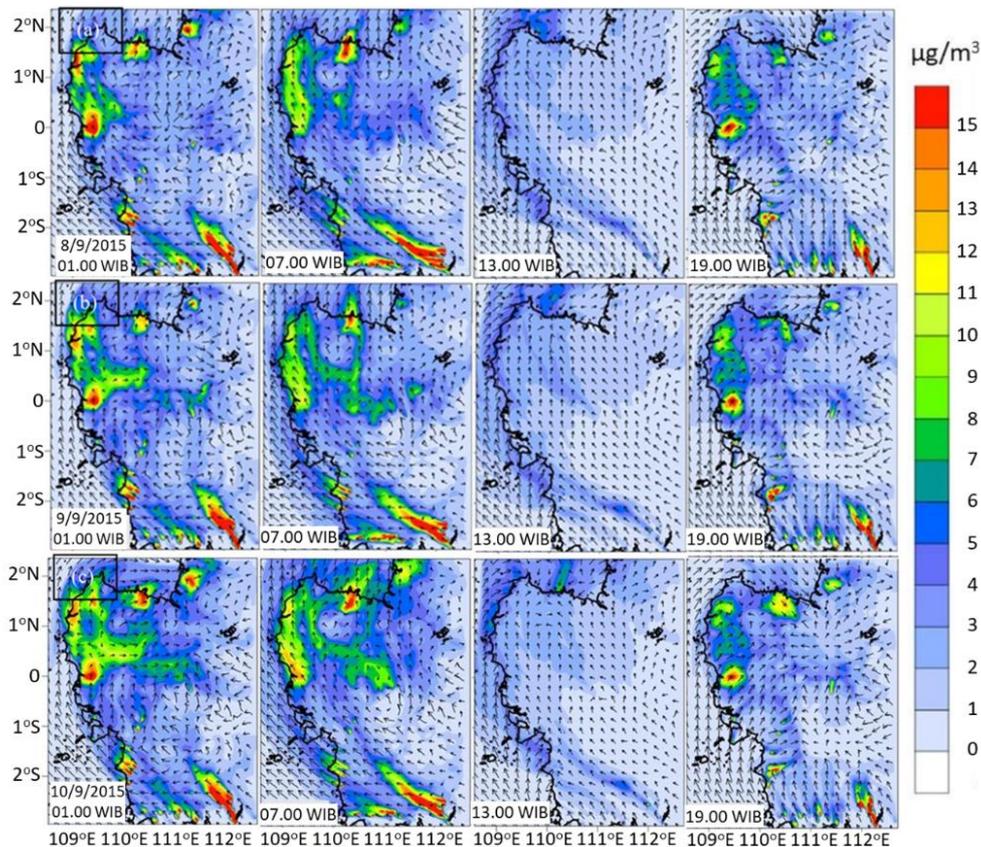


Figure 6. Map of PM₁₀ distribution in West Kalimantan on 08-10 September 2015.

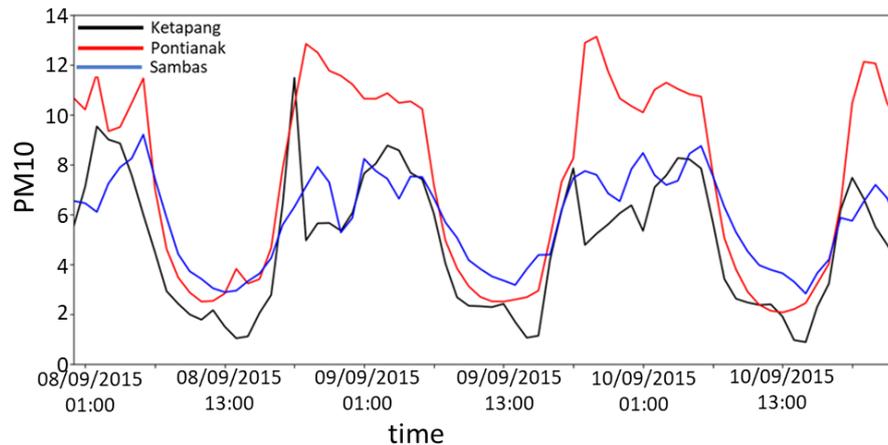


Figure 7. Time series graph of PM_{10} per 3 hours in Ketapang Regency, Pontianak City, and Sambas Regency from September 8, 2015 at 01.00 WIB to September 10, 2015 at 23.00 WIB.

Carbon Monoxide (CO)

Carbon monoxide (CO), a common emission from forest fires, contributes to climate change by affecting the concentration of greenhouse gases in the atmosphere, making it a serious environmental issue (Volkova et al., 2019; Touma et al., 2021). The WRF-Chem model output illustrates the spatial distribution of CO pollutants in the West Kalimantan region from September 8 to September 10, 2015, between 01:00 WIB and 23:00 WIB (Figure 8). In Ketapang, the distribution of hotspots was relatively high compared to other regions in West Kalimantan Province, resulting in high CO concentrations from 19:00 WIB to 01:00 WIB. This occurred because pollutants accumulated near the fire source at night when air temperatures were relatively low, and wind speeds were calmer. At 07:00 WIB, CO concentrations began to disperse as pollutants were carried away by wind toward northern areas, such as Pontianak City and Sambas Regency. By 13:00 WIB, CO concentrations decreased rapidly as high air temperatures caused pollutants to become dry and light, allowing them to spread easily with moving air masses toward the borders of neighboring countries.

In this study, wind speed and direction played a crucial role in pollutant dispersion.

Wind from the southeast caused pollutants originating from Ketapang Regency to spread northward across Kalimantan. Strong winds facilitated wider dispersion of CO, whereas weak winds led to localized concentration buildup. Surface pressure influenced pollutant concentrations at the emission source, with low-pressure systems occurring between 12:00 WIB and 16:00 WIB, associated with rising and mixing air, which helped reduce CO concentrations near the surface. Meanwhile, low temperatures between 19:00 WIB and 07:00 WIB trapped CO near the surface, resulting in higher concentrations.

The results indicate that between 01:00 WIB on September 8, 2015, and 19:00 WIB on September 10, 2015, Ketapang Regency, Pontianak City, and Sambas Regency were the areas with the highest CO concentrations. Ketapang Regency, being the primary source of the pollutant, recorded the highest CO concentration of $205.7 \mu\text{g}/\text{m}^3$ at 19:00 WIB (Figure 9). CO concentrations consistently decreased between 07:00 WIB and 16:00 WIB, with values ranging from $102.9 \mu\text{g}/\text{m}^3$. This decrease occurs because, from morning to midday, rising temperatures and stronger wind speeds facilitate the dispersion of pollutants over a wider area.

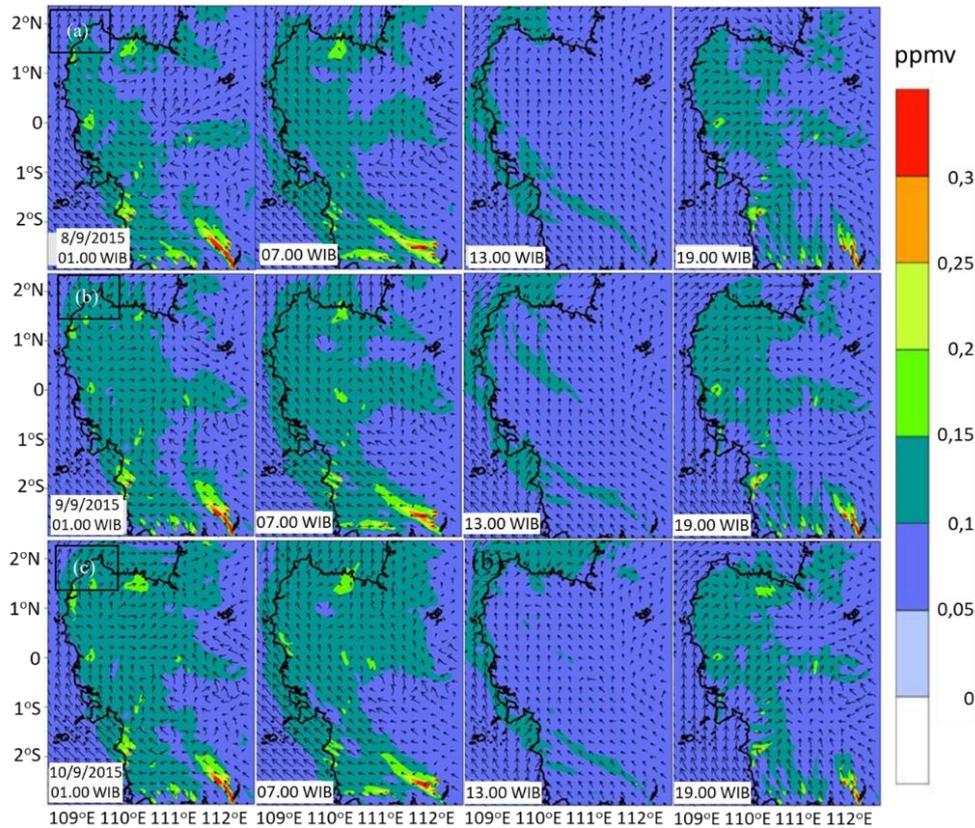


Figure 8. Map of CO distribution in West Kalimantan on 08-10 September 2015.

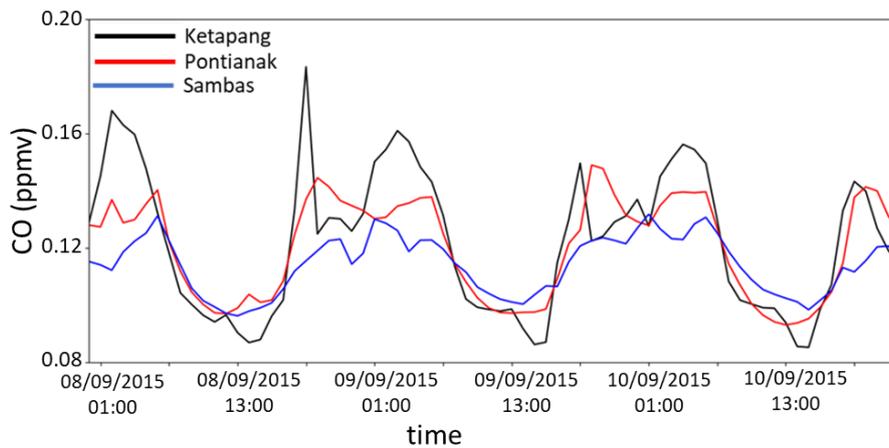


Figure 9. Time series graph of CO per 3 hours in Ketapang Regency, Pontianak City, and Sambas Regency from September 8, 2015 at 01.00 WIB to September 10, 2015 at 23.00 WIB.

Meteorological parameters significantly influence the distribution of pollutants in the atmosphere, including PM_{10} , $PM_{2.5}$, and CO (Zhang et al., 2015; Jin et al., 2021). During forest and land fires, wind direction from the southeast transported pollutants from Ketapang Regency toward the northern part of Kalimantan. Previous research similarly found that wind speed and direction can disperse pollutants over a wider area, whereas weak winds tend to

cause localized accumulation of pollutants (Fedoniuk et al., 2020; Yuval et al., 2020).

Surface pressure also affects pollutant concentrations at the emission source. In this study, low-pressure systems observed between 12:00 and 16:00 WIB were associated with rising and mixing air, which helped reduce pollutant concentrations near the surface. Conversely, low air temperatures recorded

between 19:00 and 07:00 WIB trapped pollutants near the surface, resulting in higher concentrations during these hours. Previous research supports these findings, indicating that high pollutant concentrations at night are due to stable atmospheric conditions, low temperatures, and calmer winds (Li et al., 2020).

The WRF-Chem model was able to represent the distribution of pollutants (PM₁₀, PM_{2.5}, and CO), which was influenced by meteorological factors, particularly wind direction. The simulation results indicated that wind transported pollutants from the main source in Ketapang Regency toward northern Kalimantan. A limitation of this study is that, although the model effectively represents the spatial distribution of pollutants, the concentrations of the three pollutants remain relatively low and are still classified as “good” according to the Air Pollutant Standard Index (ISPU) (Table 1). This finding contrasts with the results of previous research by Yin et al. (2020), which reported that haze from forest fires in Kalimantan had a significant negative impact on air quality.

The distribution of pollutants during forest fires poses a significant threat to human health, highlighting the need for further investigation to better understand its implications and develop effective mitigation strategies.

Conclusion

The WRF-Chem model accurately simulates meteorological parameters and effectively models the distribution of pollutants during forest fires in Ketapang. The simulation shows that pollutants spread northward to areas such as Pontianak City and Sambas Regency, as well as to neighboring countries, driven by air masses moving from the southeast to the north.

The WRF-Chem model simulation results, the temporal patterns of pollutant concentrations, including CO, PM₁₀, and PM_{2.5}, indicate high pollutant concentrations from night to early morning (between 19:00 and 03:00). This is influenced by meteorological factors such as low wind speed, high surface pressure, and low temperature, which inhibit the dispersion of pollutants. In contrast, during the daytime (between 07:00 and 16:00), high wind speed, low surface pressure, and elevated temperatures facilitate the dispersion of pollutants over a wider area, following the wind direction.

Acknowledgements

The authors would like to express their gratitude to the Pontianak Maritime Meteorological Station for its support in providing observational data (wind data), which were used as validation data for the model output in this study.

Author Contribution

AI: Conceptualization, Methodology, Data Interpretation, Writing—Reviewing and Editing, Supervision. EY: Data Collection, Statistical Analysis, Writing—Original Draft Preparation. RA (Randi Ardianto): Methodology, Statistical Analysis, Visualization, Validation. RA (Riza Adriat): Data Interpretation, Validation. MIJ: Methodology, Data Interpretation, Visualization.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

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