Malaysian Journal of Tropical Geography, 2024, 50(1): 1-17

SPATIOTEMPORAL VARIATION OF PARTICULATE MATTER (PM) 2.5 CONCENTRATION IN THE INDONESIAN MARITIME CONTINENT

Gandhi Napitupulu[1,2*], Rafid Zulfikar[3], Kadek Krisna Yulianti[4,5], Deta Ewila Sinuraya[3], Nur Faris Prih Waryatno[5], Naffisa Adyan Fekranie[6]

[1]Study Program of Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology, Cirebon, Indonesia
[2]Environmental and Applied Oceanography Research Group, Faculty of Earth Science and Technology, Bandung Institute of Technology, Bandung, Indonesia
[3]Study Program of Meteorology, Faculty of Earth Science and Technology, Bandung Institute of Technology, Bandung, Indonesia
[4]Master Program in Earth Science, Faculty of Earth Science and Technology, Bandung Institute of Technology, Bandung, Indonesia
[5]Meteorological, Climatological, and Geophysical Agency, Jakarta, Indonesia
[6]Study Program of Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology, Bandung, Indonesia

Email: gandhinapitupulu88@gmail.com

ABSTRACT

Indonesia is recognized as the country with the highest level of Particulate Matter (PM) 2.5 pollution in Southeast Asia. This study aims to investigate the spatial and temporal variations of PM2.5 concentrations in the Indonesian maritime continental region (IMC) over a span of 38 years (1980-2018), based on seasonal and El Niño-Southern Oscillation (ENSO) phenomena. The data used are surface PM2.5, rainfall, wind components at 850 hPa pressure, and fire hotspot points in the IMC region. The results showed higher PM2.5 anomalies in summer (JJA) compared to winter (DJF). There is a positive PM2.5 anomaly during the JJA period and a negative anomaly during the DJF period in the IMC region, which is caused by particle deposition by rain. Seasonal wind patterns carry pollutants from urban areas and hotspots towards the countryside, significantly increasing PM2.5 concentrations in rural areas. Riau and South Sumatra provinces show the highest hotspot density on Sumatra Island, Central Kalimantan and West Kalimantan provinces show the highest hotspot density on Kalimantan Island, and southern Papua has the highest hotspot density on Papua Island. The peak number and density of hotspots in Sumatra, Kalimantan, and Papua occurred in September. The rainfall patterns in IMC are closely linked to ENSO years. During El Niño years, rainfall decreases, and the atmosphere tends to become drier, leading to an increase in hotspots. These hotspots contribute to elevating the concentrations of PM2.5, as observed in 1997/1998 and 2015/2016 when the region experienced its highest hotspot density and a corresponding rise in PM2.5 levels. This association underscores the complex interplay between climatic phenomena, atmospheric conditions, and air quality dynamics in the Indonesian context.

Keywords: *ENSO, Indonesian maritime continent, PM2.5, Rainfall, Seasonal, Wind*

INTRODUCTION

Air pollution has become a significant global issue that requires serious attention due to its impact on human health and environmental quality. Air pollution is widely recognized as a cause of environmental, health, and social problems in several countries, including Indonesia. Particulate matter (PM) is a ubiquitous air pollutant, consisting of a mixture of solid and liquid particles suspended in the air. PM can be classified based on its size into PM10 and PM2.5 with mass median aerodynamic diameters less than 10 μm and 2.5 μm, respectively. Incoming solar radiation will be scattered and absorbed by PM as a direct effect on climate. PM can also modify the amount and properties of clouds by increasing cloud condensation nuclei and cloud albedo as an indirect effect on climate. PM is the sixth leading cause of premature death worldwide (Hadei et al., 2020).

In Europe, the United States, and China, PM2.5 has been extensively measured for several years. Studies on PM2.5 have focused mainly on its chemical composition, including elemental constituents, major inorganic ions, and organic compounds (He et al., 2001; Ye et al., 2003; Geng et al., 2021; Wang et al., 2022). High concentrations of fine particles in the air can have significant adverse effects on visibility and health. Several investigations have been conducted on the chemical composition and emission sources of PM2.5 (Juda-Rezler et al., 2020; Pan et al., 2022; Zhang et al., 2022). These studies have revealed that SO_4^{2-}, NO_3^-, NH_4^+, organic matter, crustal materials, and carbon elements are the dominant species that constitute PM2.5 (Li et al., 2023; Wang et al., 2020). The primary sources of PM2.5 are identified as dust, secondary aerosol, coal combustion, motor vehicle exhaust, and biomass burning (Dahari et al., 2021; Ghosh et al., 2024; Hassan et al., 2021; Istiqomah & Marleni, 2020).

Jakarta is a megacity in Indonesia, surrounded by industrial areas that are0-30 km from the city center (Hobbie & Grimm, 2020). Kusumaningtyas et al. (2018) measured suspended particulate matter (SPM) from 1980 to 2016 and short-term PM10 and PM2.5 data. Santoso et al. (2020) measured the ambient air quality of Jakarta for 2010-2017 as part of the urban air quality reporting in 17 locations across Indonesia. However, research in Indonesia has only focused on short-term events and is limited to urban areas (Amin et al., 2021; Hobbie & Grimm, 2020). Relevant information and actions are still insufficient to control fine particulate pollution fully.

In this study, PM2.5 mass concentration has been measured using daily MERRA satellite data from 1980 to 2018 covering the Indonesian maritime continent (IMC). Using these observations, we analyze the seasonal and intraseasonal variations in PM2.5, the difference in PM2.5 behaviour between urban and rural areas, and the influence of meteorological conditions on PM2.5 behaviour.

METHODOLOGY

Data

The data used is the MERRA-2 M2R1NXAER reanalysis data, which is a data product from the NASA Global Modeling and Assimilation Office (GMAO). The MERRA-2 reanalysis data product has a spatial resolution of 0.5° × 0.625° and a temporal resolution of one hour. The data source can be obtained via:https://disc.gsfc.nasa.gov/datasets/M2T1NXAER_5.12.4/summary (DOI: 10.5067/KLICLTZ8EM9D). The PM2.5 analysis will be carried out to see the average PM2.5 throughout the year from 1980 to 2018. The concentration data from the MERRA-2 reanalysis with units of µg m^{-3} can be found using the following equation:

$$[PM_{2.5}] = 1.375 \times [SO_4] + 1.8 \times [OC] + [BC] + [DS_{2.5}] + [SS_{2.5}] \qquad (1)$$

SO_4 is the reanalysis sulfate parameter; OC is the reanalysis organic carbon parameter; BC is the reanalysis black carbon parameter; $DS_{2.5}$ is the reanalysis 2.5 µm dust parameter; $SS_{2.5}$ is the reanalysis 2.5 µm sea salt parameter.

Multi-Source Weighted-Ensemble Precipitation (MSWEP) data with a spatial resolution of 0.1° × 0.1° and a temporal resolution of one day was used to obtain rainfall data (mm day^{-1}) in Indonesia from 1980 to 2018. Rainfall data is obtained from http://www.gloh2o.org/mswep/ (DOI: 10.1175/BAMS-D-17-0138.1.). Wind at 850 pa every 6 hours with a spatial resolution of 0.125° ×0.125° from 1980 to 2018 was obtained from ERA5 (DOI: 10.24381/cds.adbb2d47). This study is conducted in the Indonesian Maritime region (Figure 1), involving the selection of measurement points that represent significant geographical variations. The study area includes major islands and coastal areas with considerations for diversity of weather, topography, and anthropogenic activities.

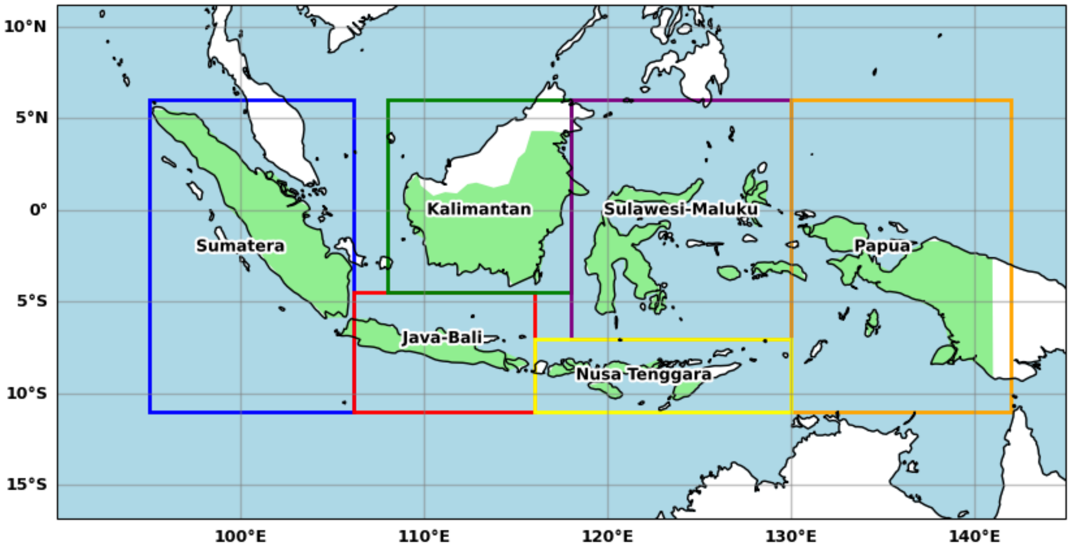


Figure 1: Study area in IMC

Empirical Orthogonal Function

Empirical Orthogonal Function (EOF) analysis aims to transform the original correlated variables into orthogonal (uncorrelated) components (Quang et al., 2023). Suppose the X in Equation 2.

$$= \begin{bmatrix} x_{11} & \cdots & x_{1p} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{np} \end{bmatrix} \qquad (2)$$

X is a matrix of size $(n \times p)$ containing a dataset with n variables and m time points (Khandani & Mikhael, 2021). SVD of X with $Rank(X) = r$ is the factorization as shown in Equation 3

$$X = U \sum V^T \qquad (3)$$

and therefore:

$$X = \sum_{i=1}^{r} u_i \sigma_i v_i(k) \qquad (4)$$

The V matrix from equation 3 is the EOF matrix and $U\Sigma$ is the matrix of principal component scores (Amrhein et al., 2024). The variance of the i^{th} principal component $(i = 1, 2, \ldots, r)$ is obtained from:

$$\mu_i = \frac{\sigma_i^2}{\sum_{i=1}^{r} \sigma_i^2} \qquad (5)$$

where $i = 1, 2, \cdots, r$ is the singular value of the X matrix. In practice, k mode of EOF_1 or principal component with k" r explains the largest proportion of variance (Sharma et al., 2020). EOF_2 mode is a linear combination of all observed variables that is orthogonal to the EOF_1 mode and has the second largest variance (Nagi et al., 2023). EOF analysis is used to find the matrix of component scores $(n \times k)$ with p time on k component which loads the matrix V containing the EOF coefficients of n variable on the k component (Hannachi, 2004).

RESULTS AND DISCUSSION

Monthly Variation of PM 2.5 in Indonesia

Based on the results of PM2.5 calculations from MERRA-2 in Maritime Indonesia from 1980 to 2018, the seasonal average PM2.5 for the DJF rainy season and the JJA dry season is shown in Figure 2. The average PM2.5 is higher in JJA than in DJF. This is thought to be due to the flushing process of PM2.5 by rainwater in the atmosphere during the rainy season. The highest PM2.5 is dominant in Sumatra and Kalimantan with concentrations exceeding 35 μg m^{-3}, while in other regions, especially the eastern part of Indonesia (Sulawesi, Papua, East Nusa Tenggara, West Nusa Tenggara, and Maluku), the average concentration value is quite low at around 5-15 µg m^{-3}, while most of Java has an average concentration value of around 10-25 µg m^{-3}. The differences in PM2.5 in each region of Indonesia are thought to be influenced by differences in human activities in each region and by meteorological factors that affect each region.

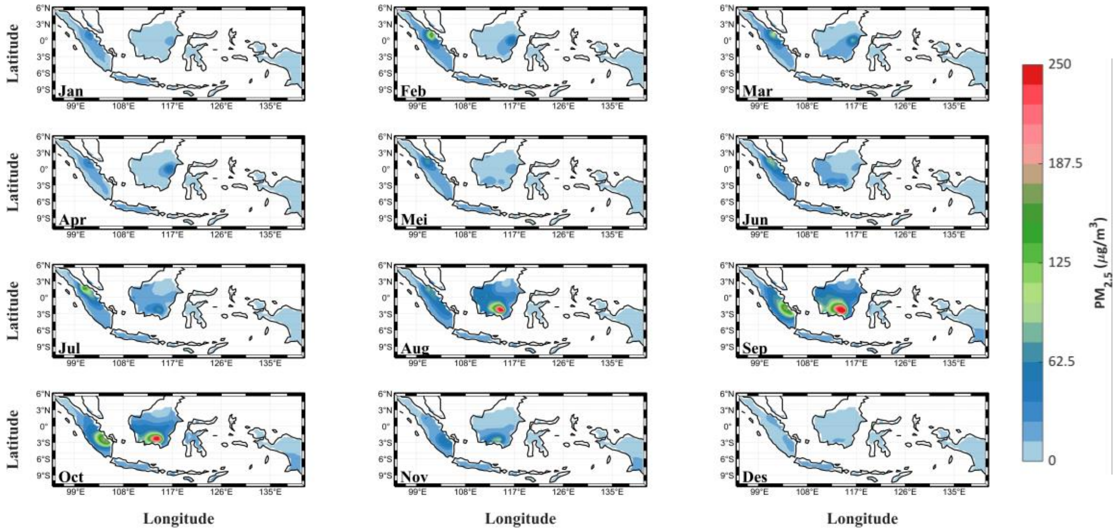


Figure 2: Climatological of PM2.5 in the IMC

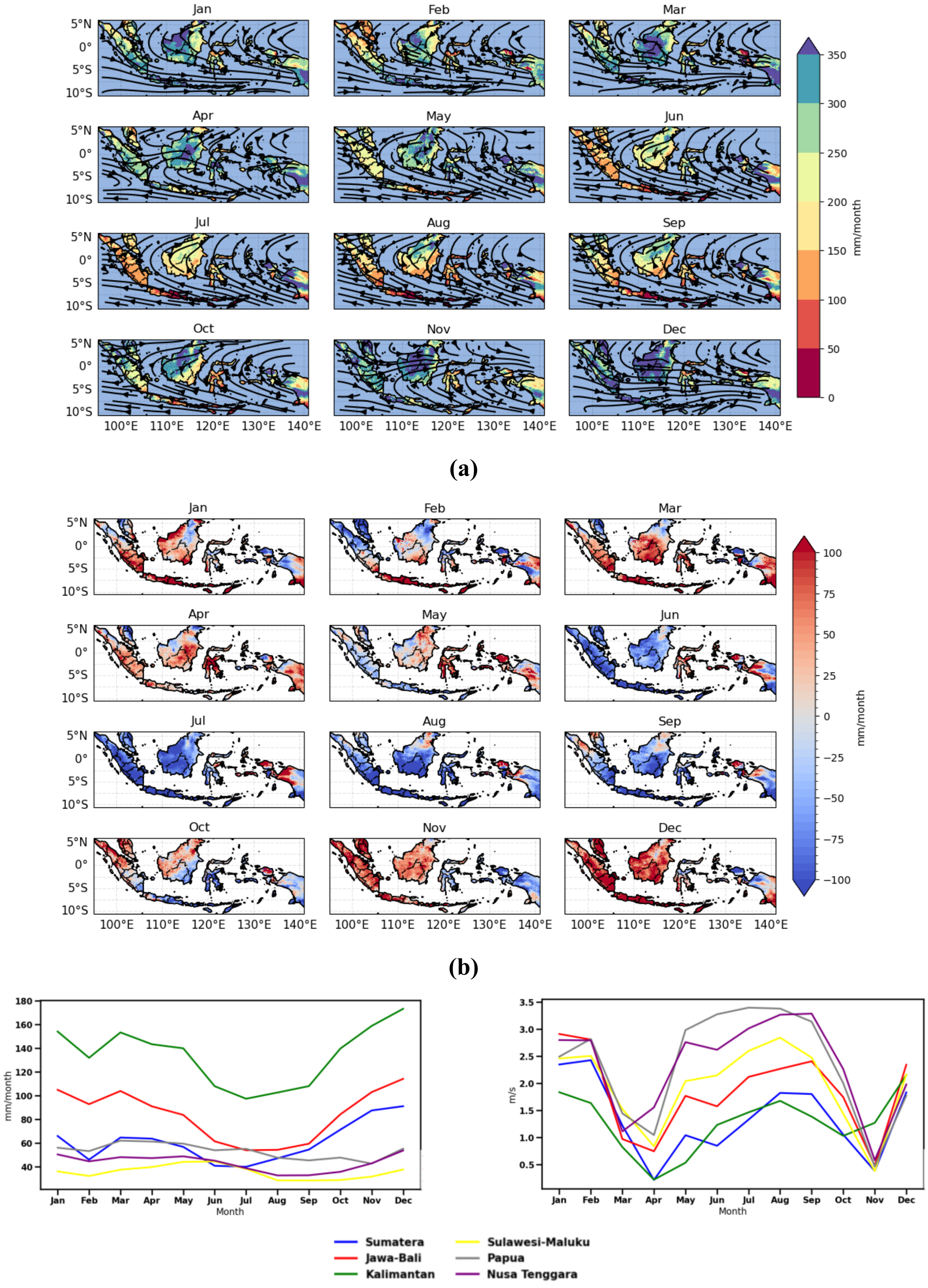
The spatial analysis of PM2.5 in Maritime Indonesia also reflects the important role of natural factors, such as topography and wind patterns, in the distribution of air pollution (Liu et al., 2021). Areas with flatter topography, such as Java, tend to have higher PM2.5 because of urbanization and local pollution generated by human activities, such as transportation and industry (Liu et al., 2021). On the other hand, areas with more hilly or mountainous topography, such as Sulawesi and Papua, may have a more limited distribution of air pollution due to natural influences that limit particulate dispersion (Latif et al., 2018).

In addition, the presence of small islands and differences in area in Maritime Indonesia also affect the distribution of PM2.5. Small islands with dense populations and high human activity tend to have higher PM2.5, especially around urban centers (Othman et al., 2018). On the other hand, islands that are more remote or less affected by human activity may have lower PM2.5. Further analysis of these distribution patterns can provide deeper insights into the factors that influence air pollution in the region.

Seasonal differences in PM2.5 also reflect environmental dynamics and human activities (Kusuma et al., 2019). In addition to weather influences, such as rainfall and wind speed, land burning activities for agriculture, land clearing and industrial activities can also contribute to seasonal variations in air pollution. This analysis demonstrates the complexity of interactions between natural and human factors that shape the spatial and temporal patterns of PM2.5 in Maritime Indonesia, requiring a holistic approach in air pollution mitigation and control efforts (Yang et al., 2023).

Monthly Variations of Rainfall and Wind in IMC

PM2.5 variations are influenced by weather factors such as wind speed, relative humidity, and rainfall, so understanding these variations can provide insight into the complex relationship between meteorological factors and air pollution levels. Climatological analysis of wind speed at 850 hPa and rainfall anomalies along the IMC provides insight into regional climate patterns (Figure 3a). Wind speed anomalies are often associated with changes in atmospheric pressure. Wind speed anomalies can be indicative of weather changes and are often studied in the context of teleconnections, which link global climate anomalies (Domeisen et al., 2019). The IMC experiences a variety of wind speed anomalies due to its geographical location and the dynamic nature of the atmosphere. These anomalies can vary seasonally and are influenced by both local and long-range factors (Seo et al., 2016).



(a)

(b)

(c)

(d)

Figure 3: Climatological of (a) Precipitation (shaded) and wind (streamlines, with the pressure of 850 hPa); (b) Rainfall anomaly in the IMC. Average of (c) rainfall and (d) wind velocity in six regions area study

Precipitation anomalies, particularly rainfall anomalies, are commonly analyzed to understand climate variations (Figure 3b). Rainfall data is collected through various means, including station records and satellite measurements, to assess anomalies. The Indonesian Maritime Islands have experienced significant rainfall anomalies, which can lead to a variety of weather outcomes, including heavy rainfall events. Wind speed anomalies can signal pressure changes and potentially influence rainfall patterns (Figures 3a, 3b), while rainfall anomalies deficits or surpluses can cause direct weather impacts and contribute to long-term climate trends.

In Sumatra, the monsoonal wind (from the southeast) brings rainfall surpluses across the region during the wet season and peaking on December, January, February (DJF), while the dry season is characterized by deficits or negative rainfall anomalies across the region that peaks on June, July, August (JJA) and winds from the northwest following the monsoon pattern (Figures 3a, 3b). In February, Sumatera precipitation begins to fall, especially in North Sumatera where rainfall deficits take place, starts to rise in March, and transitioning to dry season in May throughout the period (Figures 3b, 3c). This pattern also happens in Kalimantan, Java, and Bali areas. In contrast, despite the decreased average rainfall Java and Bali in February, there are no deficit areas across the region. Java and Bali experience fluctuating rainfall across the region, peaking in DJF and driest condition happen in JJA. Similarly, Nusa Tenggara shows a steadier monsoonal pattern, peaking in DJF and driest time in August, September, October.

Sulawesi shows a different pattern with rainfall peaks throughout the region during DJF-MAM, followed by a dry season during JJA-SON in accordance with the equatorial pattern. Kalimantan experiences peak rainfall in some areas during DJF-MAM and drier conditions in most areas during JJA-SON. The patterns vary, some following the monsoon pattern, others having a constant local pattern, and some following the equatorial pattern. Papua experiences similar variations, with peak rainfall in some areas during DJF-MAM and dry season in others during JJA-SON. Some areas, especially in southern Papua, maintain a constant local pattern throughout the year, while other areas follow an equatorial pattern.

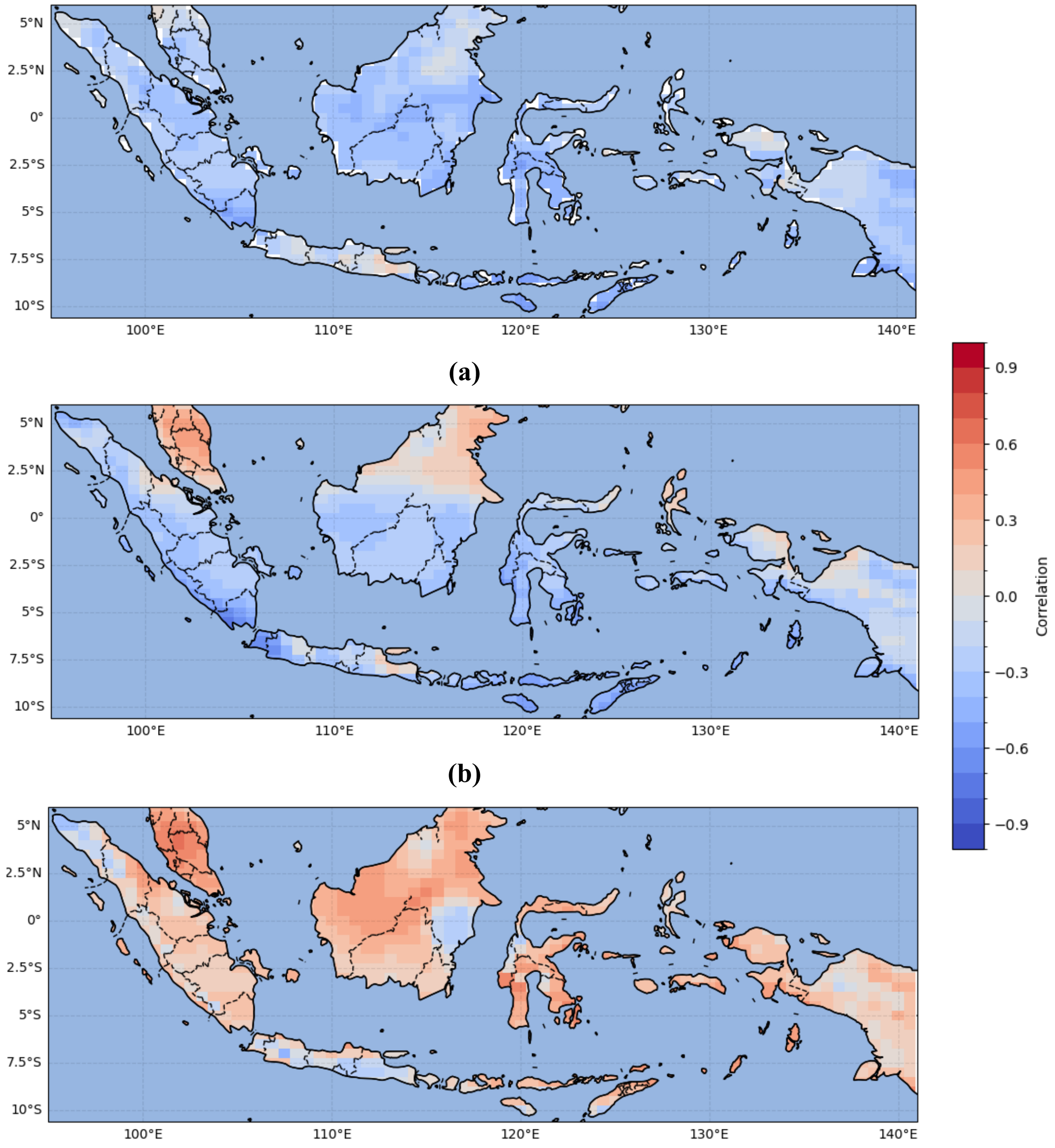
The topography of the region plays an important role. Topographic features such as mountains can affect rainfall distribution and wind patterns. Areas protected by mountains may experience higher rainfall, while areas located behind mountains experience rain shadow effects that result in lower rainfall. Equatorial patterns, such as those observed in Sulawesi, Papua, and parts of Kalimantan, can be explained by their geographical proximity to the equator. These areas may experience the direct influence of equatorial wind convergence, which results in equatorial conditions.

Spatial and temporal analysis of PM2.5 is an important step in understanding air pollution in Maritime Indonesia. By looking at anomalies in wind speed, rainfall, and regional climate patterns, we can identify spatial and temporal patterns in PM2.5 distribution. For example, during times of significant rainfall anomalies, we may see increases or decreases in PM2.5 depending on factors such as dry deposition and air movement. Understanding these spatial and temporal patterns can help develop more effective mitigation strategies to reduce PM2.5 exposure in the region.

In addition, the interaction between meteorological and geographical factors also plays a role in determining the distribution of PM2.5. For example, coastal areas may experience different impacts from air pollution compared to inland areas, due to the influence of ocean and land air flows and local wind patterns. By looking at geographic and topographic variability, we can better understand how local conditions can affect PM2.5 in different regions along Maritime Indonesia.

Effect of Rainfall and Wind Direction on PM2.5 in Indonesia

Weather conditions can affect the distribution and concentration of PM2.5 (Reiminger et al., 2020; Xu et al., 2018, 2020). The relationship between rainfall and PM2.5 can be seen in Figure 4a. Rainfall acts as a cleaner of pollutants from the air through the clear or wet deposition process (Pu et al., 2011). In the clear deposition process, falling raindrops will bind pollutant particles in the air. Meanwhile, in the wet deposition process, pollutant particles dissolve in rainwater and fall with the water. Both processes can clean the air of pollutants like PM2.5 in the atmosphere. The correlation between rainfall and PM2.5 shows negative values in most parts of Indonesia. This shows an inverse relationship: when rainfall increases, PM2.5 levels decrease, and conversely, when rainfall decreases, PM2.5 levels tend to increase. This pattern is consistent with the understanding that rainfall acts as a natural cleaner of the atmosphere, clearing particulate matter including PM2.5.



(a)

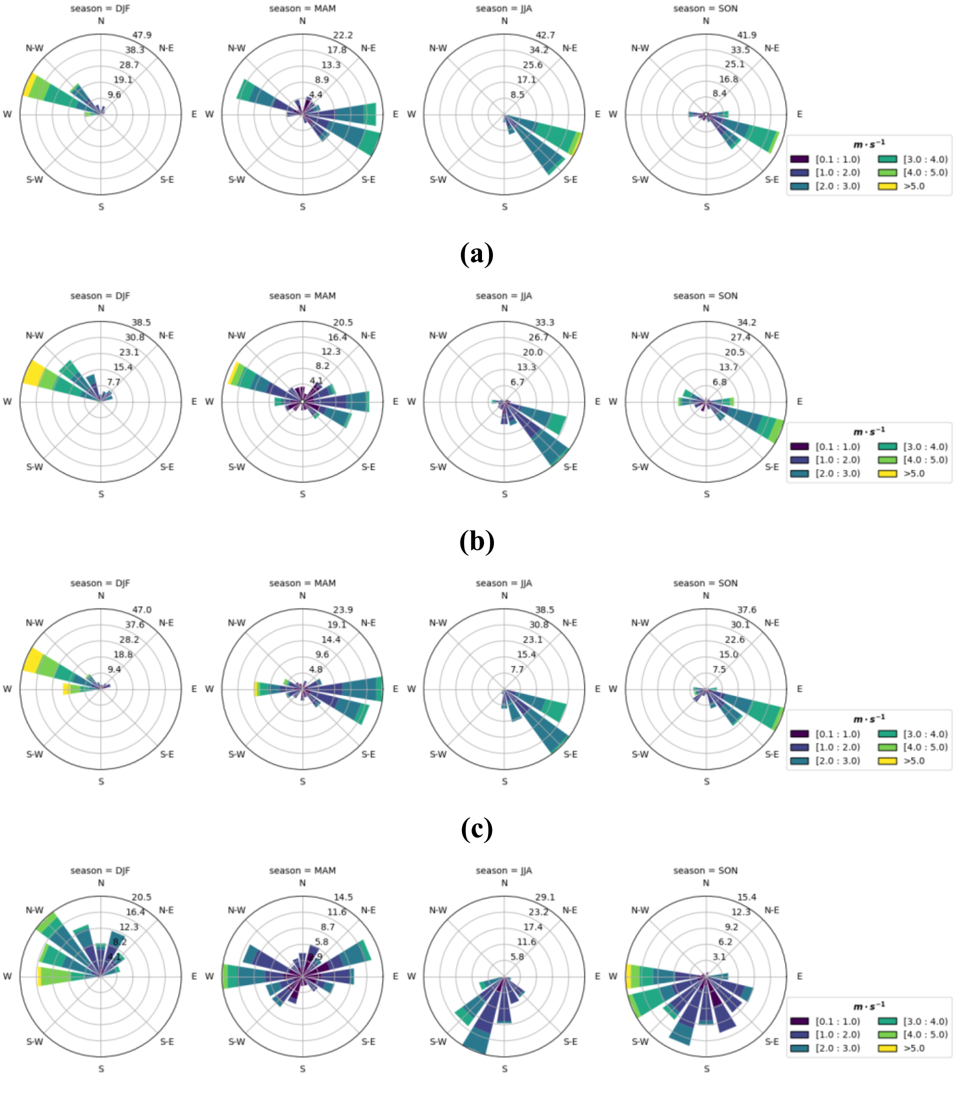
(b)

(c)

Figure 4: Correlation values between (a) rainfall, (b) zonal component of the wind (u), and (c) meridional component of the wind $(v)$with PM2.5 in the IMC

However, an interesting deviation from this trend is observed in the eastern part of Java and western Papua, where there is a positive correlation between rainfall and PM2.5. This shows that in these areas, higher rainfall is associated with increased PM2.5. This phenomenon can be attributed to various local factors such as industrial activities, motor vehicle emissions, or geographical features that can contribute to the release or accumulation of PM2.5 even in the presence of rainfall.

Rainfall and wind direction are two closely related meteorological parameters. To investigate the relationship between wind direction and PM2.5, a correlation analysis was conducted between the u and v wind components and PM2.5 (Figures 4b, 4c). The results of the analysis show that the u wind direction component shows a significant negative correlation in most parts of Indonesia. This indicates that when the wind blows from the west, the PM2.5 tends to decrease. This phenomenon occurs because the westerlies carry wet water vapor that increases rainfall in Indonesia, making it easier for PM2.5 particles to be deposited from the atmosphere. This finding is consistent with the DJF seasonal pattern, where windrose data (Figure 5a) shows the dominance of winds from the west and northwest. Conversely, when the dominant wind comes from the east, the PM2.5 tends to increase. This is because the easterlies carry dry water vapor which reduces the intensity of rainfall in Indonesia, making it difficult for PM2.5 particles to be deposited. This pattern is mainly observed during the JJA period, by the results of the windrose analysis which shows the dominance of wind direction from the southeast.



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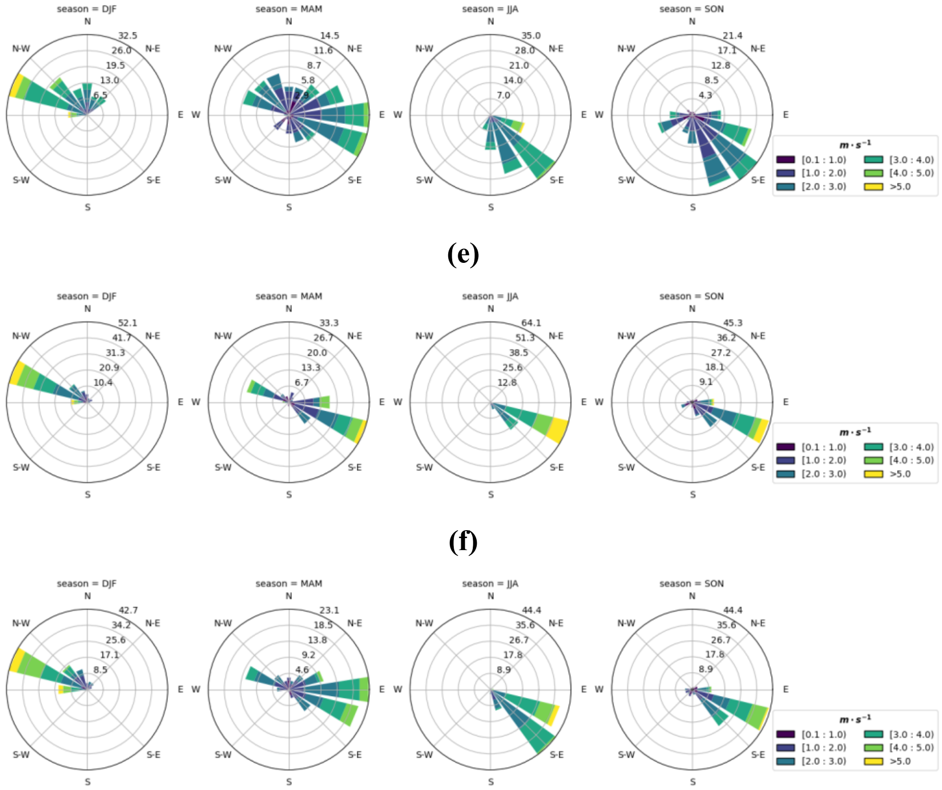


(e)

(f)

(h)

Figure 5: Windrose diagram of seasonal wind velocity at (a) Indonesian Continent Maritime; (b) Sumatera; (c) Java-Bali; (d) Kalimantan; (e) Sulawesi-Maluku; (f) Papua; and (g) Nusa Tenggara

In addition, an analysis of the v wind direction component was also conducted to examine its effect on PM2.5. The findings show a positive correlation between the v-component wind and PM2.5. When the wind moves from the south, the PM2.5 tends to increase. Winds from the south carry dry water vapor, which causes PM2.5 particles not to be deposited efficiently in the atmosphere. This phenomenon is mainly observed in the JJA season, where the dominant wind is dominated by the Southeast wind direction.

According to research by Pu et al. (2011), wind direction has a significant influence on the movement of PM2.5 (Figure 5). Satellite observations of particle movement show a large spread of PM2.5 in the JJA-SON months in the Kalimantan region, as shown in the seasonal PM2.5 image. In June, the highest PM2.5 levels were recorded in Central Kalimantan, followed by a continuous increase and expansion of PM2.5 distribution to the northeast and north. This finding is consistent with the dominant wind pattern blowing from the Southeast to the South during the JJA-SON.

Overall, the complex interaction between wind direction and PM2.5 and other regional factors contribute to the observed variation in the correlation between wind components and PM2.5 in different regions of Indonesia. However, some areas, such as eastern Java and eastern Kalimantan, show different correlations. Therefore, further research is needed to understand these complex dynamics fully.

Intraseasonal Variation of PM2.5 in Indonesia

Indonesia's forests have been worrying due to frequent disruptions, one of which is forest fires. Forest fires occur every year in various regions with different intensity, frequency, and extent (Figure 6). In fact, a huge fire during the 1997/1998 El Niño (ENSO) event burned a massive 25 million hectares of forests worldwide (Miettinen et al., 2011). In the IMC, most hotspots were detected in Sumatra, Kalimantan, and southern Papua. The annual time series graph indicates that the highest hotspot occurrences occurred in 2015, coinciding with a strong El Niño event. The forest and land fires in 2015, particularly in provinces like Riau, Jambi, and South Sumatra, resulted in severe air pollution across several Southeast Asian countries (Yin et al., 2020). This event led to dense smoke covering approximately 80% of Sumatra and Kalimantan (Endrawati, 2016). The peak number of hotspots for the entire IMC region occurred in August, September, and October.

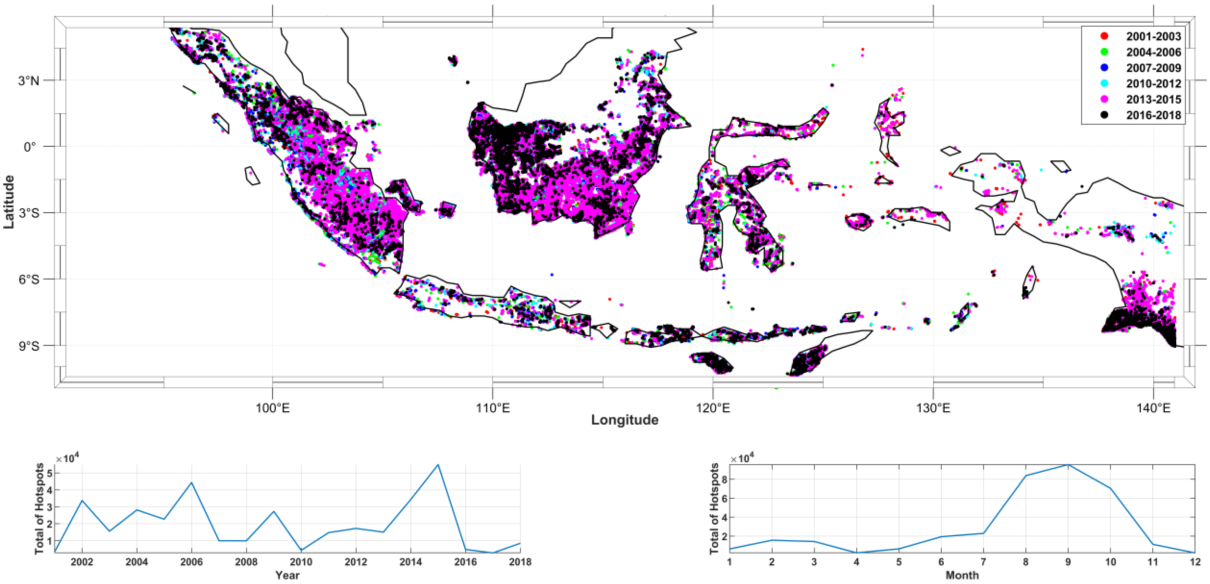
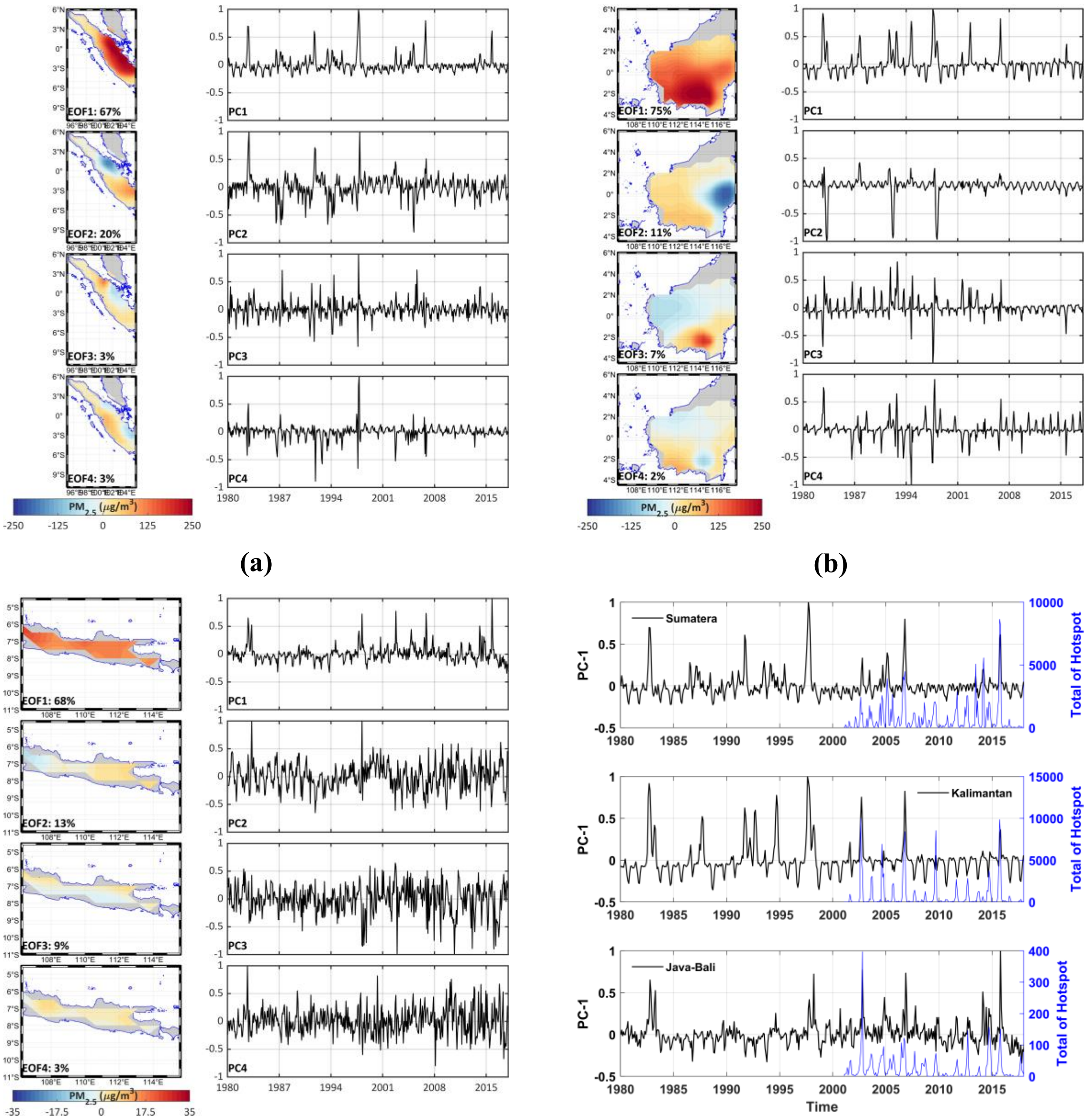


Figure 6: Distribution of hotspots in IMC in 2001-2018

Analyzing PM2.5 dynamics due to variations in rainfall and wind involves understanding the complex interactions between these factors that affect PM2.5 in the air. Forest fires are a frequent phenomenon in Indonesia (Gellert, 1998)and have become a local and global concern (Herawati & Santoso, 2011). Historical records indicate the long-standing occurrence of forest fires in Kalimantan dating back to the 19th century (Barber & Schweithelm, 2000; Levine & D'Antonio, 1999). In addition to economic losses, the impact of forest and land fires is the emergence of haze that disrupts health and land, sea and air transportation systems. The impact of forest fires on agricultural production is not expected to be too great because burning is done for land preparation unless the fires reach productive agricultural land. Forest fires produce carbon emissions that are released into the atmosphere (Cahyono et al., 2015). The characteristics of forest fires in Southeast Asia are closely related to peatland status and land management status (S. A. Cahyono et al., 2015). This leads to high variations in fire activity in the region each year over longer time frames (Miettinen et al., 2011).

During the dry season, the number of hotspots in the Sumatra and Kalimantan regions will increase significantly (Figure 7). Almost every year, hotspots always appear in Sumatra and Kalimantan, especially in peatlands with the highest concentration(Albar et al., 2016). This is certainly a special concern for the region, especially when entering the peak of the dry season. In recent years, fires in Sumatra and Kalimantan have often occurred in areas with peatland cover. On the island of Sumatra, these areas are mostly along the east coast of Sumatra Island, such as the provinces of South Sumatra, Jambi, and Riau. Meanwhile, on the island of Kalimantan, areas often affected by forest and land fires are on the west and south coasts, not infrequently, forest and land fires are centred in the central part of Kalimantan Island (Mizuno et al., 2023). The emergence of hotspots on the islands of Sumatra and Kalimantan will historically begin at the end of the rainy season until it reaches its peak during the dry season (Hein et al., 2022).



(a) **(b)**

(c) **(d)**

Figure 7: EOF analysis of PM2.5 in (a) Kalimantan, (b) Sumatera, and (c) Java-Bali. (d) PC-1 overlayed with total hotspots in Kalimantan, Sumatera, and Java-Bali

The islands of Sumatra and Kalimantan are regions in Indonesia that have large areas of peatland. Peatlands are scattered along the eastern coast of Sumatra and in the southern part of Kalimantan. The nature of peatland is that it can store a lot of water, but the surface dries very quickly and burns easily during the dry season (Yin et al., 2020).

Based on the graph of the number of hotspots over the past eighteen years from 2001 to 2018 as represented in Figure 7, PM2.5 values and hotspots in the Sumatra and Kalimantan regions in 2006 and 2015 were relatively high, exceeding 50,000 hotspots. This is because in 2006 and 2015 El Niño occurred, which caused a decrease in rainfall in most parts of Indonesia (Prayoga et al., 2017). The decrease in rainfall in Indonesia due to El Niño was strongest in the southern regions of Sumatra, Java, Kalimantan, South Sulawesi, Southeast Sulawesi, North Sulawesi, North Maluku, and West Papua which occurred in September-October-November (Mulyana, 2002). In El Niño years, the dry season becomes longer with lower rainfall. Very low Southern Oscillation Index (SOI) values in 2006 and 2015, especially during the dry months, caused minimal rainfall in most parts of Indonesia. This condition causes peatlands to become drier and highly flammable, resulting in a relatively high number of hotspots in 2006 and 2015 compared to other years. Based on the map analyzing the distribution and density of hotspots in the Sumatra and Kalimantan regions represented in Figure 7, over the last ten years the concentration of hotspots in the Sumatra region has been high.

The average monthly rainfall (Figure 2) shows the rainfall pattern in the Sumatra and Kalimantan regions. Based on the processed TRMM data, it can be observed that rainfall in the Sumatra and Kalimantan regions will reach a minimum value in the July-October period. This pattern is opposite to the number of hotspots in the Sumatra and Kalimantan regions (Yamanaka, 2016). Previously, in Figure 8, it was explained that hotspots in Sumatra and Kalimantan will reach their peak in the same period. Rain conditions that reach their lowest value will trigger the emergence of many hotspots in the Sumatra and Kalimantan regions. Based on the visualization of the spatial distribution of average rainfall, the number, distribution, and concentration/destination of hotspots each month in the Sumatra and Kalimantan regions are also negatively correlated with the average monthly rainfall in the region (Afghani et al., 2023).

High PM2.5 in Palangka Raya, Central Kalimantan, occurred during the forest fires in October 2015. The observed PM2.5 reached 377 µg m^{-3} (Lestiani et al., 2019). The impact of the 2015 forest fires on air quality in Palangka Raya, Central Kalimantan, was much higher than normal values. Similar results were reported by (Sulong et al., 2017). In October 2015, PM2.5 in Kuala Lumpur reached 180 µg m^{-3}. The degradation of air quality during these haze episodes not only impacts on human health (especially in children and the elderly) but also on the economy due to the direct costs of illness and lost productivity (Othman et al., 2018). The fires in 2015 had a worse impact on air quality compared to fires in previous years (Sulong et al., 2017). The very dry period from July to October 2015 caused by very strong El Niño conditions in 2015 resulted in more intense fires (Latif et al., 2018). Compared to 2012, PM2.5 during forest fires was about 7-8 times higher than normal (Lestiani et al., 2019). Therefore, efforts to reduce the occurrence of large fires by the government and their consequences need to be continued.

PM2.5 in Surabaya, East Java, , tends to be higher than in Jakarta (Figure 2). Increased motor vehicle usage and dense population are the main factors of high pollution in Surabaya, as well as the contribution of surrounding industrial emissions (Moustakis et al., 2020). As the capital of Central Java Province, Semarang has an industrial park with various industries including electronic assembly, automotive industry, and garment industry.

The data on the spatial distribution of average monthly rainfall represented in Figure 2 presents a graph showing the rainfall pattern in the Sumatra and Kalimantan regions (Damastuti et al., 2020). Based on the processed TRMM data, it can be observed that the rainfall in the Sumatra and Kalimantan regions will reach a minimum value in the period July-October. This has a pattern that is opposite to the number of hotspots in the Sumatra and Kalimantan regions. Previously, in Figure 7, it was explained that the hotspots in the Sumatra and Kalimantan regions will reach their peak in the same period. The rainy conditions that reach their lowest value will trigger the emergence of many hotspots in the Sumatra and Kalimantan regions. Based on the visualization of the spatial distribution of average rainfall, the number, distribution, and concentration/density of hotspots each month in the Sumatra and Kalimantan regions also negatively correlated with the average monthly rainfall in the region (Wang et al., 2023).

The number of hotspots in the Sumatra and Kalimantan regions began to increase significantly in June and peaked in September, in line with the decrease in the average monthly rainfall in the region. The average rainfall in June in most parts of Sumatra and Kalimantan is relatively small, around 80-150 mm, compared to previous months. The rainfall continues to decrease, and the peak decrease is in September, which is around 25-150 mm. This is the same as the peak of hotspots in the Sumatra and Kalimantan regions. In October, the rainfall in the Sumatra and Kalimantan regions has increased relatively, although not significantly, so the number of hotspots is still relatively large (Guo et al., 2003). Meanwhile, from November to December, rainfall increased significantly in most parts of Sumatra and Kalimantan, so the number of hotspots in this month was relatively exceedingly small.

The increase in the number of hotspots and PM2.5 concentrations during the same period also correlates with other environmental factors. Wind patterns and relative humidity play a significant role in the dispersal of smoke and particulate matter into the air. During the dry season, intense winds from the northeast and southeast tend to carry haze and PM2.5 particles from hotspots in Sumatra and Kalimantan to a wider area, including major cities on the island of Java (Dan et al., 2004). In addition, low relative humidity during the dry season exacerbates the condition by reducing the effectiveness of particle absorption by the atmosphere and increasing PM2.5 concentrations in the air. Therefore, a deeper understanding of wind patterns and relative humidity is key in planning mitigation and adaptation strategies to reduce the impact of forest fires on air quality (Lelieveld et al., 2019; Siregar et al., 2022; Vohra et al., 2021).

The long-term impacts of high PM2.5 concentrations on human and ecosystem health must also be seriously considered (Xu et al., 2008). Long-term exposure to PM2.5 has been linked to a variety of health problems, including respiratory disorders, heart disease, and even an increased risk of premature death (Purwadi et al., 2020). In addition, the deposition of PM2.5 particles onto soil and water can also have negative impacts on ecosystems, including loss of biodiversity, habitat destruction, and water pollution.

CONCLUSION

This study provides a comprehensive overview of the seasonal dynamics of rainfall and wind speed and their implications for PM2.5 in the Indonesia maritime continent (IMC) region from 1980 to 2018. Spatial and temporal analysis has revealed significant seasonal patterns in the distribution of rainfall and wind speed, with direct impacts on air quality. PM2.5 anomalies are higher in summer (JJA) compared to winter (DJF). There are positive PM2.5 anomalies during the JJA period and negative anomalies during the DJF period in the IMC region, caused by particle deposition by rain. The rainy months, characterized by intensive rainfall, are a key factor in reducing PM2.5 through airborne particles' "cleaning" effect. Seasonal wind patterns carry pollutants from urban areas and hotspots to the countryside, significantly increasing PM2.5 concentrations in rural areas. Meanwhile, high wind speeds also positively contribute to the dispersion and transportation of PM2.5 particles, resulting in lower concentration levels. Riau and South Sumatra provinces are the areas with the highest hotspot density on Sumatra Island. Meanwhile, Central Kalimantan and West Kalimantan provinces are the areas with the highest hotspot density on Kalimantan Island. Monthly hotspot distribution shows that the number and density of hotspots in Sumatra and Kalimantan will peak in September. Years with strong El Niño events, such as 1997/1998 and 2015/2016, are associated with lower rainfall and higher temperatures compared to non-ENSO or neutral years. El Niño events significantly reduced rainfall in the IMC, while La Niña events resulted in increased rainfall. As rain has a sweeping effect on aerosols, El Niño events lead to a decrease in rainfall frequency and intensity, which contributes to an increase in the number of hotspots and PM2.5. The pattern of hotspot density and its relationship with monthly rainfall can inform strategies for disaster management of forest and land fires in Indonesia. The implications for public health and the environment are significant, with these findings providing a basis for recommending more targeted mitigation measures during the JJA-SON seasonal period.

REFERENCE

Afghani, F. A., Mashuri, I., Khirtin, R., Cahyo, M. A., Tinggi, S., Klimatologi, M., Geofisika, D., & Selatan Indonesia, T. (2023). Topography Effects on Rainfall Characteristics in Bandung City and Cilacap Regency for the 2016-2020 Period. *Sainmatika: Jurnal Ilmiah Matematika Dan Ilmu Pengetahuan Alam*, *20*(2), 157–167. https://doi.org/10.31851/SAINMATIKA.V20I2.11898

Albar, I., Jaya, I. N. S., Saharjo, B. H., & Kuncahyo, B. (2016). Spatio-temporal typology of land and forest fire in Sumatra. *Indonesian Journal of Electrical Engineering and Computer Science*, *4*(1), 83–90.

Amin, M., Putri, R. M., Handika, R. A., Ullah, A., Goembira, F., Phairuang, W., Ikemori, F., Hata, M., Tekasakul, P., & Furuuchi, M. (2021). Size-segregated particulate matter down to pm0.1 and carbon content during the rainy and dry seasons in sumatra island, Indonesia. *Atmosphere*, *12*(11), 1441. https://doi.org/10.3390/ATMOS12111441/S1

Amrhein, D. E., Stephenson, D., & Thompson, L. (2024). A dynamics-weighted principal components analysis of dominant atmospheric drivers of ocean variability with an application to the North Atlantic subpolar gyre. *Journal of Climate*.

Barber, C. V., & Schweithelm, J. (2000). Trial by fire. *World Resources Institute, Washington, DC*.

Bayu Rizky Prayoga, M., Yananto, A., Della Ananto Kusumo, dan, Besar Teknologi Modifikasi Cuaca -Badan Pengkajian dan Penerapan Teknologi, B., Ir Mohammad Soebagio, G., Puspiptek, K., Selatan, T., Informasi Geospasial, B., Raya Bogor Km, J., Kunci, K., Hutan, K., Titik Api, K., & Hujan, C. (2017). ANALISIS KORELASI KERAPATAN TITIK API DENGAN CURAH HUJAN DI PULAU SUMATERA DAN KALIMANTAN. *Jurnal Sains & Teknologi Modifikasi Cuaca*, *18*(1), 17–24. https://doi.org/10.29122/JSTMC.V18I1.2037

Cahyono, S. A., Warsito, S. P., Andayani, W., & Darwanto, D. H. (2015). Faktor-faktor yang mempengaruhi kebakaran hutan di indonesia dan implikasi kebijakannya. *Jurnal Sylva Lestari*, *3*(1), 103–112.

Cahyono, T. D., Wahyudi, I., Priadi, T., Febrianto, F., Darmawan, W., Bahtiar, E. T., Ohorella, S., & Novriyanti, E. (2015). The quality of 8 and 10 years old samama wood (Anthocephalus macrophyllus). *Journal of the Indian Academy of Wood Science*, *12*, 22–28.

Dahari, N., Muda, K., Latif, M. T., & Hussein, N. (2021). Studies of Atmospheric PM2.5 and its Inorganic Water Soluble Ions and Trace Elements around Southeast Asia: a Review. *Asia-Pacific Journal of Atmospheric Sciences*, *57*(2), 361–385. https://doi.org/10.1007/S13143-019-00132-X/METRICS

Dan, M., Zhuang, G., Li, X., Tao, H., & Zhuang, Y. (2004). The characteristics of carbonaceous species and their sources in PM2.5 in Beijing. *Atmospheric Environment*, *38*(21), 3443–3452. https://doi.org/10.1016/J.ATMOSENV.2004.02.052

Dewi Ayu Kusumaningtyas, S., Aldrian, E., Wati, T., & Atmoko, D. (2018). The Recent State of Ambient Air Quality in Jakarta. *Aerosol and Air Quality Research*, *18*, 2343–2354. https://doi.org/10.4209/aaqr.2017.10.0391

Domeisen, D. I. V., Garfinkel, C. I., & Butler, A. H. (2019). The Teleconnection of El Niño Southern Oscillation to the Stratosphere. *Reviews of Geophysics*, *57*(1), 5–47. https://doi.org/10.1029/2018RG000596

Endrawati, S. H. (2016). Analisis Data Titik Panas (Hotspot) dan Areal Kebakaran Hutan dan Lahan tahun 2016. *Kementerian Lingkungan Hidup Dan Kehutanan*, *1*.

Gellert, P. K. (1998). A brief history and analysis of Indonesia's forest fire crisis. *Indonesia*, *65*, 63–85.

Geng, G., Zheng, Y., Zhang, Q., Xue, T., Zhao, H., Tong, D., Zheng, B., Li, M., Liu, F., Hong, C., He, K., & Davis, S. J. (2021). Drivers of PM2.5 air pollution deaths in China 2002–2017. *Nature Geoscience 2021 14:9*, *14*(9), 645–650. https://doi.org/10.1038/s41561-021-00792-3

Ghosh, A., Nagar, P. K., Maddhesia, J., Sharma, M., Azmi, S., Singh, B., & Dutta, M. (2024). A district-level emission inventory of anthropogenic PM2.5 from the primary sources over the Indian Indo Gangetic Plain: Identification of the emission hotspots. *Science of The Total Environment*, *914*, 169865. https://doi.org/10.1016/J.SCITOTENV.2023.169865

Guo, Z. G., Sheng, L. F., Feng, J. L., & Fang, M. (2003). Seasonal variation of solvent extractable organic compounds in the aerosols in Qingdao, China. *Atmospheric Environment*, *37*(13), 1825–1834. https://doi.org/10.1016/S1352-2310(03)00064-5

Hadei, M., Shahsavani, A., Krzyzanowski, M., Querol, X., Stafoggia, M., Nazari, S. S. H., ... & Khosravi, A. (2020). Burden of mortality attributed to PM2. 5 exposure in cities of Iran; contribution of short-term pollution peaks. *Atmospheric Environment*, *224*, 117365.

Hannachi, A. (2004). A primer for EOF analysis of climate data. *Department of Meteorology, University of Reading*, *1*(29), 3.

Hassan, H., Latif, M. T., Juneng, L., Amil, N., Khan, M. F., Fujii, Y., Jamhari, A. A., Hamid, H. H. A., & Banerjee, T. (2021). Chemical characterization and sources identification of PM2.5 in a tropical urban city during non-hazy conditions. *Urban Climate*, *39*, 100953. https://doi.org/10.1016/J.UCLIM.2021.100953

He, K., Yang, F., Ma, Y., Zhang, Q., Yao, X., Chan, C. K., Cadle, S., Chan, T., & Mulawa, P. (2001). The characteristics of PM2.5 in Beijing, China. *Atmospheric Environment*, *35*(29), 4959–4970. https://doi.org/10.1016/S1352-2310(01)00301-6

Hein, L., Spadaro, J. V., Ostro, B., Hammer, M., Sumarga, E., Salmayenti, R., Boer, R., Tata, H., Atmoko, D., & Castañeda, J. P. (2022). The health impacts of Indonesian peatland fires. *Environmental Health: A Global Access Science Source*, *21*(1), 1–16. https://doi.org/10.1186/S12940-022-00872-W/TABLES/4

Herawati, H., & Santoso, H. (2011). Tropical forest susceptibility to and risk of fire under changing climate: A review of fire nature, policy and institutions in Indonesia. *Forest Policy and Economics*, *13*(4), 227–233.

Hobbie, S. E., & Grimm, N. B. (2020). Nature-based approaches to managing climate change impacts in cities. *Philosophical Transactions of the Royal Society B*, *375*(1794). https://doi.org/10.1098/RSTB.2019.0124

Istiqomah, N. A., & Marleni, N. N. N. (2020). Particulate air pollution in Indonesia: quality index, characteristic, and source identification. *IOP Conference Series: Earth and Environmental Science*, *599*(1), 012084. https://doi.org/10.1088/1755-1315/599/1/012084

Juda-Rezler, K., Reizer, M., Maciejewska, K., Błaszczak, B., & Klejnowski, K. (2020). Characterization of atmospheric PM2.5 sources at a Central European urban background site. *Science of The Total Environment*, *713*, 136729. https://doi.org/10.1016/J.SCITOTENV.2020.136729

Kalantari Khandani, M., & Mikhael, W. B. (2021). Effect of sparse representation of time series data on learning rate of time-delay neural networks. *Circuits, Systems, and Signal Processing*, *40*, 3007–3032.

Kusuma, W. L., Chih-Da, W., Yu-Ting, Z., Hapsari, H. H., & Muhamad, J. L. (2019). PM2.5 Pollutant in Asia—A Comparison of Metropolis Cities in Indonesia and Taiwan. *International Journal of Environmental Research and Public Health*, *16*(24). https://doi.org/10.3390/IJERPH16244924

Latif, M. T., Othman, M., Idris, N., Juneng, L., Abdullah, A. M., Hamzah, W. P., Khan, M. F., Nik Sulaiman, N. M., Jewaratnam, J., Aghamohammadi, N., Sahani, M., Xiang, C. J., Ahamad, F., Amil, N., Darus, M., Varkkey, H., Tangang, F., & Jaafar, A. B. (2018). Impact of regional haze towards air quality in Malaysia: A review. *Atmospheric Environment*, *177*, 28–44. https://doi.org/10.1016/J.ATMOSENV.2018.01.002

Lelieveld, J., Klingmüller, K., Pozzer, A., Burnett, R. T., Haines, A., & Ramanathan, V. (2019). Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proceedings of the National Academy of Sciences*, *116*(15), 7192–7197.

Lestiani, D. D., Santoso, M., Kurniawati, S., Sari, D. K., Kusmartini, I., Manurung, A., & Riadi, A. (2019). Chemical Composition of Fine Particulate Matter from Peat Forest Fires at Palangka Raya and Its Dispersion using HYSPLIT. *IOP Conference Series: Earth and Environmental Science*, *303*(1), 012035. https://doi.org/10.1088/1755-1315/303/1/012035

Levine, J. M., & D'Antonio, C. M. (1999). Elton revisited: a review of evidence linking diversity and invasibility. *Oikos*, 15–26.

Li, W., Wu, J., Zhou, Y., Wang, Q., Yu, F., & Wang, R. (2023). Chemical Characteristics and Sources Analysis of PM2.5 in Shaoxing in Winter. *Atmosphere 2023, Vol. 14, Page 1256*, *14*(8), 1256. https://doi.org/10.3390/ATMOS14081256

Liu, Y., He, L., Qin, W., Lin, A., & Yang, Y. (2021). The Effect of Urban Form on PM2.5 Concentration: Evidence from China's 340 Prefecture-Level Cities. *Remote Sensing 2022, Vol. 14, Page 7*, *14*(1), 7. https://doi.org/10.3390/RS14010007

Miettinen, J., Shi, C., & Liew, S. C. (2011). Deforestation rates in insular Southeast Asia between 2000 and 2010. *Global Change Biology*, *17*(7), 2261–2270.

Mizuno, K., Masuda, K., Syahza, A., Mizuno, K., Masuda, K., & Syahza, A. (2023). *Peatland Degradation, Timber Plantations, and Land Titles in Sumatra*. 17–49. https://doi.org/10.1007/978-981-99-0906-3_2

Moustakis, Y., Onof, C. J., & Paschalis, A. (2020). Atmospheric convection, dynamics and topography shape the scaling pattern of hourly rainfall extremes with temperature globally. *Communications Earth & Environment 2020 1:1*, *1*(1), 1–9. https://doi.org/10.1038/s43247-020-0003-0

Nagi, A., Napitupulu, G., Radjawane, I. M., Nurdjaman, S., Supriadi, D., & Nurhayati, D. (2023). Pemetaan Zona Potensial Penangkapan Ikan Tongkol di Perairan Teluk Banten. *Buletin Oseanografi Marina*, *12*(3), 379–394. https://doi.org/10.14710/BULOMA.V12I3.50374

Othman, S. M., Ba-Alwi, F. M., Alsohybe, N. T., & Al-Hashida, A. Y. (2018). Intrusion detection model using machine learning algorithm on Big Data environment. *Journal of Big Data*, *5*(1), 1–12. https://doi.org/10.1186/S40537-018-0145-4/**FIGURE**S/5

Pan, S., Qiu, Y., Li, M., Yang, Z., & Liang, D. (2022). Recent Developments in the Determination of PM2.5 Chemical Composition. *Bulletin of Environmental Contamination and Toxicology*, *108*(5), 819–823. https://doi.org/10.1007/S00128-022-03510-W/METRICS

Pu, W., Zhao, X., Zhang, X., & Ma, Z. (2011). Effect of meteorological factors on PM2. 5 during July to September of Beijing. *Procedia Earth and Planetary Science*, *2*, 272–277.

Purwadi, A., Suhandi, S., & Enggarsasi, U. (2020). Urban air pollution control caused by exhaust gas emissions in developing country cities in public policy law perspective. *International Journal of Energy Economics and Policy*, *10*(1), 31–36.

Quang, N. H., Loc, H. H., & Park, E. (2023). Characterizing sediment load variability in the red river system using empirical orthogonal function analysis: Implications for water resources management in data poor regions. *Journal of Hydrology*, *624*, 129891.

Reiminger, N., Jurado, X., Vazquez, J., Wemmert, C., Blond, N., Dufresne, M., & Wertel, J. (2020). Effects of wind speed and atmospheric stability on the air pollution reduction rate induced by noise barriers. *Journal of Wind Engineering and Industrial Aerodynamics*, *200*, 104160.

Santoso, M., Lestiani, D. D., Damastuti, E., Kurniawati, S., Kusmartini, I., Dwi Atmodjo, D. P., Sari, D. K., Muhtarom, T., Permadi, D. A., & Hopke, P. K. (2020). Long term characteristics of atmospheric particulate matter and compositions in Jakarta, Indonesia. *Atmospheric Pollution Research*, *11*(12), 2215–2225. https://doi.org/10.1016/J.APR.2020.09.006

Santoso, M., Lestiani, D. D., Kurniawati, S., Damastuti, E., Kusmartini, I., Atmodjo, D. P. D., Sari, D. K., Hopke, P. K., Mukhtar, R., Muhtarom, T., Tjahyadi, A., Parian, S., Kholik, N., Sutrisno, D. A., Wahyudi, D., Sitorus, T. D., Djamilus, J., Riadi, A., Supriyanto, J., … Suprayadi, L. S. (2020). Assessment of Urban Air Quality in Indonesia. *Aerosol and Air Quality Research*, *20*(10), 2142–2158. https://doi.org/10.4209/AAQR.2019.09.0451

Seo, K. H., Lee, H. J., & Frierson, D. M. W. (2016). Unraveling the Teleconnection Mechanisms that Induce Wintertime Temperature Anomalies over the Northern Hemisphere Continents in Response to the MJO. *Journal of the Atmospheric Sciences*, *73*(9), 3557–3571. https://doi.org/10.1175/JAS-D-16-0036.1

Sharma, S., Hamal, K., Khadka, N., & Joshi, B. B. (2020). Dominant pattern of year-to-year variability of summer precipitation in Nepal during 1987–2015. *Theoretical and Applied Climatology*, *142*, 1071–1084.

Siregar, S., Idiawati, N., Lestari, P., Berekute, A. K., Pan, W.-C., Yu, K.-P., & others. (2022). Chemical composition, source appointment and health risk of PM2. 5 and PM2. 5-10 during forest and peatland fires in Riau, Indonesia. *Aerosol and Air Quality Research*, *22*(9), 220015.

Sulong, N. A., Latif, M. T., Khan, M. F., Amil, N., Ashfold, M. J., Wahab, M. I. A., Chan, K. M., & Sahani, M. (2017). Source apportionment and health risk assessment among specific age groups during haze and non-haze episodes in Kuala Lumpur, Malaysia. *Science of The Total Environment*, *601–602*, 556–570. https://doi.org/10.1016/J.SCITOTENV.2017.05.153

Vohra, K., Vodonos, A., Schwartz, J., Marais, E. A., Sulprizio, M. P., & Mickley, L. J. (2021). Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environmental Research*, *195*, 110754. https://doi.org/10.1016/J.ENVRES.2021.110754

Wang, W., Gao, Y., Shao, L., Fan, C., Li, X., Li, Y., Liu, M., & Zhou, X. (2023). Chemical compositions and possible transportation of PM2.5 during two haze periods in a coastal city of the North China Plain. *Geological Journal*, *58*(12), 4417–4427. https://doi.org/10.1002/GJ.4850

Wang, W., Zhang, W., Dong, S., Yonemachi, S., Lu, S., & Wang, Q. (2020). Characterization, Pollution Sources, and Health Risk of Ionic and Elemental Constituents in PM2.5 of Wuhan, Central China. *Atmosphere 2020, Vol. 11, Page 760*, *11*(7), 760. https://doi.org/10.3390/ATMOS11070760

Wang, Y., Xiao, S., Zhang, Y., Chang, H., Martin, R. V., Van Donkelaar, A., Gaskins, A., Liu, Y., Liu, P., & Shi, L. (2022). Long-term exposure to PM2.5 major components and mortality in the southeastern United States. *Environment International*, *158*, 106969. https://doi.org/10.1016/J.ENVINT.2021.106969

Xu, B., Lin, W., & Taqi, S. A. (2020). The impact of wind and non-wind factors on PM2. 5 levels. *Technological Forecasting and Social Change*, *154*, 119960.

Xu, J., Holbourn, A., Kuhnt, W., Jian, Z., & Kawamura, H. (2008). Changes in the thermocline structure of the Indonesian outflow during Terminations I and II. *Earth and Planetary Science Letters*, *273*(1–2), 152–162. https://doi.org/10.1016/J.EPSL.2008.06.029

Xu, Y., Xue, W., Lei, Y., Zhao, Y., Cheng, S., Ren, Z., & Huang, Q. (2018). Impact of meteorological conditions on PM2. 5 pollution in China during winter. *Atmosphere*, *9*(11), 429.

Yamanaka, M. D. (2016). Physical climatology of Indonesian maritime continent: An outline to comprehend observational studies. *Atmospheric Research*, *178–179*, 231–259. https://doi.org/10.1016/J.ATMOSRES.2016.03.017

Yang, H., Yao, R., Sun, P., Ge, C., Ma, Z., Bian, Y., & Liu, R. (2023). Spatiotemporal Evolution and Driving Forces of PM2.5 in Urban Agglomerations in China. *International Journal of Environmental Research and Public Health*, *20*(3). https://doi.org/10.3390/IJERPH20032316

Ye, B., Ji, X., Yang, H., Yao, X., Chan, C. K., Cadle, S. H., Chan, T., & Mulawa, P. A. (2003). Concentration and chemical composition of PM2.5 in Shanghai for a 1-year period. *Atmospheric Environment*, *37*(4), 499–510. https://doi.org/10.1016/S1352-2310(02)00918-4

Yin, S., Wang, X., Guo, M., Santoso, H., & Guan, H. (2020). The abnormal change of air quality and air pollutants induced by the forest fire in Sumatra and Borneo in 2015. *Atmospheric Research*, *243*, 105027.

Zhang, X., Ji, G., Peng, X., Kong, L., Zhao, X., Ying, R., Yin, W., Xu, T., Cheng, J., & Wang, L. (2022). Characteristics of the chemical composition and source apportionment of PM2.5 for a one-year period in Wuhan, China. *Journal of Atmospheric Chemistry*, *79*(2), 101–115.