The Impact of Atmospheric Stability Affected by Peat Forest Fire on Surface PM2.5 Concentration in Pontianak Urban Area during La Nina Events 2022

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***Abstract*—Pontianak is the capital city of West Kalimantan province, which is affected by forest fires, especially forests on peatlands that also burn peat. The forest and peatland fires produce a lot of smoke-content particulates because of incomplete combustion of underground biomass. This paper investigates the PM2.5 concentration in 2021 coinciding with moderate La Nina when the effect of a short dry season does not support the occurrence of fires. PM2.5 concentration is analyzed by considering the air quality standard, atmospheric stability, and hotspot account observed by the SNPP satellite in the area with a radius of less than 0.5°, 1°, and 2°. Analysis of the hotspot counts shows a good relationship with the dry season pattern in equatorial rainfall-type regions. Forest fires at locations less than 0.5° and strong inversion layers created heavy pollution in Pontianak, where the air environment is at dangerous levels, with daily concentrations exceeding the National Ambient Air Quality Standards and WHO air quality guidelines. Seasonal analysis shows a very high concentration difference in day and night in the December, January Febturay (DJF) and March, April, May (MAM) periods. This is related to the inversion event at 07:00, where there were many double inversions during the DJF and MAM periods, namely surface inversion and subsidence inversion, causing particulate matter to settle on the earth's surface.**

***Keywords*—air quality, PM2.5, hotspot, temperature inversion**

I. Introduction

Pontianak, the Capital city of West Kalimantan Province, is affected by forest fires, which mostly occur in peatland areas that produce a lot of smoke-content particles. Air quality assessment in forest fire-prone areas is interesting because good air quality suddenly becomes terrible when a fire occurs [1, 2]. Hazardous air quality conditions are often encountered during fires and unfavourable meteorological conditions, especially calm winds and temperature inversions [3, 4]. The particles released as a result of forest fires are very complex, containing many elements, including radioactive elements, but there are four dominant elements, namely carbon, sulfur, potassium, and silicate [5−7]. Particles from forest fires are hazardous, even more dangerous than particles from other sources [8], causing many patients to visit hospitals for respiratory problems [9−11].

In addition to the impact of forest fires, Pontianak, as an urban area, has very high transportation activities. The burning of fuel in transportation, residential, and industrial activities is an important PM2.5 source that is continuously burning, even though the quantity is relatively small, unlike momentary forest fires, but the amount is very large. The main elements of particles produced from fossil fuel burning in transportation activities are almost the same as biomass burning. The four main features released by the transportation sector consist of carbon, aluminium, sulfur, and silicate [5]. Pontianak is located close to the coast, so there is a potential contribution of natural Particulate Matter (PM) 2.5 from the sea, namely marine aerosols. Marine aerosols are hygroscopic particles, so their size becomes coarse or more than 2.5 μm [12, 13].

In the bibliographic study of the causes and impacts of tropical rainforest fires, the Kalimantan tropical rainforest fires are the second most exciting case, and El Nino event years are the primary time of the research [14]. Kalimantan occurs in long dry seasons during El Niño years, thus supporting severe fires. The consequence is that there is a dense and long-lasting smoke haze. In contrast, in South America, where the ENSO has the opposite effect on PM2.5 concentration, the concentrations of PM2.5 in Argentina during La Niña years (drought) were higher than in El Niño years (wet). This increase has been attributed to forest fires [15].

This paper investigates the impact of forest fire and the atmospheric stability on the PM2.5 concentration in Pontianak, West Kalimantan. However, the investigation was carried out in 2021 when the La Nina event occurred, while forest fires are often associated with El Nino [16]. As usual, such weather conditions did not lead to widespread forest fires. This paper investigates how the concentration of PM2.5 in the La Nina year is associated with the short dry season.

II. Literature Review

PM2.5 refers to particles that have an aerodynamic diameter of less than 2.5 μm. The aerodynamic diameter is defined as the diameter of a sphere with a density of 1 g/cm^3 or water density. The primary sources of PM2.5 are fuel, dust, and fires. Exposure to PM2.5 is a risk factor for Acute Respiratory Infections (ARI), as well as long-term health problems such as stroke, ischemic heart disease, lung cancer, type II diabetes, and Chronic Obstructive Pulmonary Disease (COPD) [17]. The physical properties of PM2.5 that absorb and reflect solar radiation play a role in the radiation budget that influences surface temperature.

The PM2.5 concentration depends on the amount of emissions and meteorological conditions [18]. The significant PM2.5 source emissions in Pontianak are peat and forest fires. The peat and forest fires are not continuous yearly emissions but in vast quantities. The amount of PM2.5 emission from forest fires depends on the amount of biomass burnt and the combustion condition. The amount of forest biomass burned is determined by forest biomass density and burned forest area, and the hotspot counts can represent the burned forest area [19, 20].

In addition to the amount of PM2.5 emission, meteorological conditions also affect the concentration of PM2.5 on the surface. An important meteorological parameter that affects the concentration of PM2.5 on the surface is atmospheric stability. Atmospheric stability is divided into classes, from very stable to very unstable. Several methods for determining atmospheric stability classes include Pasquil, Richardson number, Monin-Obukhov length, and temperature profile methods.

In principle, to maintain good air quality, the process of dispersing pollutants from an emission source must be accessible; air parcels containing high concentrations mix easily with ambient air so that the pollutants are widely distributed. Atmospheric stability influences whether pollutants mix easily with ambient air. The more stable the atmosphere, the more difficult it is for pollutants to mix with the ambient air. Low wind speeds can worsen the unstable atmospheric conditions in the dispersion of air pollutants process [21]. The unstable atmospheric conditions result in worse air quality in urban areas [22].Temperature profile is a simple method to classify atmospheric stability, and the quantity stability is calculated by temperature gradient. The temperature gradient is the change in temperature with height ($\Delta T/\Delta Z$), where T denotes atmospheric temperature and represents altitude. The greater the temperature gradient value, the more stable the atmospheric conditions. The concentration of PM2.5 on the surface is directly proportional to the temperature gradient; the greater the temperature gradient, the greater the PM2.5 concentration on the surface [23].

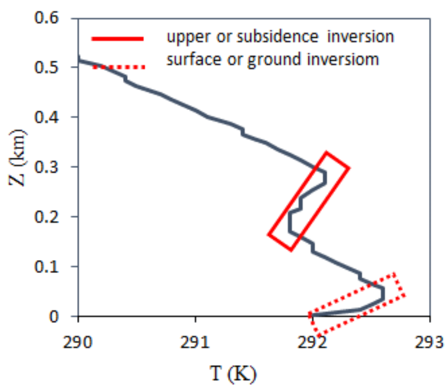


Fig. 1. Temperature inversion layers. Data source: radiosonde launching in Kototabang on 11 Dec 2005 at 23.45 local time.

Under normal conditions, the temperature gradient in the troposphere is negative. However, under special needs, the temperature gradient is positive, namely the inversion temperature. Inversion temperature is an anomaly of layers in the troposphere with extremely stable conditions. According to the vertical position, the inversion temperature is classified into surface inversion or ground inversion and upper inversion or subsidence inversion. Based on the mechanism that forms them, Busch et al. type inversion into subsidence, advective, contact, and radiative inversions [24].

The inversions associated with concentrating particulate on the surface are ground inversion and upper inversion close to the surface, depicted in Fig. 1. These inversion layers cause the subsidence of particulate on the surface, resulting in a dense concentration. The inversion layer becomes very important in studying air pollution, especially when the concentration of pollutants, including particulates, is high [4]. Low air quality is caused by the high activity of pollutant sources and the inversion temperature [25]. Even with the increasing frequency of inversion temperature events, there is an increase in patients due to air pollution [26].

III. Material and Methods

The PM2.5 concentrations were monitored using the air quality monitoring system conducted by Dinas Lingkungan Hidup (Environmental Services) for Pontianak City, located at coordinate (109.35° E, –0.08° S). The research was carried out in 2021 and related to the year of moderate La Nina following the Ocean Nino Index (ONI).

Forest fires as an essential source of PM2.5 were represented by hotspots, and the area burned was proportional to the hotspot counts. The hotspot counts was the responsibility of several Indonesian institutions including the Ministry of Environment and Forestry, Peatland and Mangrove Restoration Agency, Meteorology Climatology and Geophysical Agency, National Research and Innovation Agency, and National Agency for Countermeasure Disaster. Three satellites are used to monitor hotspots, namely SNPP, MODIS, and NOAA20. Hotspot counts are limited to three circular areas centered at the PM2.5 observation site, with a circle’s radius of 0.5°, 1°, and 2° respectively (Fig. 2)

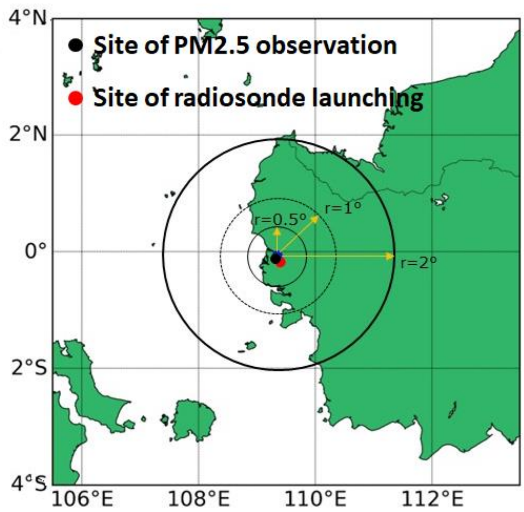


Fig. 2. Study area.

Average daily PM2.5 concentrations were analyzed over time and compared with national ambient air quality standards for Indonesia and Air Quality Guidelines (AQGs)-

WHO of 55 μg/m^3 and 35μg/m^3 for PM2.5 daily averages, respectively. The daily average was only taken if the amount of PM2.5 data in 30 min fulfilled the requirements of more than 60% in one day. Temporal analysis was carried out on diurnal and seasonal periods, namely December, January,February (DJF), March, April, May (MAM), June, July, August (JJA), and September, October, November (SON). Atmospheric stabilities were determined by a temperature gradient ($\Delta T/\Delta Z$) at 00.00 UTC or 07:00 local time and were analyzed seasonally to find its effect on PM2.5 concentrations.

IV. Result and Discussion

A. *PM2.5 Concentration and Forest Fire*

As shown in Fig. 2, the PM2.5 observation position in Pontianak is close to the coast in the west and the mainland in the east, where there are a lot of peatlands. Because of the work of PM2.5 observation, sea breezes carrying marine aerosols affect the location, in addition to anthropogenic particulates, especially those generated from transportation, household, industrial, and household solid waste burning. However, marine aerosols are hygroscopic particles, so their size tends to be coarse, so they include PM10 instead of PM2.5 [12].

The interesting PM2.5 source in Pontianak is peatland and forest fire. Although these events are only temporary, forest fires cause heavy PM2.5 pollution in the atmospheric environment, even significantly reducing visibility [1, 27]. To determine the intensity of peatland and forest fires is identified by hotspot counts. In this study, the SNPP satellite was chosen to obtain hotspot counts because observations of the SNPP satellite hotspot have the best correlation with the land and forest burned area in Kalimantan [28]. Therefore, the hotspot counts represent the land and burned forest areas around the PM2.5 monitoring site.

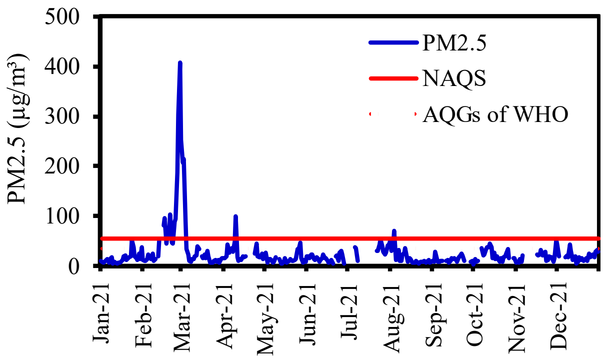


Fig. 3. Time series of daily PM2.5 concentration.

The daily average of PM2.5 during 2021, which is in a moderate La Nina condition, is shown in Figure 2. Based on Indonesian Government Regulation No. 22, 2022, as much as 5% of the existing data shows the daily average PM2.5 concentration exceeds the Indonesian national ambient air quality standards. However, in case referring to the AQGs-WHO, as much as 15% of the existing data, the daily average PM2.5 concentration exceeds the threshold value. Polluted air conditions, one of which is identified by a PM2.5 concentration that exceeds the ambient air quality threshold, can potentially cause disease, especially respiratory syndrome. According to the Health Agency of Pontianak City report, most of the hospital visitors were sufferers of acute respiratory infectious and hypetension, and the other disease is shown in Table 1.

Table 1. Patients in 2021

Disease cases	Number of patients
Acute respiratory infections	18,356
Hypertension	17,835
Indesgition	12,395
Skin disease	7,273
Pulp and tissue disease	6,684
Diabetes mellitus	6,383
Influenza	4,160
Fewer	1,825
Diarrhea	1,509
Others	1,496

Data source: Health Agency of Pontianak City.

Acute respiratory infection is a direct or short-term risk when breathing air with very high PM2.5 concentrations [29]. However, acute respiratory infection is caused by particulates released by transportation or forest fires and other factors such as smoking. In addition, in 2021, there was a COVID-19 pandemic that had an impact on the respiratory tract [30, 31]. Meanwhile, high blood pressure is a long-term or chronic impact of an air environment with high PM2.5 concentrations [32−34]. Such as ARI, air pollution, especially PM2.5, is not the only cause of hypertension; many other factors cause hypertension, such as smoking, alcohol, consuming lots of salt, and obesity. [35, 36]. Cases of ARI and hypertension are not only caused by PM2.5 pollution, but if the air environment is rich in PM2.5 pollutants, it will increase instances of these two diseases.

The high concentration of PM2.5 in Pontianak, as in other cities, is mainly attributed to fossil burning in transportation activities. As an area affected by forest and peatland fires, the atmospheric environment becomes heavily polluted during fires [1]. The hotspot counts indicating the land and forest burned area are divided into circles with the center at the observation location with a radius of 0.5° (55.5 km), 1° (111 km), and 2°(222 km) shown in Fig. 4. In 2021 where the ONI value shows moderate La Nina events, only a few hotspots are found supposing fires. The La Nina effect causes a positive anomaly of 5% of rainfall in Kalimantan [37], which the environment does not support wild forest fires.

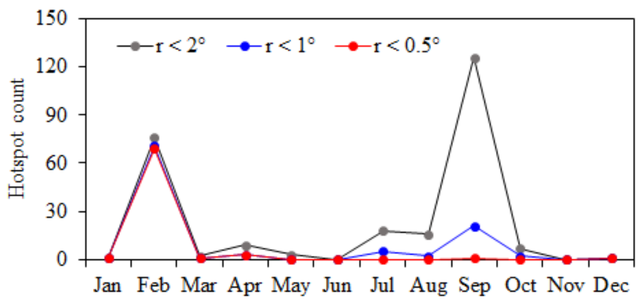


Fig. 4. The monthly hotspot amount by SNPP satellite in the area within radius 0.5°, 1°, and 1° from the observation site.

There are two peaks of monthly hotspot counts. These are February and September. The peak of the hotspot counts in February occurred in the circular area with a less than 55.5 km radius from the observation location. The rise of the hotspot in September happened at a place with a distance between 111 km and 222 km from the observation location. Based on hotspot counts monitoring, the high concentration of PM2.5 is caused by peatland or forest fires at less than 0.5° (55.5 km). Peatlands and forest fires at more than 55.5 km in September have no impact on increasing PM2.5 concentrations on the monitoring observation. There is no long-range transport air pollution impact on the compliance monitoring in 2021 associated with the La Nina phenomenon.

Long-range transport, according to the UNESCEWA Glossary, is the movement of pollutants from their source over more than 100 km. This phenomenon occurs if there is a huge amount of air pollutant emission and the pollutant's lifetime is not short. Hotspots at a distance of more than 55.5 km do not produce much PM2.5, or the wind does not carry PM2.5 to the observation location, so at the observation location, there is no increase in PM2.5, indicating no long-range transport of air pollution.

Hotspot counts can be associated with rainfall, and the character of the hotspot counts is opposite to the rainfall pattern. According to rainfall pattern types by Aldrian [38], the location of PM2.5 observation is in the region with equatorial rainfall type characterized by the peak of the dry season in February and September. However, the dry height in February is lower than in September. The other parts of Borneo Island have a monsoon rainfall type characterized by the peak of the dry season only in September. The Moderate La Nina event in 2021 resulted in weather conditions in which only a few supported forest and land fires in February in the equatorial rainfall-type region and still kept fires in the monsoon-type region in September. The short dry season in February remains important in creating fire conditions in the La Nina year of 2021, which produces high PM2.5 concentrations in regions with equatorial rainfall types. Meanwhile, in the areas with monsoon rainfall, such as Palangkaraya (Central Kalimantan), there was no increase in PM2.5 in February-March in both El Niño and La Niña years [1].

B. Temporal Pattern of PM2.5 Concentration and the Atmospheric Stability

The diurnal pattern of PM2.5 in one year of data observation and the diurnal pattern seasonally is shown in Fig. 5. The diurnal pattern of PM2.5 concentration is low during the day, around 10 μm/m^3, and high at night which reaches more than 30 μm/m^3. The diurnal pattern in one year, when it spares down into seasonal periods, shows that the DJF and MAM periods are higher than the JJA and SON periods, especially in the early morning. The difference in seasonal concentration values is by time series data, in which very high concentrations case occur at the end of February (DJF) and early March (MAM).

The concentration pattern is influenced by the amount of emission, especially land and forest fires indicated by the hotspot counts in February, which still has an impact in early March, as mentioned above. Besides the source pollutant activities, the meteorological condition has a role in pollutant concentrations in the atmosphere. One of the meteorological conditions that plays an important role in increasing the concentration of particulate on the surface is atmospheric stability, which can be determined by temperature gradient [39].

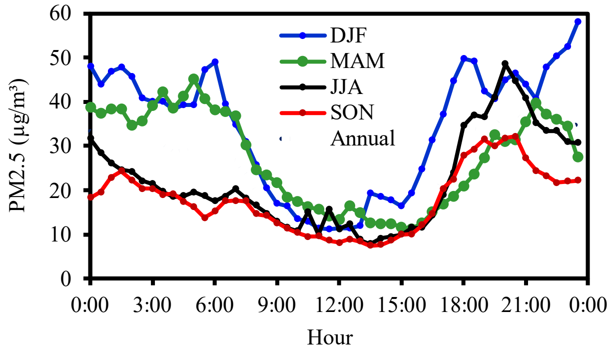


Fig. 5. Annual and seasonal of PM2.5 diurnal pattern.

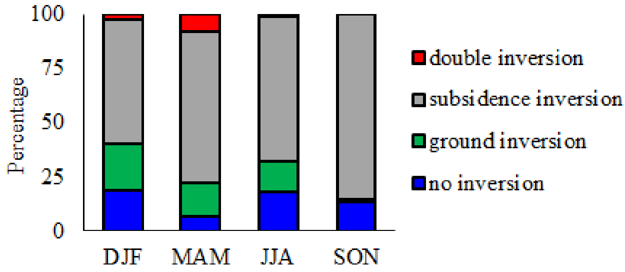


Fig. 6. Frequency of inversion occurrence.

When the temperature gradient is positive, the frequency of the inversion temperature event is obtained from the temperature profile of the Wyoming radiosonde data in Pontianak station. The complete data can be found only in the morning, at 00:00 UTC (07:00 local time). The temperature profile is classified into no inversion, inversion on the surface or ground inversion, inversion on the upper layer or subsidence inversion, and double inversion, including ground inversion and subsidence inversion. The percentage of the frequency of seasonal temperature inversion at 07:00 WIB is presented in Fig. 6.

It is seen that the highest frequency of temperature inversion events occurs in the MAM period, including the possibility of double inversions, both ground and subsidence inversions. The second-highest event of the dual inversion temperature is found in the DJF period. The double inversion denotes very stable atmospheric conditions from the surface to the upper layer. The double inversion layer in these two periods causes the pollutants to subside at the surface, resulting in high concentrations [25]. Therefore, high PM2.5 concentrations are not only associated with forest fires but also with inversion layers.

The difference in PM2.5 concentration during the day and night in Pontianak, which is at the equator region, is very high, reaching more than doubled. As a comparison, the increase at night in the subtropics region is only about half [23]. This condition is caused by the atmospheric conditions in the equatorial region being very unstable during the day; there are a lot of eddies due to strong turbulence in the atmosphere, so the pollutants are well dispersed vertically. The good impact is the low pollutants on the surface where humans live. Unfortunately, no supported quantity data clearly shows the atmosphere's stability during the day.

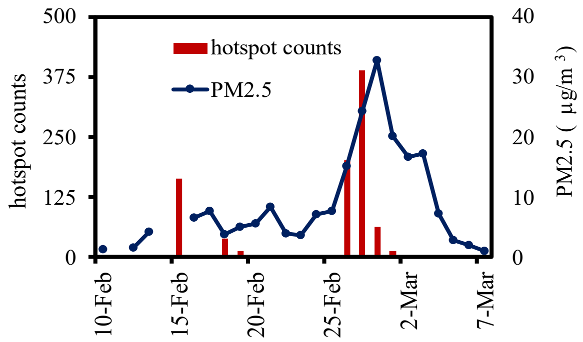
C. Heavy Pollution Event

The heavy pollution event occurs at the end of February and the beginning of March. Fig. 7(a) shows the concentration of PM2.5 and hotspot counts during the heavy pollution. The investigation focuses on February 25 to March 6, corresponding to the peak of hotspot counts and PM2.5 concentration. Many hotspots were detected on February 15; unfortunately, PM2.5 data was incomplete. However, there was an increase in PM2.5 concentrations on the following day. The temperature profile that represents the atmospheric stability to determine whether there is an inversion event is depicted in Fig. 7(b).

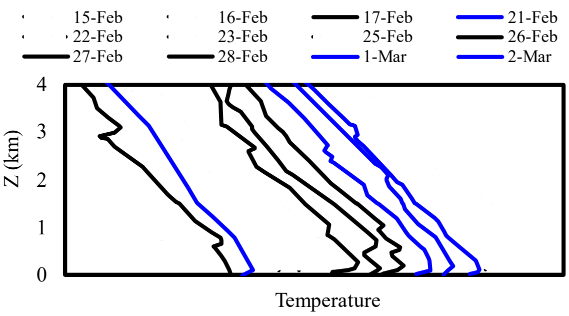
Based on the Indonesian standard air pollution index, during heavy pollution from February 26 to March 6, the air pollution standard index was at dangerous levels (February 27−28 and March 1) and very unhealthy (February 26, March 2−3). PM2.5 pollutants are classified as very harmful air quality if the concentration is between 150.4−250.4 $\mu g/m^3$ and dangerous air quality if the PM2.5 concentration is more than 205.4 $\mu g/m^3$.

The fire initiated the heavy pollution of PM2.5 pollutants. Many hotspots were detected on February 26 and 27, which released a lot of PM2.5 into the atmosphere. PM25 concentrations were very high on February 28 because of the accumulation of PM2.5 emissions from large fires two days before.

Besides the significant PM2.5 emissions due to forest fires, stable atmospheric conditions support this heavy pollution event [4, 23, 26]. It can be seen in Fig. 7(b) that the temperature profile describes the atmospheric stability. During heavy pollution, many strong inversion layers were formed both of surface and subsidence inversions. There are even three layers of inversion on the day when the peak of heavy pollution occurs. These inversion layers worsen air quality, moreover, in high emission conditions.



(a)



(b)

Fig. 7. Hotspots and PM2.5 concentrations (a) and temperature profiles (b) at heavy PM2.5 pollution event.

After the peak of the heavy pollution event, i.e. March 1 - 3, even though the hotspots were no longer there, PM2.5 was high. The PM2.5 emitted previously remains in the air, and there are strong inversion layers on both surface and subsidence inversions. The surface inversion layer usually occurs under low wind speed conditions, causing an increase in PM2.5 concentrations [21]. The presence of inversion layers creates an extremely stable atmosphere, causing the PM2.5 concentrations not to decrease quickly. Although there are no hot spots as a source of PM2.5, it decays slowly.

An interesting temperature profile is shown in Fig. 7(b). Some strong inversion layers are formed when many hot spots are detected, correlated with the large forest fire occurrence. The figure raises whether forest fires can generate inversion layers in the surrounding area. No research discusses the influence of forest fires on the formation of the inversion layer. However, many studies examine the impact of the inversion layer on the particulates released by forest fires.

The mechanism that allows the formation of an inversion layer due to forest fires is as follows: The hot air mass resulting from forest fires passes through cold air outside the forest fire area. Based on the inversion layer formation process, the inversion layer is called frontal inversion. Investigation similar cases are still needed to ensure the impact of forest fires on the formation of the inversion layer.

V. Conclusion

The hotspot counts indicating forest fires around Pontianak in 2021 follow the equatorial rainfall pattern, which has a bimodal pattern with peak hotspots occurring at the end of the dry months, namely February and September. High rainfall as an impact of La Nina in 2021 does not support the occurrence of long and large wild forest fires. The effects of forest fires on PM2.5 concentrations in Pontianak are only in forest fires less than 55.5 km away that occurred in February. Apart from forest fires, another factor that influences PM2.5 concentrations is the inversion layer. Unfortunately, strong inversion layers are generated when forest fires are going on, causing heavy pollution in Pontianak. Therefore, to avoid exposure to outdoor PM2.5 pollutants, people must not only pay attention to intense PM2.5 emission source activity, especially forest fires, but also to weather conditions especially wind and atmospheric stability. The government can facilitate it by providing air pollution predictions based on source activity and weather conditions. The government can facilitate it by providing air pollution predictions based on source activity, namely forest fire and weather conditions. Further research is needed to prove if forest fires can form subsidence inversion layers through a frontal inversion mechanism using many fire cases and meteorological data to support the analysis.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This paper is a contribution of some authors with the following contributions. Sumaryati conducted research and wrote the paper Estiningtyas, Lambang, and Teguh collected data. Risyanto and Atep analyzed the data.. Saipul analyzed and reviewed the manuscript draft. Syafridjon reviewed and submitted the manuscript.

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