Effect of meteorological parameter to variability of Particulate Matter (PM) concentration in urban Jakarta city, Indonesia

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Abstract. Air quality degradation has been reported in Jakarta during 2019. Air pollution in the urban area is attributed to anthropogenic activities and influenced by meteorological parameters. This study attempted to investigate the effect of a meteorological parameter such as Mixing Level Height (MLH) to PM concentration and its seasonal variation in Jakarta during 2019. PM concentrations are obtained from BMKG and United States Embassy; meteorological parameters, as well as radiosonde observation, are derived from Soekarno Hatta Meteorological Office. Seasonal and diurnal variation of PM concentration and its relationship with MLH have been assessed. The study found that PM increased during the dry season (DS) and decreased in the rainy season (RS). During DS, frequency of occurrence of PM\textsubscript{10} (PM\textsubscript{2.5}) concentration that exceeded the national and WHO standard were 2.2% (6.5%) and 96.1% (65%) respectively. Daily variation of PM\textsubscript{2.5} mass ranged from 0.05 to 11.72 times of the PM\textsubscript{10} and increased during RS. The MLH is negatively correlated with PM concentration. PM monthly concentration is always higher in the morning with the lowest MLH, particularly in DS. Radiation inversion type is the most common with height is quite low at 115.30 m causing high PM concentration of 59.17 µg/m\textsuperscript{3} (PM\textsubscript{2.5}) and 122.67 µg/m\textsuperscript{3} (PM\textsubscript{10}).

1. Introduction

Air pollution is widely known for causing environmental, health, and social issue in several countries including Indonesia. Particulate matter (PM) is a widespread air pollutant, consisting of a mixture of solid and liquid particles suspended in the air [1]. Incoming solar radiation is scattered and absorbed by PM as its direct effect on climate. PM could also alter cloud amounts and properties by increase cloud condensation nuclei and cloud albedo as an indirect effect on climate [2]. PM is the sixth cause of premature mortality worldwide [3].

Air pollution caused by PM is commonly the result of burning activities, road traffic, and industrial activities [4]. These particles impair the local and regional air quality and atmospheric visibility [5]. Some of the factors that could affect PM concentration and composition are earth topography, emission...
sources, monsoon seasons, and the meteorological parameters [6]. Balasubramanian et al. [7] reported that Singapore PM$_{2.5}$ mass temporal variability was influenced by emission strength, wind direction, and other meteorological parameters.

Another meteorological parameter that affects near-surface air pollutants in urban areas is Mixing Layer Height (MLH). MLH determines the volume of air into which pollutants and their precursors are emitted [8]. Diurnal evolution of MLH strongly controls the temporal evolution of pollutant concentration, which is in line with the research undertaken by Pissimanis et al. [9]. In addition, studies revealed that the concentration of particles in an urban area is higher than in rural/remote areas [10] due to local sources (fumes from vehicles, emissions from industrial, and power generation).

Jakarta as the capital city often experiences the worst air quality. Being the most densely populated area in Indonesia, the city experiences rapid economic development accompanied by land use changes and massive transportation utility. In Qodar [11], Air Quality Index (AQI) in Jakarta was reported to be the most polluted city in the world three days in a row from 10th until 12nd of July in 2019. This work aims to study the influence of meteorological parameters on PM concentration and its seasonal variation in Jakarta. According to Liu et al. [12], the level of PM concentration varies in different seasons. Therefore, PM concentration during 2019 and MLH will be examined. This study is expected to be useful for policymakers related to air quality management and control.

2. Data and methods

PM$_{2.5}$ and PM$_{10}$ were obtained from the United States Embassy and Meteorological, Geophysical, and Climatological Agency of Indonesia (BMKG) in Kemayoran Jakarta, respectively. PM$_{2.5}$ measurement conducted by the U.S Embassy is carried out in two sites, both in Central and South Jakarta as presented in figure 1, and could be accessed publicly through www.airnow.gov. Both PM$_{2.5}$ and PM$_{10}$ are measured using a beta ray attenuation method continuously every hour using BAM MetOne 1020 instrument and placed around building offices and busy streets. Meteorological parameters such as temperature and pressure are observed using radiosonde at Soekarno-Hatta Meteorological station, west Jakarta (figure 1).

![Figure 1. Measurement sites of PM$_{10}$ and rainfall (A), PM$_{2.5}$ (B and C), and radiosonde observation (D).](image)

Radiosonde measurement is carried out to study the characteristics and dynamics of the upper atmosphere by measuring several weather parameters and launched twice a day, at 00 UTC (7 am Local Time/LT) and 12 UTC (7 pm LT). All data are collected in 2019. MLH and inversion data are the result.
of further processing of the radiosonde observation. MLH can be accessed at http://weather.uwyo.edu/upperair/sounding.html using the Soekarno-Hatta Meteorological Station code, 96749. While inversion data is obtained from the results of radiosonde data processing using The Universal Rawinsonde Observation Program (RAOB) Software. Descriptive statistics such as correlation was conducted for PM concentration and MLH.

3. Results and discussion

3.1. Variation of PM concentration

Figure 2 depicts the daily variation of PM$_{10}$ and PM$_{2.5}$ during the dry (DS) and rainy (RS) season. The daily average of PM$_{10}$ concentrations ranged from 8.3 µg/m$^3$ to 172.6 µg/m$^3$ (N= 261). The highest daily value of PM$_{10}$ reached 172.6 µg/m$^3$ on November 12th with an annual mean which is 72.15 µg/m$^3$. The annual mean value is higher than the annual national threshold at 50 µg/m$^3$ and also greater than those found in other major cities in Indonesia like Bandung, Serpong, and Makassar, at 61.0, 51.8, and 32.9 µg/m$^3$ respectively, as reported by Lestari and Mauliadi [13], Santoso et al. [14], and Rashid et al. [15]. The Ministry of Environment of Indonesia (PP RI No. 41) set the National Air Quality Standard (NAQS) of PM$_{2.5}$ and PM$_{10}$ (24-h) to not exceed 65 and 150 µg/m$^3$ (black dashed lines in figure 2) respectively. Furthermore, the World Health Organization (WHO) set the guideline for 24-h of PM$_{2.5}$ and PM$_{10}$ as 25 and 50 µg/m$^3$ [16]. During DS in 2019, the frequency of occurrence of PM$_{10}$ concentration that exceeded the NAQS and WHO were 2.2% and 96.1% respectively. While, during the rainy season daily concentration of PM$_{10}$ was recorded lower than the national standard, however still higher 42.7% from WHO standard.

![Figure 2. Daily variation of PM during rainy (RS) and dry season (DS) in 2019. Dashed lines represent the threshold set by national and WHO for PM$_{10}$ (black) and PM$_{2.5}$ (grey).](image)

The daily average of PM$_{2.5}$ concentration varied from 1.4 to 98.0 µg/m$^3$ with the highest was 98.0 µg/m$^3$ on August 7th. During DS, 6.5% and 65.0% (N=365) of PM$_{2.5}$ concentrations exceeded the national and WHO standards respectively. The percentage of national excess is higher than PM$_{10}$. According to Lestari and Mauliadi [13], PM$_{2.5}$ in urban areas during DS is composed of high black carbon and sulphate produced from diesel vehicle emission. The annual mean of PM$_{2.5}$ was 27.8 µg/m$^3$ which is comparable with other urban areas such as Taipei [17], Singapore [18], at 28, 22, and 27 µg/m$^3$ accordingly. However, Jakarta’s PM$_{2.5}$ annual mean value is almost double the national annual standard (15 µg/m$^3$), which is 27.8 µg/m$^3$.

Daily variation of PM$_{2.5}$ mass ranged from 0.05 to 11.72 times of the PM$_{10}$ mass in 2019 with the average is 0.7 times of the PM$_{10}$ mass during the year of 2019. In DS, PM$_{2.5}$ mass ranged between 0.05 and 3.42 (with an average of 0.71) times of PM$_{10}$. On the other hand, the PM$_{2.5}$ proportion was greater than PM$_{10}$ during RS which ranged from 0.05 to 11.7 (with an average of 0.9). This is showing that the
PM$_{2.5}$/PM$_{10}$ ratio increases during RS than in DS. Blanco-Becerra et al. [19] revealed that the PM$_{2.5}$/PM$_{10}$ ratio increases during periods of higher precipitation. Salazar et al. [20] also determined a ratio of 0.8 during the rainy season, versus 0.5 during the dry season. PM$_{2.5}$/PM$_{10}$ ratios higher than 0.60 would be expected under the direct influence of combustion sources [21]. Monthly variation is clearly shown by the increase of PM concentration during DS. Furthermore, the PM concentrations were much higher during the transition periods. This could be due to the various wind directions and speeds that occurred during this period [22].

![Figure 3. Hourly average of PM$_{10}$ and PM$_{2.5}$ during RS and DS in 2019.](image)

The distinct pattern of hourly variation is shown by the PM$_{10}$ and PM$_{2.5}$ during DS (Fig. 3). During DS, PM$_{10}$ started to increase at night and reached a peak in the morning at 7 am LT and decreased during the day. This is due to the formation of inversion layers marked by the atmospheric stability, with weather tends to be sunny (no clouds) at night, and calm wind/low wind speed (<3 m/s). The existence of an inversion layer resembles a "serving hood" that surrounds the surface of the air, causing pollutants on the surface to be unable to move vertically. The inversion layer is broken by sunlight radiation in the morning so that pollutants can be distributed vertically and horizontally.

3.2. Effect of MLH and inversion to PM variation
The main parameters to understand the distribution of air pollution are temperature inversion and MLH. The MLH is negatively correlated with particle concentration. The monthly average of MLH at 7 am LT is lower than at 7 pm LT throughout the year, except in April as presented in Figure 4. Whereas if seen based on the season, MLH at 7 pm LT is higher in DS than in RS. However, the difference between DS and RS at 7 am LT is not significant. The MLH at 07 am LT is from 336 m to 1024 m and the difference between months is not significant. Whereas MLH at 7 pm LT has differences during DS and RS. MLH ranges from 688 m to 1403 m and 1444 to 2640 m during RS and DS respectively.

MLH is lower at 7 am LT than 7 pm LT due to insufficient energy in the morning to expand the atmosphere, thus creates a lower mixing layer. Low mixing layer leads particulate matter to remain on the surface so that causing a high concentration of PM due to their accumulation. Most of the year both PM$_{10}$ and PM$_{2.5}$ monthly concentration values are always higher at 7 am LT compared to 7 pm LT. Accumulation of intense emitted pollutants within the shallow mixing layer will cause air pollution. MLH varies over the 24 hours and is inexistent during the night due to ground inversion, unless there is another source of heat, like in urban areas. The development of MLH starts in the morning and increases during the day in Jakarta. Wagner and Schäfer [23] also found that the maximum mixing layer occurred at 6 pm LT in an urban area and fell abruptly to a low level at 7 pm LST. This study could not show the decrease of the mixing layer at the time after 6 pm LT due to the limitation of the data provided by radiosonde observation.
There were four inversion types that occurred in Jakarta namely no inversion, frontal, subsidence, and radiation inversion. Radiation and subsidence inversion are the two basic types of inversions in the lower layer [24]. Radiation inversion is caused by the conditions when there is no incoming solar radiation to balance the surface cooling due to longwave radiation that can come out. Therefore, radiation inversion usually occurs at night and reaches maximum strength around sunrise, but can last until noon [24]. Subsidence inversion is an inversion layer that is lifted away from the surface so that the base of the inversion tends to occur in the higher layers, whereas the basis of radiation inversion is on the surface [24].

Radiation inversion type is the most common occurred one at 7 am LT as presented in Table 1. This is consistent with the study conducted by Iacobellis et al. [24]. The average radiation inversion height was quite low at 115.30 m causing the concentration of PM$_{2.5}$ and PM$_{10}$ high. Subsidence inversion is the second highest type of inversion. Frontal inversion is the third highest type of inversion. The condition of no inversion is the rarest occurred with concentrations of PM$_{2.5}$ and PM$_{10}$ respectively 46.38 µg/m$^3$ and 61.33 µg/m$^3$. This explains that if there is no inversion, the concentration of PM is the lowest during the study period. This could be due to pollutants which are not held back by the inversion layer resulting in lifting itself to the upper layer.

The most common type of inversion at 7 pm LT was subsidence inversion. The second inversion type that often occurred is no inversion. The third highest type of inversion is radiation inversion. Frontal inversion is the least inversion type at 7 pm LT. In general, PM$_{2.5}$ and PM$_{10}$ concentrations at 7 pm LT are smaller than at 7 am LT in all inversion types. This is probably due to the presence of solar radiation during the day which causes the volume of air to expand so that the concentration of pollutants is smaller.
PM concentration is also influenced by the height of the inversion layer, the higher the inversion layer, the smaller the concentration of pollutants.

Table 1. Inversion type and average particulate matter concentration (µg/m³).

| Inversion Type | Time   | Occurrence | Average Inversion Height (m) | PM 2.5 Average | PM 10 Average |
|---------------|--------|------------|-----------------------------|----------------|---------------|
| No Inversion  | 7 am LT| 26         | -                           | 46.38          | 61.33         |
|               | 7 pm LT| 53         | -                           | 29.55          | 58.44         |
| Frontal       | 7 am LT| 47         | 882.57                      | 47.76          | 109.48        |
|               | 7 pm LT| 30         | 1961.00                     | 27.53          | 52.00         |
| Radiation     | 7 am LT| 175        | 115.30                      | 59.17          | 122.67        |
|               | 7 pm LT| 38         | 73.58                       | 24.44          | 47.50         |
| Subsident     | 7 am LT| 112        | 1598.21                     | 49.32          | 96.93         |
|               | 7 pm LT| 233        | 2629.07                     | 35.85          | 57.74         |

4. Conclusion
This study assessed the impact of meteorological parameters on PM concentration during DS and RS. The study found that during DS, the frequency of occurrence of PM₁₀ (PM₂.₅) concentrations exceeded the NAQS and WHO were 2.2% (6.5%) and 96.1% (65%) respectively. The percentage of national exceedances of PM₂.₅ concentrations is higher compared to PM₁₀. Daily variation of PM₂.₅ mass ranged from 0.05 to 11.72 times of the PM₁₀ mass and the ratio of PM₂.₅/PM₁₀ increased during RS. A distinct seasonal pattern was clearly shown by the PM concentration which increased during DS and decreased in RS. Increased concentrations of pollutants from night to morning, particularly during DS, due to the formation of inversion layers and was indicated from low MLH at 7 am LT. This also supports by the forming of radiation inversion at 7 am LT with a low height at 115.30 m. This type of inversion was the most common occurrence during 2019 and causing higher PM concentrations, which were 59.17 µg/m³ (PM₂.₅) and 122.67 µg/m³ (PM₁₀).

Other inversion types were no inversion, frontal inversion, and subsidence inversion. In general, PM₂.₅ and PM₁₀ concentrations at 7 pm LT are smaller than at 7 am LT in all inversion types. PM concentration is also influenced by the height of the inversion layer, the higher the inversion layer, the smaller the concentration of pollutants.

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