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Characterization of Diurnal Ozone and Its Precursors Variation in Bogor Area, West Java, Indonesia

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Abstract: This study analyzes the diurnal variation of ozone (O_3) and its precursors: nitric oxide (NO) and nitrogen dioxide (NO_2), in the Bogor area, using observational data from the BMKG Citeko and CCROM-SEAP IPB monitoring. The research aims to characterize temporal patterns of ozone formation in urban (Baranangsiang) and rural (Citeko) locations, and to examine the influence of precursor availability and meteorological factors. Average hourly concentration data were evaluated, followed by correlation analyses to assess the relationships between ozone and precursor gases. Results showed that ozone levels in both locations follow typical photochemical behavior, low in the early morning, rising as solar radiation increases, and peaking in the afternoon. Ozone concentrations in the dry season (September) were notably higher than in the rainy season (December), reflecting the influence of solar radiation intensity and cloud cover. Citeko consistently recorded higher ozone concentrations than Baranangsiang, despite lower NOx levels, suggesting a stronger influence of transported or background ozone in rural areas. Correlation analysis revealed a strong negative relationship between ozone and NO in Baranangsiang (R^2 = 0.86), while weaker correlations were observed in Citeko. Temperature also displayed a positive correlation with ozone (R^2 > 0.8), emphasizing its key role in photochemical processes. These findings highlight the importance of precursor emissions, meteorology, and regional transport in shaping ozone dynamics in the Bogor region.

Keywords: atmospheric transport, diurnal variation, nitrogen oxides, ozone, photochemical

1. INTRODUCTION

Air pollutants exert significant adverse effects on human health, ecosystems, and the overall quality of the environment. These pollutants originate from both natural and anthropogenic sources. Natural sources encompass volcanic activity, soil weathering, biogenic processes within vegetation, as well as forest fires. Conversely, anthropogenic sources primarily emerge from the combustion of fossil fuels across the transportation, industrial, and domestic sectors (Seinfeld & Pandis, 2016). The increase in anthropogenic activities is largely driven by rapid population growth and urbanization, which results in a heightened burden of air pollutant emissions, particularly in urban regions.

Jakarta, one of Indonesia's most densely populated areas, exemplifies high levels of anthropogenic activity. According to the Jakarta Regional Environmental Status report for 2014, dust emissions amounted to 10,177,309.40 tons per year, nitrogen oxide (NO) emissions totaled 51,210,542.60 tons per year, and hydrocarbon emissions reached 60,697,839.10 tons per year (SLHD DKI, 2015). These emissions have implications not only locally but also in surrounding areas, affecting air quality through atmospheric transport and dispersion. One potential area impacted by pollutant transport from Jakarta is Bogor City, situated in the southern part of Greater Jakarta (Jabodetabek).

Bogor is recognized as a tourist destination and functions as a buffer zone for the capital, experiencing substantial traffic volumes, particularly during weekends and holiday periods. The region's hilly and mountainous topography further contributes to complex atmospheric dynamics. Variations in wind direction and speed, coupled with temperature differentials between Jakarta and Bogor, can significantly influence the movement of air masses and associated pollutants between these areas. Zannetti (1990) posits that pollutants can traverse considerable distances owing to atmospheric transport, a phenomenon referred to as long-range transport. Numerous studies have demonstrated that ozone (O_3) and nitrogen oxides (NO and NO_2, collectively known as NO_x) are air pollutants capable of long-distance transport (Harrison & Holman, 1979; Tiel et al., 2010; Al-Razi & Hiroshi, 2012).

Tropospheric ozone is classified as a secondary pollutant, formed via photochemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) under solar radiation (Tie et al., 2010). The concentrations of ozone in ambient air are influenced by meteorological conditions, such as temperature, solar radiation intensity, and wind direction, as well as by the availability of precursor compounds (NO and NO_2). Typically, ozone exhibits a distinct diurnal pattern, characterized by increased concentrations during daylight hours due to elevated photochemical activity, and a reduction during nighttime as a result of reaction with NO.

An examination of the diurnal patterns of ozone and its precursor gases is essential for advancing the understanding of ozone formation dynamics within a specific region and its relationship with meteorological factors alongside anthropogenic activities. This study aims to analyze the diurnal characteristics of ozone and its precursor gases (NO and NO_2) within the Bogor region. In addition to delineating the daily temporal patterns of these gases, the research seeks to elucidate the potential influence of pollutant transport from surrounding regions, particularly Jakarta, on ozone concentrations in Bogor. The findings from this study are anticipated to contribute to air quality management efforts and the formulation of environmental policies within the Greater Jakarta area.

2. MATERIALS AND METHODS

2.1 Data

Per-minute observational data of temperature, ozone, NO, and NO_2 obtained from the BMKG Citeko and CCROM-SEAP IPB monitoring stations for September and December 2017 were subsequently pre-processed by aggregating the raw measurements into hourly averages, which were then further averaged to derive monthly mean concentrations for use in the analysis.

2.2 Study Site

The study area was located in Bogor, with two air quality monitoring stations: the BMKG Citeko and the CCROM-SEAP IPB. The map of the study area is showed in Figure 1.

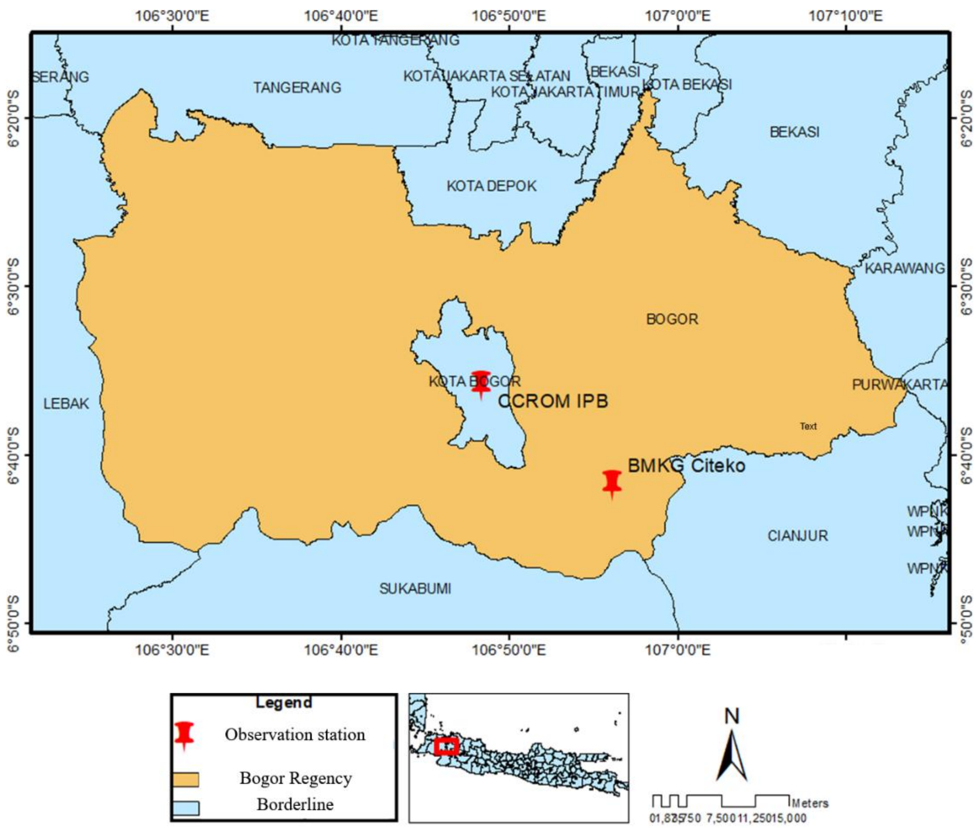


Figure 1. Research study location

2.3 Calculating the Average Value of Data

The calculation of the average value of observational data is formulated as follows.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} X_i$$

x_i = pollutant concentration data
n = number of days in a month
$\bar{x}$ = average pollutant concentration

2.4 Correlation Test

The analysis of the relationship between ozone and precursors was analyzed using Pearson correlation. The Pearson correlation coefficient is defined as the covariance between two variables divided by the product of their standard deviations; as such, it is a unit-less metric that standardizes different variables onto a comparable scale (Nakyai et al., 2025).

$$r = \frac{\sum(c_{w-}\ \overline{c_w})\ (c_{o-}\ \overline{c_o})}{\sqrt{\sum(c_{w-}\ \overline{c_w})^2\sqrt{\sum(c_{o-}\ \overline{c_o})^2}}}$$

r = correlation coefficient
c_o = observed pollutant concentration
c_w = modeled pollutant concentration
$\overline{c_o}$= observed mean pollutant concentration
$\overline{c_w}$= modeled mean pollutant concentration

3. RESULTS AND DISCUSSION

3.1. Diurnal variation of ozone concentrations

Diurnal fluctuations in ozone levels during September and December display a consistent pattern: they rise during periods of high radiation intensity and decline during periods of low radiation. In Baranangsiang, ozone concentrations commence an increase after 7:00 AM, reaching a peak at 3:00 PM. Conversely, in Citeko, the increase begins one hour later, at 8:00 AM, with peak concentrations occurring at 4:00 PM. As evening approaches, a downward trend in ozone concentrations is observed. Nevertheless, ozone levels remain detectable at night, as they are influenced by the deposition of pollutants carried by the wind to these regions.

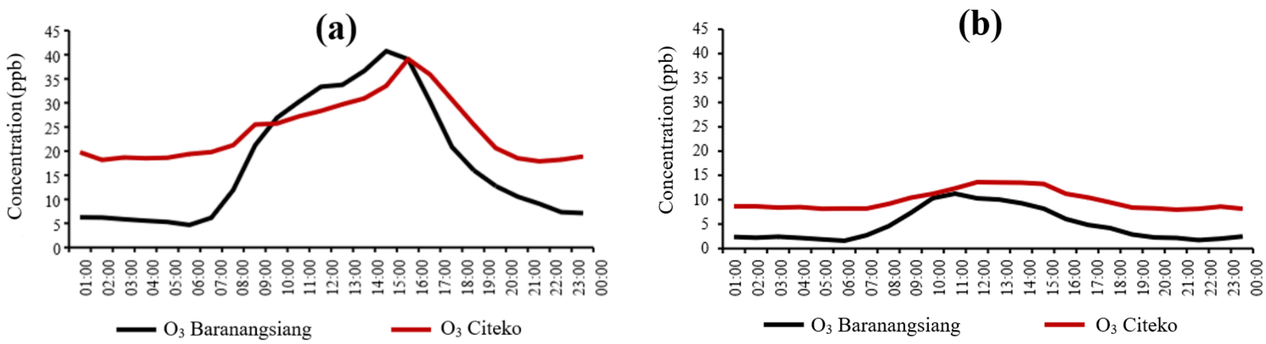


Figure 2. Diurnal ozone pattern in Baranangsiang and Citeko areas during (a) September and (b) December

Ozone concentration values recorded in December are notably lower than those observed in September. December coincides with the rainy season, which results in increased cloud cover that diminishes the intensity of solar radiation reaching the Earth's surface. This phenomenon significantly impacts the ozone formation process. Conversely, during the dry season in September, the Bogor area experiences reduced cloud cover, allowing for unobstructed solar radiation, thereby facilitating increased ozone formation. Analysis of observational data from the CCROM and BMKG Citeko indicates that the average ozone concentration in the Citeko region is higher than that of the Baranangsiang area. Specifically, in September, the average ozone concentrations were 24 parts per billion (ppb) in Citeko and 18 ppb in Baranangsiang. In December, these values decreased to 14 ppb and 11 ppb, respectively. This data underscores the trend that rural areas exhibit higher ozone concentrations compared to urban environments, consistent with the findings reported by the CEC in 1997.

3.2. Diurnal variation of NO_x concentration

Fluctuations in ozone concentration are significantly influenced by the presence of its precursor, nitrogen monoxide (NO) (Stern et al., 1984). In Baranangsiang, NO concentrations are observed to be higher than those in Citeko, which would typically lead to increased ozone formation and higher concentrations. However, empirical data indicate the contrary; ozone concentrations in Baranangsiang are lower than those in Citeko. According to various studies, both ozone and its precursors can be transported over considerable distances, thereby impacting local concentrations. As the primary source of ozone precursors is NO, it is essential to link the analysis of ozone fluctuations with the examination of NO fluctuations.

Data from December reveal an average NO concentration that is higher compared to September. This trend is correlated with the rainy season in December, during which relatively low temperatures reduce the oxidation of NO to nitrogen dioxide (NO_2). The Central Environmental Council (CEC, 1997) elucidates that the oxidation reaction of NO to NO_2 is significantly affected by air temperature. In September, fluctuations in NO levels were associated with fluctuations in ozone levels in Baranangsiang. While ozone concentrations in Baranangsiang exhibited an increase after 7:00 AM, NO concentrations experienced a marked decrease at the same time, resulting in a reversal of anticipated patterns. This phenomenon did not extend to the Citeko area. Furthermore, in December, this pattern was not observed in either location.

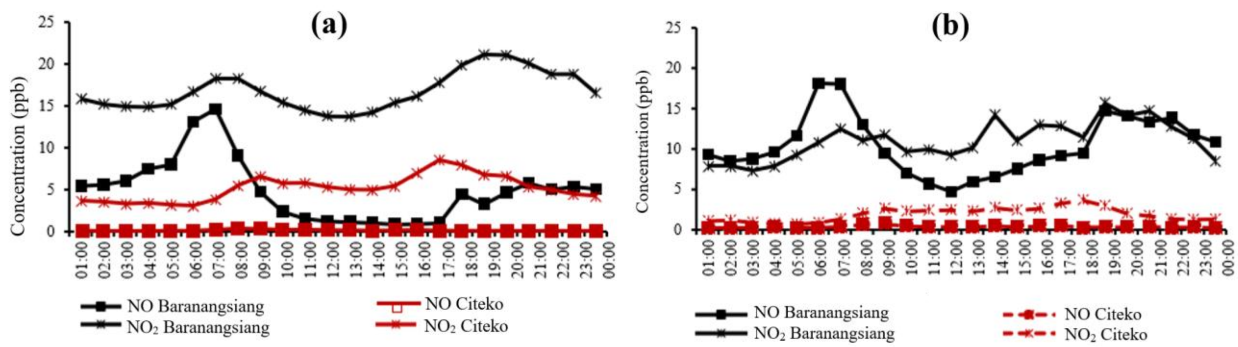


Figure 3. Diurnal NO_x pattern in the Baranangsiang and Citeko areas on (a) September and (b) December

In addition to nitrogen monoxide (NO), nitrogen dioxide (NO_2) constitutes another significant precursor of ozone formation. Nitrogen dioxide is generated through the reaction of nitrogen monoxide with ozone and hydrocarbons. The concentration of NO_2 is generally higher than that of NO, as it can be formed through multiple reactions and from various sources of pollutant emissions (The Royal Society, 2008). In the region of Baranangsiang, the average concentration of NO_2 exceeds that of Citeko. In September, the recorded concentrations were 16 parts per billion (ppb) in Baranangsiang and 5 ppb in Citeko. By December, these values declined to 11 ppb in Baranangsiang and 2 ppb in Citeko. The trend of NO_2 concentrations in September demonstrates greater regularity compared to December. The combination of high rainfall and low temperatures during December facilitates the leaching of pollutants, leading to notable fluctuations in concentration levels.

3.3. O_3 and NO_x fluctuations during September period

The concentrations of ozone and its precursors exhibit distinct maximum and minimum values between Citeko and Baranangsiang. Notably, the fluctuations in ozone levels in Baranangsiang are considerably more pronounced than those observed in Citeko. In September, the recorded minimum and maximum ozone values for Baranangsiang were 5 ppb and 41 ppb, respectively, resulting in a range of 36 ppb. In comparison, Citeko reported values of 22 ppb and 40 ppb, yielding a range of 18 ppb. In December, Baranangsiang displayed a range of 9.5 ppb, while Citeko showed a range of 5.5 ppb. Figure 4 presents a comparative analysis of the intervals for ozone and nitrogen oxides (NO) in Baranangsiang and Citeko during September. The observed differences in these intervals imply that the formation of ozone in Citeko is lower, potentially due to the elevated initial concentrations prevalent in the area. This observation is supported by findings from the CEC (1997), which indicate that urban areas may experience a moderate decline in ozone levels, whereas rural areas demonstrate minimal change.

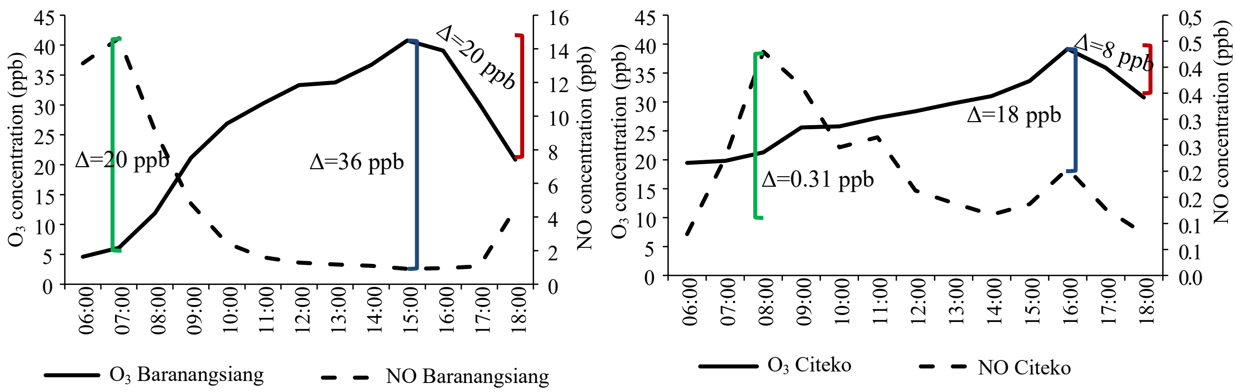


Figure 4. Intervals of NO and O_3 concentrations in Baranangsiang and Citeko during September

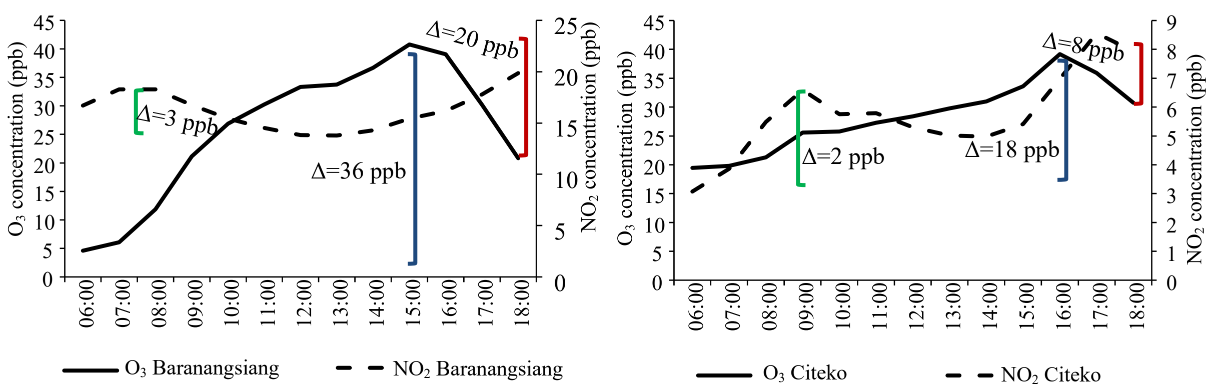


Figure 5. Intervals of NO_2 and O_3 concentrations in Baranangsiang and Citeko during December

According to The Royal Society (2008), the reduction in ozone concentration in urban areas during the night occurs at a more rapid rate due to a decrease in the primary sources of ozone precursors and the absence of solar radiation. Consequently, the photochemical reactions responsible for ozone formation do not take place. In contrast, rural areas experience minimal anthropogenic activity, resulting in ozone levels that are primarily derived from external sources, natural processes in the vicinity, and stratospheric ozone. Collectively, these components are referred to as hemispheric ozone. The observed decline in ozone concentration in rural regions is chiefly attributed to the process of dry deposition; however, the rate of ozone removal through chemical reactions surpasses that of dry deposition.

3.4. O_3 and NO_x fluctuations during December period

Figure 6 and 7 illustrates the diurnal variations of ozone and its precursors (NO and NO_2) at Baranangsiang and Citeko during December. The overall pattern shows that ozone concentrations increased gradually after sunrise, reached a peak around midday, and subsequently decreased toward the evening. In contrast, NO and NO_2 concentrations exhibited an inverse trend, decreasing during the morning hours and slightly increasing again in the late afternoon (Zhang et al., 2002). At Baranangsiang, the ozone concentration showed a substantial increase of approximately 13 ppb from 06:00 to 11:00, indicating active photochemical formation driven by solar radiation. This period coincided with a decrease in NO concentration, suggesting reaction of ozone by freshly emitted NO during the early morning. The ozone concentration then declined after 12:00 as photochemical activity weakened and NO levels gradually increased again. The afternoon rise in NO indicates renewed emissions likely related to traffic activities during the return home hours.

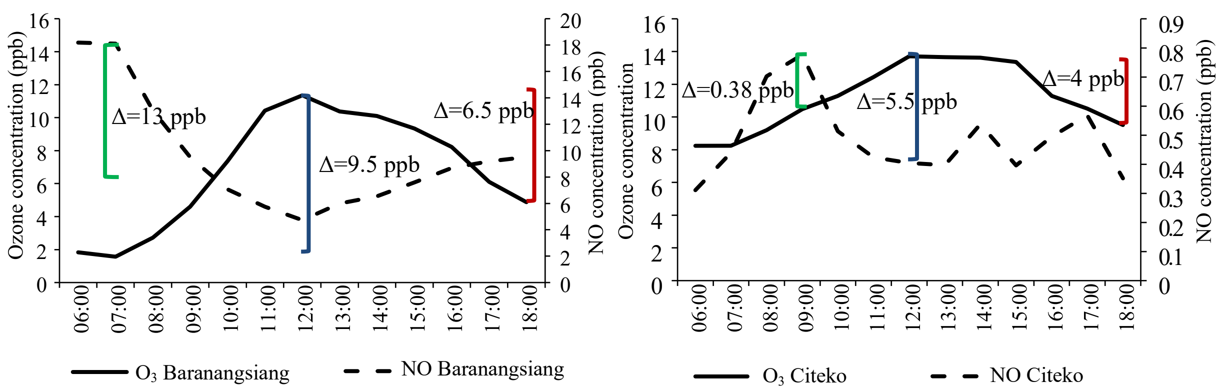


Figure 6. Intervals of O_3 and NO concentrations in Baranangsiang and Citeko during December

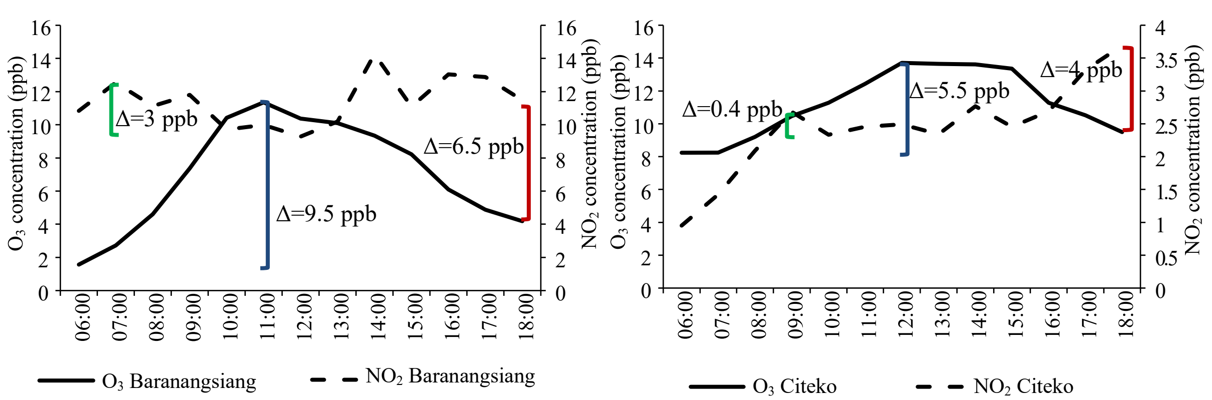


Figure 7. Intervals of O_3 and NO_2 concentrations in Baranangsiang and Citeko during December

At Citeko, the ozone fluctuation was less pronounced, with an increase of only 0.38–0.4 ppb in the morning and a midday increment of about 5.5 ppb. The smaller variation compared to Baranangsiang reflects the cleaner and more elevated characteristics of the Citeko site, where precursor emissions are relatively lower. The concurrent NO and NO_2 concentrations remained below 1 ppb and 35 ppb, respectively, showing that photochemical ozone formation is limited by precursor availability rather than solar radiation intensity. The differences between the two sites highlight the influence of local emission sources and topography. Baranangsiang, being an urban area with high traffic intensity, showed stronger diurnal variability and a more pronounced ozone-NOx interplay. Meanwhile, Citeko, located in a highland and less urbanized environment, exhibited smoother ozone fluctuations with lower NO_x levels. These findings confirm that ozone formation in December is predominantly NO_x-limited, and urban areas contribute significantly to the enhancement of daytime ozone due to abundant precursor emissions and favorable meteorological conditions for photochemical reactions.

3.5. Correlation Between Ozone and Nitrogen Oxides (NO_x) Parameters During September

Based on the analysis of average hourly concentration data for a duration of one month, a discernible fluctuation pattern exists among ozone, nitric oxide (NO), and nitrogen dioxide (NO_2). To mitigate the impact of irregular patterns induced by rainfall fluctuations, further correlation analysis was conducted exclusively in September. The results from this analysis indicated a more robust relationship between ozone parameters and NO compared to that with NO_2. It is noteworthy that nitric oxide possesses a very short residence time of only a few minutes due to its high reactivity with ozone, resulting in its rapid conversion (oxidation) to nitrogen dioxide.

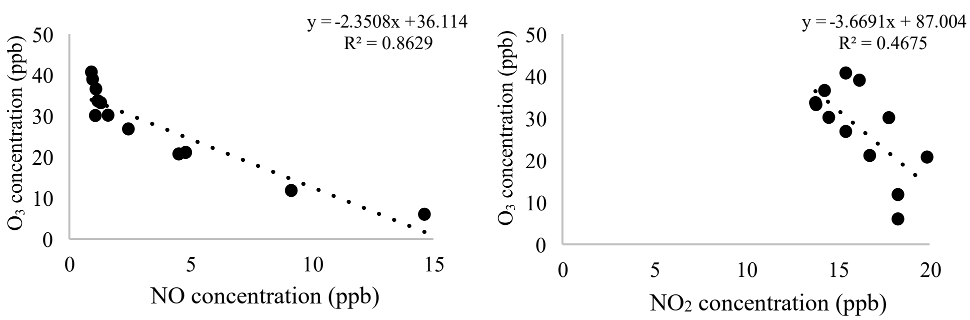


Figure 8. Correlation between O_3 and NO_x in Baranangsiang during daylight (06:00-18:00) in September

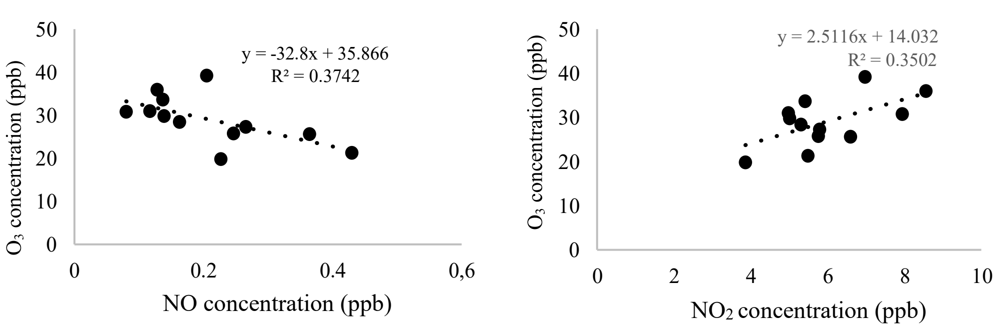
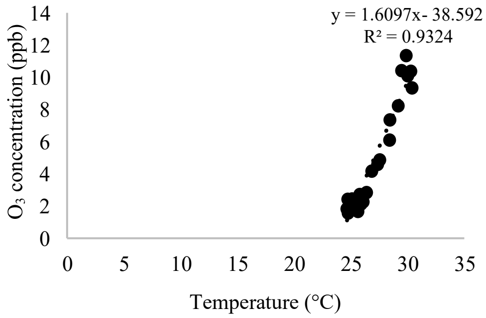


Figure 9. Correlation between O_3 and NO_x in Citeko during daylight (06:00-18:00) in September



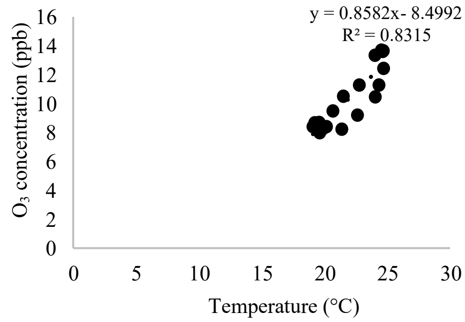


Figure 10. Correlation between O_3 and temperature in Baranangsiang (left) and Citeko (right) during daylight (06:00-18:00) in September

Figures 9 and 10 illustrate the relationships between ozone parameters and their precursors during daylight hours in September, while the correlation analysis for nighttime is provided in an attached document. During the daytime, the correlation between ozone and its precursors predominantly exhibits negative characteristics, with the exception of NO_2 in the Citeko area (Figure 10). In Baranangsiang, the coefficient of determination (R^2) for the relationship between ozone and NO is calculated to be 0.8629, while that for NO_2 is 0.4675. Conversely, in Citeko, R^2 values for ozone are at 0.3742 for NO and 0.3502 for NO_2, indicating a positive correlation for the latter.

The positive correlation observed between ozone and nitrogen dioxide (NO_2) levels in Citeko can be attributed to the presence of NO_2 and ozone stemming not only from chemical reactions but also from natural processes and various anthropogenic sources. Additionally, lower ambient air temperatures influence the rate at which reactions occur, particularly those related to the decomposition and removal of ozone and its precursors. Ozone formation is predominantly driven by the availability of radiant energy, with increased concentrations of ozone during daylight hours additionally affected by solar radiation. The relationship between ozone levels and solar radiation is evidenced by the correlation with air temperature; a positive correlation exists between ozone concentrations and temperature. An R^2 value exceeding 0.8 signifies that temperature has a significant impact on ozone formation. Therefore, as temperatures rise, ozone production increases correspondingly, which is directly proportional to the intensity of radiation—recognized as the primary factor influencing ozone formation.

These findings highlight the importance of considering meteorological influences when formulating air quality policies in the Bogor area. Since ozone formation is highly sensitive to temperature and solar radiation, peak ozone levels are more likely to occur during dry seasons or heat-intensive periods. This suggests that emission control measures targeting ozone precursors such as NO_x should be strengthened particularly during high-temperature months to minimize photochemical ozone formation. Furthermore, integrating local weather forecasting into air-quality early-warning systems could support preventive actions, such as temporary traffic restrictions or advisories for vulnerable groups (e.g., children, elderly, individuals with respiratory conditions). These results also emphasize the need for coordinated emission management strategies in both urban (e.g., Bogor City) and regional background areas like Citeko, given that transported pollutants may continue to contribute to ozone formation even far from primary emission sources. Ultimately, this study underscores the relevance of adopting climate-responsive air quality management to better protect public health and environmental sustainability in Bogor.

4. CONCLUSION

This study enlightens the distinct diurnal patterns of ozone concentrations in Bogor, which are primarily influenced by photochemical processes and meteorological conditions. It was observed that ozone levels were consistently elevated during the dry season, attributed to increased solar radiation, whereas lower concentrations were recorded during the rainy season due to the effects of cloud cover and wet deposition. In the Citeko area, characterized by its rural setting and elevated terrain, background ozone levels were found to be higher when compared to the urban locality of Baranangsiang, despite Citeko's lower precursor emissions. This discrepancy indicates the significant influence of regional pollutant transport.

Furthermore, strong negative correlations between ozone and nitrogen oxides (NO) in Baranangsiang underscore the importance of reaction processes and locally emitted precursors. In contrast, the weaker correlations observed in Citeko suggest a more intricate interaction involving background ozone levels and reduced availability of nitrogen oxides (NO_x). Temperature emerged as a crucial factor affecting ozone formation, reinforcing the predominant role of solar-driven photochemical activity. In conclusion, the findings of this study highlight that the dynamics of ozone in Bogor are shaped by local emission characteristics, atmospheric chemistry, and regional transport mechanisms. These insights are crucial for informing air quality management strategies and enhancing the understanding of photochemical pollution behavior within the Bogor region.

REFERENCES

Ahrens, C.D. (2007) *Meteorology today: an introduction to weather, climate, and the environment*. 8th edn. Canada: Thomson Brooks/Cole.

Al-Razi, K.M. and Hiroshi, M. (2012) 'Assessment of the Weather Research and Forecasting/Chemistry model to simulate ozone concentrations in March 2008 over coastal areas of the Sea of Japan', *Atmosphere*, 3(2), pp. 288–319.

CEC (Commission for Environmental Cooperation) (1997) *Long-range transport of ground-level ozone and its precursors: assessment of methods to quantify transboundary transport within the Northeastern United States and Eastern Canada*. Canada: Secretariat of the Commission for Environmental Cooperation.

Harrison, R.M. and Holman, C.D. (1979) 'The contribution of middle- and long-range transport of tropospheric photochemical ozone to pollution at a rural site in northeast England', *Atmospheric Environment*, 13(11), pp. 1535–1545.

Nakyai, T., Santasnachok, M., Thetkathuek, A. and Phatrabuddha, N. (2025) 'Influence of meteorological factors on air pollution and health risks: A comparative analysis of industrial and urban areas in Chonburi Province, Thailand', *Environmental Advances*, 19, 100608.

Seinfeld, J.H. and Pandis, S.N. (2016) *Atmospheric chemistry and physics: from air pollution to climate change*. Hoboken: John Wiley & Sons.

SLHD (Status Lingkungan Hidup Daerah) (2015) *Laporan SLHD Provinsi DKI Jakarta Tahun 2015*. Jakarta: Pemerintah Provinsi Daerah Khusus Ibu Kota Jakarta.

Stern, A.C., Boubel, R.W., Turner, D.B. and Fox, D.L. (1984) *Fundamentals of air pollution*. 2nd edn. Orlando: Academic Press.

The Royal Society (2008) *Ground-level ozone in the 21st century: future trends, impacts, and policy implications*. Science Policy Report 15/08. London: The Royal Society.

Tie, X., Brasseur, G. and Ying, Z. (2010) 'Impact of model resolution on chemical ozone formation in Mexico City: application of the WRF-Chem model', *Atmospheric Chemistry and Physics*, 10(18), pp. 8983–8995.

Zannetti, P. (1990) *Air pollution modelling*. Canada: Springer.

Zhang, B.N. and Oanh, N.T.K. (2002) 'Photochemical smog pollution in the Bangkok Metropolitan Region of Thailand in relation to O_3 precursor concentrations and meteorological conditions', *Atmospheric Environment*, 36(26), pp. 4211–4222.