Atmospheric and Climate Sciences, 2025, 15(2), 402-425
https://www.scirp.org/journal/acs
ISSN Online: 2160-0422
ISSN Print: 2160-0414

Spatial and Temporal Variation of Criteria Air Pollutants over Rwanda (2019-2023) and the Influence of Meteorological Factors

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How to cite this paper: Akimana, D., Yu, M.Y., Kazora, J., Geremew, T., Matthews, N., Kamukama, G.E. and Magara, G. (2025) Spatial and Temporal Variation of Criteria Air Pollutants over Rwanda (2019-2023) and the Influence of Meteorological Factors. *Atmospheric and Climate Sciences*, **15**, 402-425.
https://doi.org/10.4236/acs.2025.152021

Received: January 22, 2025
Accepted: March 28, 2025
Published: March 31, 2025

Abstract

Air pollution is among the most serious environmental and public health problems worldwide, especially in low and middle-income countries like Rwanda. This study explores the spatial and temporal variations of criteria air pollutants across Rwanda from 2019 to 2023, utilizing data from 18 national air quality monitoring stations and 16 weather stations. Results reveal that $PM_{2.5}$ and PM_{10} concentrations exceeded WHO guidelines, with the mean reaching 90 μg/m³ ($PM_{2.5}$) and 127 μg/m³ (PM_{10}), predominantly in Kigali City, Northern, and Western provinces. CO concentration peaked in the Eastern province and Kigali. In contrast, NO_2 and O_3 were highest in the Central and Northern provinces. Over five years, NO_2 showed a slight increase trend, while CO, O_3, and SO_2 displayed minor declines and remained in line with WHO guidelines. Diurnal variations highlighted morning (06:00-07:00 am) and evening (06:00-09:00 pm) pollutant peaks, driven by morning rush hour traffic, domestic stoves, and industrial activities. Border stations like Bugeshi-Rubavu recorded elevated pollutant levels due to cross-border emissions from the bordering countries. Seasonal analysis revealed higher pollutant levels during dry seasons, influenced by reduced rainfall and increased anthropogenic activities. CO concentration was positively correlated with temperature during MAM ($r = 0.69$) due to increased biomass burning and agricultural emissions. Wind speed is negatively correlated with $PM_{2.5}$ and PM_{10} in JJA, aiding pollutant dispersion, while $PM_{2.5}$ is positively correlated with humidity in MAM ($r = 0.7$), linked to secondary aerosol formation. These findings underscore the urgent need to improve air quality, particularly in urban and border regions, and address Rwanda's transboundary pollution concerns.

Keywords

Air Pollutants, Meteorological Influence, Spatiotemporal Variation, Rwanda

1. Introduction

Air pollution is a critical global environmental issue that poses serious risks to human health and ecological sustainability. The adverse effects of air pollution are especially severe in low- and middle-income countries, where it significantly contributes to diseases like cardiovascular and respiratory conditions, like lung cancer [1]. Beyond human health, air pollution negatively impacts ecosystems by affecting animals and damaging plant environments [2]. Key pollutants, such as particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ground-level ozone (O_3), and carbon monoxide (CO), are widely recognized as "criteria air pollutants" due to their known harmful effects, which depend on exposure levels, duration, pollutant type, as pollutants [3] [4]. The primary anthropogenic sources of these pollutants include biomass burning, fossil fuel combustion, vehicle emissions, industrial activities, and dust, with PM_{10}, and $PM_{2.5}$ being generated from power production, residential heating, cooking, and mining activities. Ground-level ozone, a secondary pollutant, forms through sunlight-driven chemical reactions with precursor pollutants such as VOCs [5]. Seasonal variations and meteorological conditions, such as atmospheric stability, weather patterns, and wind speeds, further influence these pollutants' concentrations.

In East Africa, air pollution arises predominantly from biomass and coal combustion, volcanic eruptions, vehicle emissions, industrial effluents, and dust particles [6]. Rwanda, like other developing nations, faces growing air quality concerns due to rapid urbanization, increased vehicular emissions, and industrial expansion [7]-[9]. Population growth has spurred demand for transportation, energy, and infrastructure, leading to an upsurge in emissions that pose risks to both health and the environment. Biomass remains the dominant energy source, accounting for 85% of Rwanda's energy use, particularly wood in rural areas and charcoal in urban areas. Petroleum fuels for transportation and liquefied petroleum gas (LPG) for household cooking comprise 13% of national energy [10] [11].

In 2018, about 77% of on-road vehicles were produced before 2005, significantly increasing roadside pollution levels [10] [12]. Regional forest fires and seasonal shifts further influence Rwandan air quality [13]. Additionally, Rwanda's electricity generation, relying on a mix of hydropower, diesel, methane, peat, and solar, contributes to ambient air pollution, especially during diesel-powered peak loads [14] [15]. Understanding the spatial and temporal variations of criteria air pollutants is vital for pinpointing areas with elevated pollution levels, or "pollution hotspots," and informing targeted management and public health initiatives [16]. In Kigali, the most urbanized area in Rwanda, vehicular emissions, industrial activities, and construction significantly elevate pollution levels compared to rural regions, where agriculture and biomass burning are more prevalent. Air pollutants fluctuate seasonally and annually; the wet seasons March-May MAM and September-December SOND) and the dry seasons (June-August JJA, and January-February, JF) generally see increased pollution from reduced rainfall and intensified human activities like agricultural burning. Such seasonal and annual fluctuations also depend on broader climate patterns and economic factors [17]. The effects of meteorological conditions on air pollutant levels are critical to understanding and mitigating pollution. Rwanda's tropical climate influences pollutant dispersion and removal through parameters such as temperature, humidity, wind speed, and precipitation [18]. For instance, dry seasons can see higher pollution levels due to increased dust and reduced rain, whereas the wet season often reduces pollution levels due to atmospheric mixing and rain "washing" pollutants from the air [4]. Thus, investigating the seasonal and inter-annual variations of air pollutants in Rwanda is key to understanding air quality dynamics.

Previous studies have examined Kigali's air pollution, particularly concerning $PM_{2.5}$. There is a significant research gap regarding the spatial and temporal variations of major pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, and O_3) across Rwanda. Thus, this research aims to investigate the spatial and temporal variation of criteria air pollutants over Rwanda during 2019-2023 by analyzing the correlation between meteorological parameters (temperature, humidity, wind patterns) and air pollutants and identifying the driving factors that cause seasonal concentration in Rwanda to furthermore understand the influence of weather on air pollution level concentration to provide insights for policymakers and environmental managers to develop effective air quality control measures.

2. Materials and Methods

2.1. Study Area

Rwanda, a small landlocked country in East Africa, has a varied geography that ranges from mountains in the west to savanna plains in the east. Rwanda covers roughly 26,338 square kilometers and borders Uganda to the north, Tanzania to the east, Burundi to the south, and the Democratic Republic of Congo (DRC) to the west. Kigali, Rwanda's capital city, is the primary urban and commercial hub. Rwanda's climate is primarily tropical, moderated by its high elevation, with two primary seasons influencing air quality: the dry season and the wet season. Savannas are the main biomes in Sub-Saharan Africa (SSA), covering about 65 % of the landmass, and are the main source of fire emissions [19]. Located in a highly elevated region, Rwanda is generally surrounded by savanna regions, except to the west, where the tropical rainforests of Africa are located.

Rwanda's meteorology is governed by the East African monsoon, with peak rainfalls in April and November. The country experiences two rainy seasons from MAM and SOND, while the dry seasons occur in JJA and JF [20]. These seasonal variations have a significant effect on meteorological parameters such as temperature, humidity, wind speed, and precipitation, all of which impact the concentration of air pollutants [21]. The capital city, Kigali, is the most densely populated urban area and serves as a central hub for industrial and commercial activities. It has a rapidly growing population, which leads to increased vehicular emissions and industrial pollution, making it a critical location for studying air quality. Gicumbi, a rural area in Rwanda, relies heavily on biomass burning for cooking and agricultural practices, which significantly contributes to local air pollution. Unlike urban areas, Gicumbi experiences lower pollutant levels from vehicular emissions but higher concentrations from sources such as biomass burning and agricultural activities. These variations highlight the distinct pollution profiles influenced by local socioeconomic and environmental factors across different regions of Rwanda.

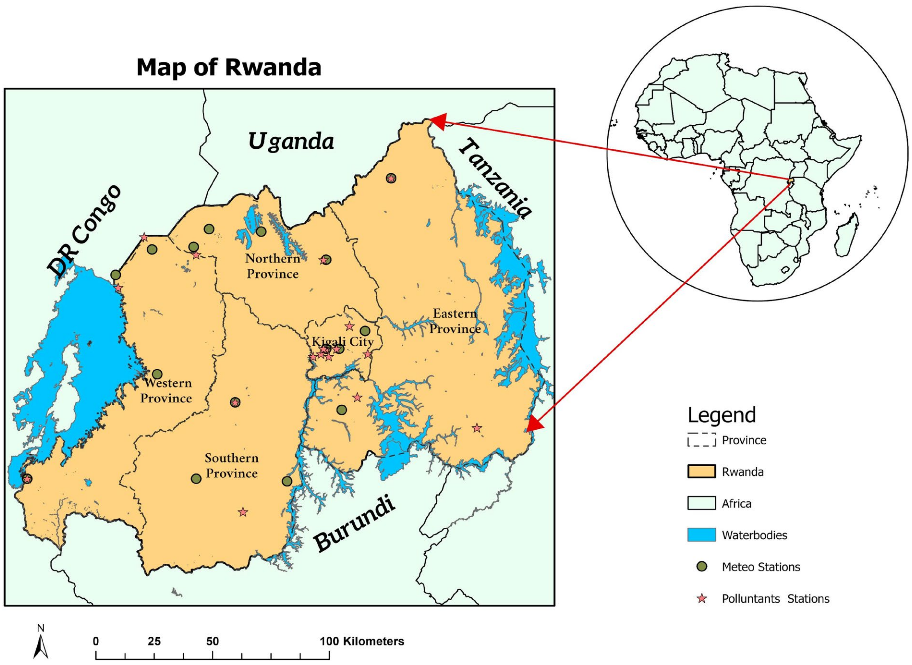

Figure 1. Map of Rwanda with air pollution stations marked in pink stars and meteorological stations marked in green circles with waterbodies in blue.

2.2. Data

The study uses hourly concentration data of six criteria air pollutants and meteorological factors like precipitation, temperature, relative humidity, wind speed, and wind direction in Rwanda over five years (2019-2023). Six criteria pollutants were measured from Rwanda National Air Quality Monitoring stations over 18 monitored observation stations across the country in rural and urban areas. Daily surface meteorological data from 16 weather stations were obtained from the Rwanda Meteorology Agency (Meteo-Rwanda) (as indicated in **Figure 1** above) to assess the correlation with air pollutant levels during 2019-2023. The statistical summary of the monthly averaged concentrations of criteria air pollutants, expressed in units of μg/m^3 for $PM_{2.5}$ and PM_{10}, and ppb for CO, NO_2, SO_2, and O_3, along with the station types (urban, suburban and rural area), across Rwanda during the study period, is presented in **Table S1**.

2.3. Methods

This study uses linear regression for trend analysis of long-term changes in air pollution concentrations across Rwanda. The trend (β) represents the slope predicted by the linear regression model, as shown in equation one below.

$$y = \alpha + \beta x + \varepsilon \tag{1}$$

where β represents the slope, α is a constant, and ε is the error term.

Trend significance will be tested using the autocorrelation and variability on trend estimation and detection [22] method, considering the trend significance at a 95% confidence level ($p < 0.05$) when $|\beta/\varepsilon| > 2$. This method effectively captures both the magnitude and direction of long-term trends and has been validated in previous studies [23]-[26] or analyzing atmospheric pollutants. We also used the Pearson correction coefficient in analysis to study the relationship between meteorological parameters and criteria air pollutants.

We employed bivariate polar analysis to analyze the effect of wind patterns on the criteria air pollutant concentration at the station levels. Pollutants behavior was determined using the Polar Plot program, which generated two-variable distribution graphs based on pollution concentrations, wind speed, and direction. Wind components u and v are calculated in equation two.

$$u = \underline{u} \cdot \sin\left(\frac{2\pi}{\theta}\right), v = \underline{u} \cdot \cos\left(\frac{2\pi}{\theta}\right) \tag{2}$$

where u, represents daily average wind speed, θ, average wind direction (degrees, 90 degrees west wind). To calculate a station, point on the graph, the generalized additive model is utilized. GAM is a useful model approach used in forecasting air pollution. Because the relationships between the variables are not linear, the interactions of the variables are important [27]. The GAM approach is expressed in equation three.

$$\sqrt{C_i} = \beta_0 + \sum_{j=1}^{n} S_j\left(X_{ij}\right) + e_i \tag{3}$$

where C_i is the ith pollutant concentration, β_0 is the overall mean of the response, $s_j(x_{ij})$ is the smooth function of ith value of covariate j, n is the total number of covariates, and e_i is the ith residual. The model selected for estimation of concentration level is given in Equation (4). In this model, the concentration in the square root is a linear function.

$$\sqrt{C_i} = s(u,v) + e_i \tag{4}$$

All calculations about bivariate polar analysis were done using the Openair R software package designed for atmospheric data analysis [28] [29].

3. Results

3.1. Spatial Distribution and Temporal Trends of Criteria Air Pollutants over Rwanda

The spatial distribution of criteria air pollutants in Rwanda from 18 monitoring observation stations, was mapped to analyze air quality changes across the country. The data were interpolated over Rwanda's five provinces (Northern, Southern, Eastern, Western, and Kigali City), revealing areas with high pollution levels. **Figure 2** shows that $PM_{2.5}$ and PM_{10} concentrations display the same pattern peak in North and West province and Kigali City, with concentration mean values around 90 μg/m^3 and 127 μg/m^3 especially at Bugeshi_Rubavu and Mugogo stations. $PM_{2.5}$ shows a low mean value at the Gicumbi and Nyagatare stations. At the same time, PM_{10} is significantly low at Kirehe station in East province by 64 μg/m^3. Where key sources are biomass burning, cooking stoves, vehicle emissions, industrial activity, agriculture-related activities, transboundary pollution from Uganda, Burundi, and the DRC, and nearby mining activities. $PM_{2.5}$ and PM_{10} concentration results are higher than those of WHO interim target 1 [10]. CO concentrations are highest in the Eastern province (Bugesera, Nyagatare) and central areas, particularly around Kigali City (Gacuriro, Gikondo, Kiyovu), where mean concentration is between 314 - 320 ppb. These elevated concentrations are associated with dense population centers and incomplete fossil fuel combustion from transportation and industry especially in Kigali City. Northern province showed lower CO values, ranging from 273 to 279 ppb. SO_2 level is more concentrated in the western province due to volcanic activity, where the mean value is 56 ppb and concentrations are higher than WHO Interim Target 1 and the most common national standards. O_3 and NO_2 are highest in Kigali City, North province especially at Gicumbi stations by 32 and 45 ppb respectively which is driven by industrial and vehicular emissions, as the city's vehicle count has increased from 50,000 in 2000 to over 250,000 in 2022 [30], whereas Peripheral regions, particularly in the west show lower O_3 and NO_2 levels, with a minimum concentration value of 9 and 17 ppb. Maps highlight pollution hotspots near urban and industrial areas like Kigali, and Rubavu. Pollutants are influenced by wind patterns, topography, temperature, and human-made activities as well as cross-border pollution from neighboring countries. And exceed WHO guidelines and the most common national standards as indicated in the inventory of sources of air pollution in Rwanda [10]. (**Figure 2**)

3.2. Interannual Variation of Criteria Air Pollutants Across the Country

The interannual and monthly temporal variations provide valuable insights into the dynamics of air pollutant concentrations over time and the factors influencing Rwanda's air quality. **Figure 3** illustrates the inter-annual and monthly trends of Rwanda's criteria air pollutants from 2019 to 2023. The box plots capture interannual variability, highlighting clear trends for each pollutant (subplots a-f) throughout the study period. CO concentrations remained relatively stable, peaking at mean of 315 ppb in 2020 before declining to 290 ppb in 2023. NO_2 concentrations exhibited steady increases, reaching a maximum annual means of 44 ppb in 2022, followed by slight declines in 2023. At the same time, O_3 remained stable throughout the study period with an annual mean value of 20 ppb. $PM_{2.5}$ and PM_{10} show moderate variability, with their highest annual means recorded in 2019 (74 μg/m^3 and 115 μg/m^3). SO_2 yearly mean value declined from 14 ppb in 2019 to 8 ppb in 2023. The analysis revealed that the annual mean concentrations of CO, O_3, and SO_2, are aligned with recommended air quality standards for Rwanda. However, NO_2, and particulate matter their annual mean exceeds ambient air quality standards of Rwanda and WHO significantly throughout five years. The concentrations of $PM_{2.5}$ and PM_{10} observed in this study are lower than those reported by [31] in an urban area like Kigali City; the main source was high densities of older vehicles, according to [32].

Figure 4 complements these findings from **Figure 3** by capturing monthly temporal trends, showing both seasonal fluctuations and long-term change. CO exhibits a slightly declining trend at −0.01, with R^2 of 0.02, indicating the minimal change in CO levels over the observed period, NO_2 shows a slight positive slope of 0.003 indicating a gradual increase in concentrations over five years (2019-2023) with R^2 of 0.09, it reveals a weak but more discernible upward trend compared to the other pollutants, while O_3 and SO_2 demonstrates significant monthly variability, with a small negative slope at −0.004 and −0.005 respectively, implying a slight decline, but the high variability indicates that the trend is not statistically significant. $PM_{2.5}$ and PM_{10} remained relatively stable, with small monthly

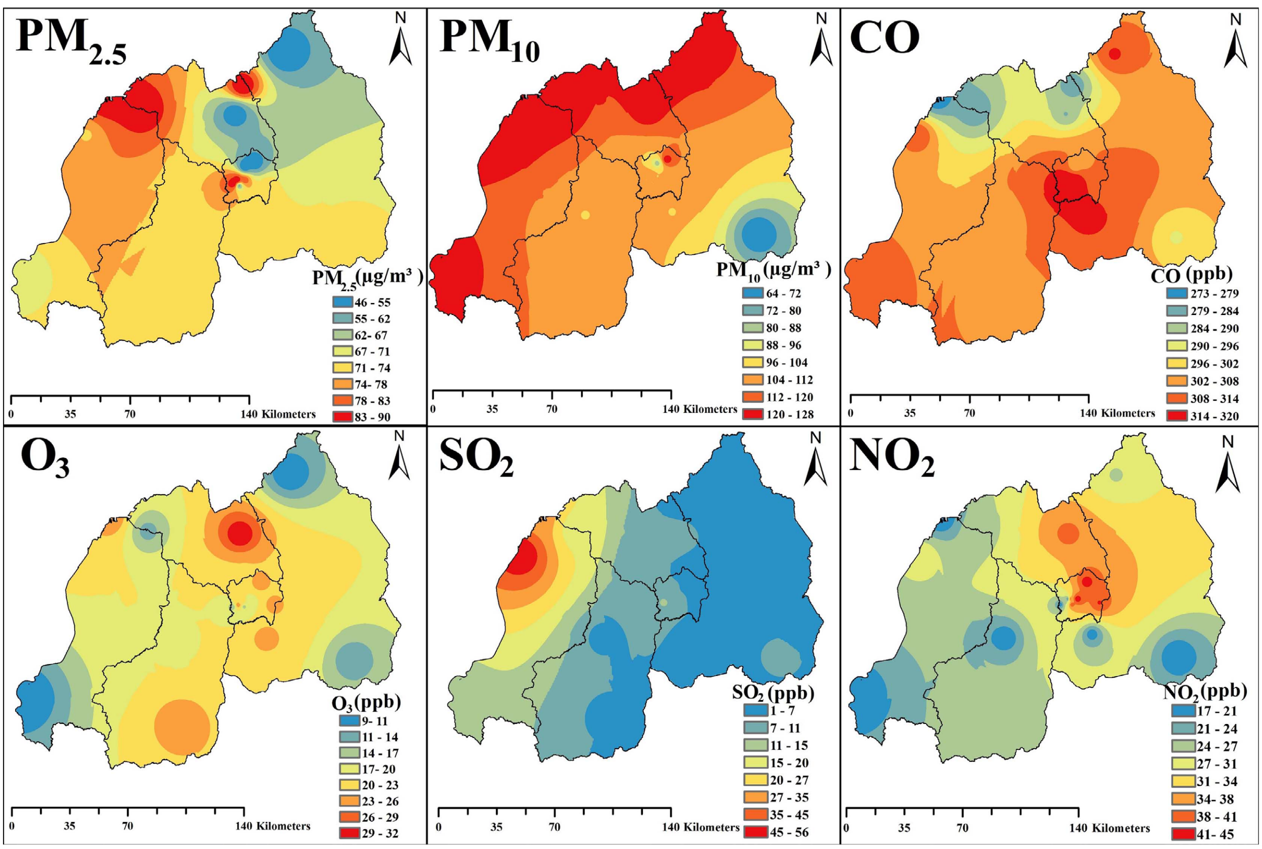

Figure 2. Spatial distribution of $PM_{2.5}$, PM_{10}, CO, O_3, SO_2, and NO_2 concentration across Rwanda during 2019 to 2023.

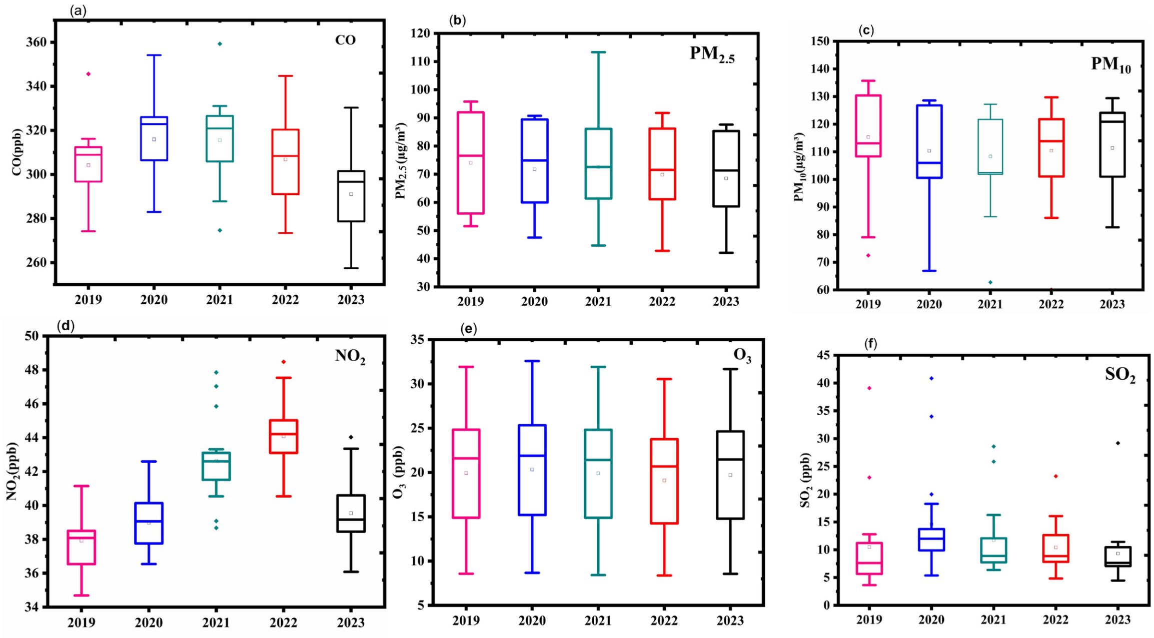

Figure 3. The boxplot design illustrates Rwanda's inter-annual variation of critical air pollutants from 2019 to 2023. Panels (a), (b), (c), (d), (e), and (f) represent CO, $PM_{2.5}$, PM_{10}, NO_2, O_3, and SO_2, respectively, the central box represents the interquartile values range from 25th to 75th percentiles, the extended whiskers indicate the values from10th to 90th percentiles, and the solid line within the box denotes the median concentration. The small square at the center of each box represents the annual average concentration, while dots outside the whiskers identify statistical outliers.

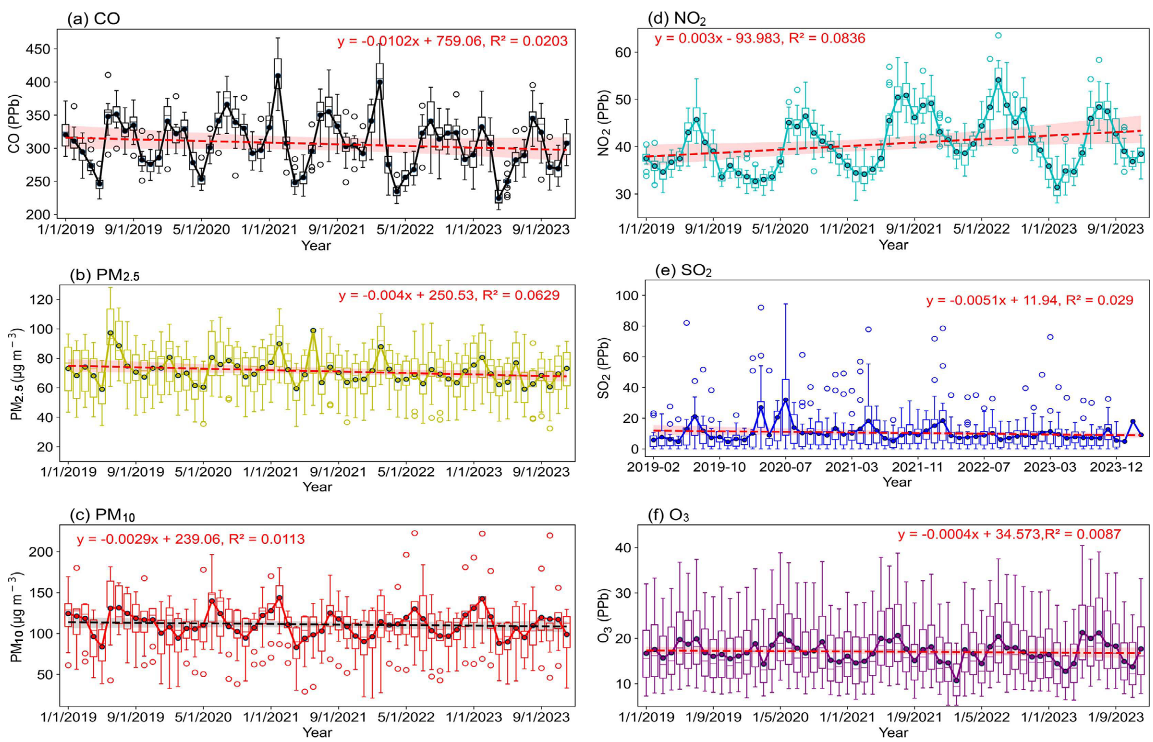

Figure 4. Temporal monthly variations in air pollution trends: (a) CO, (b) $PM_{2.5}$, (c) PM_{10}, (d) NO_2, (e) SO_2, and (f) O_3. The central boxplot depicts values ranging from the 25th to 75th. The vertical line goes from the 10th to the 90th percentile. The central solid line indicates the monthly average. Outliers are depicted as little circles. Dash line presents monthly trends from 2019 to 2023.

fluctuations with the R^2 values of 0.06 and 0.01 indicating an insignificant trend. According to the analysis of minor fluctuations in pollutant levels, most of the trends are weak, as shown by the low R^2 values, meaning that criteria air pollutants in Rwanda have remained relatively stable from 2019 to 2023, with only slight increases in NO_2 Concentration.

3.3. Seasonal Variation of Criteria Air Pollutants and Meteorological Parameters over Rwanda

Figure 5 explains the seasonal distribution of criteria air pollutants across Rwanda's four seasons: JF, MAM, JJA, and SOND during five years. The highest concentrations of PM_{10} and $PM_{2.5}$ occur during JJA and JF, with mean values ranging from 120 - 130 μg/m³ for PM_{10} and 70 - 80 μg/m³ for $PM_{2.5}$. A recent study by Subramanian *et al.*, 2020 indicated that $PM_{2.5}$ concentrations are significantly higher in the dry seasons than in the wet seasons, aligning with the observed seasonal variation in particulate matter levels. CO concentrations mean peak during JF and JJA, reaching values between 360 and 440 ppb, before declining in MAM to around 210 - 350 ppb. SOND shows a moderate increase in CO concentrations compared to JJA, indicating a rise toward the end of the year. O_3 concentrations are highest during JJA with mean value of 19 ppb. DeWitt *et al.*, 2019 found that a higher concentration of O_3 in dry seasons in Rwanda was related to the higher solar radiation, biomass burning, and anthropogenic emission from East African cities such as Nairobi, Dar es Salam, and Kampala. NO_2 levels peak in JJA, with a mean of approximately 50 ppb, while concentrations are lowest in JF, near 35 ppb. Both JF and MAM exhibit moderate NO_2 levels. SO_2 concentrations are highest in JJA, with a mean value around 20 ppb, while JF and MAM display lower concentrations, below 15 ppb. The pollutant distributions are relatively stable across seasons, with occasional outliers observed.

Figure 6 presents the seasonal variation of key meteorological variables temperature, precipitation, relative humidity (RH), and wind speed (WS) across Rwanda in five seasons (JF, MAM, JJA, and SOND) which will help us to understand the relationship between pollutants. Temperature remains stable throughout the year, with mean values ranging from 19˚C to 22˚C. The maximum temperature is 24˚C, and the minimum value drops to 11˚C, with occasional extreme outliers in JF. Precipitation is highest during the rainy seasons of MAM and SOND which make deduction of pollutants in a washout way, with the lowest levels observed in JJA, typical of the dry season where rainfall falls below 100 mm, although irregular events are indicated by outliers. MAM displays greater variability in rainfall, while JF experiences moderate precipitation, falling between the dry season (JJA) and the rainier periods. Relative humidity aligns with the seasonal precipitation trends, reaching its highest during MAM and SOND with median values around 70%, corresponding to the rainy conditions. JJA exhibits the lowest RH, averaging 45%, indicative of the dry season, while JF maintains moderate RH levels, similar to SOND. Wind speeds are generally low across all seasons, with median values between 1.5 and 3.0 m/s. JJA shows slightly higher wind

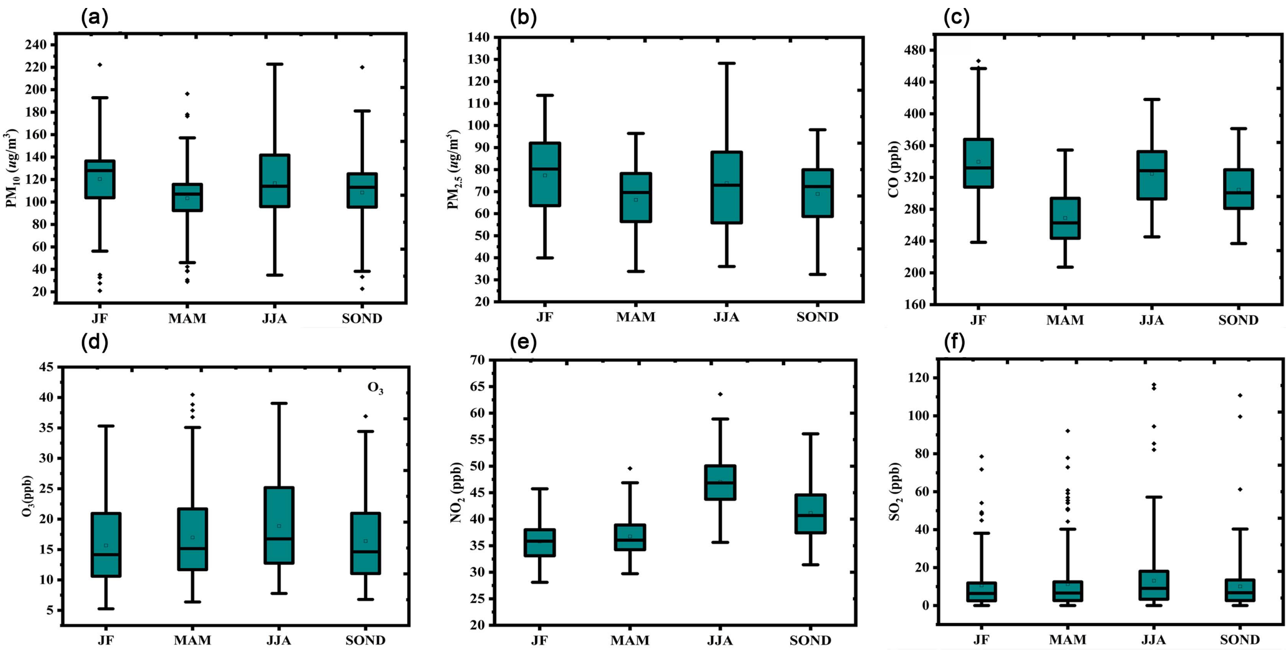

Figure 5. Seasonal variation in air pollutants over Rwanda (a) PM_{10}, (b) $PM_{2.5}$, (c) CO, (d) O_3, (e) NO_2 and (f) SO_2 respectively. The values in the central box range from the lowest to the highest percentile. The vertical line goes from the 10th to the 90th percentile. The median is represented by the solid line in the middle. The little box within the central box represents the arithmetic average. Outliers are shown as dots.

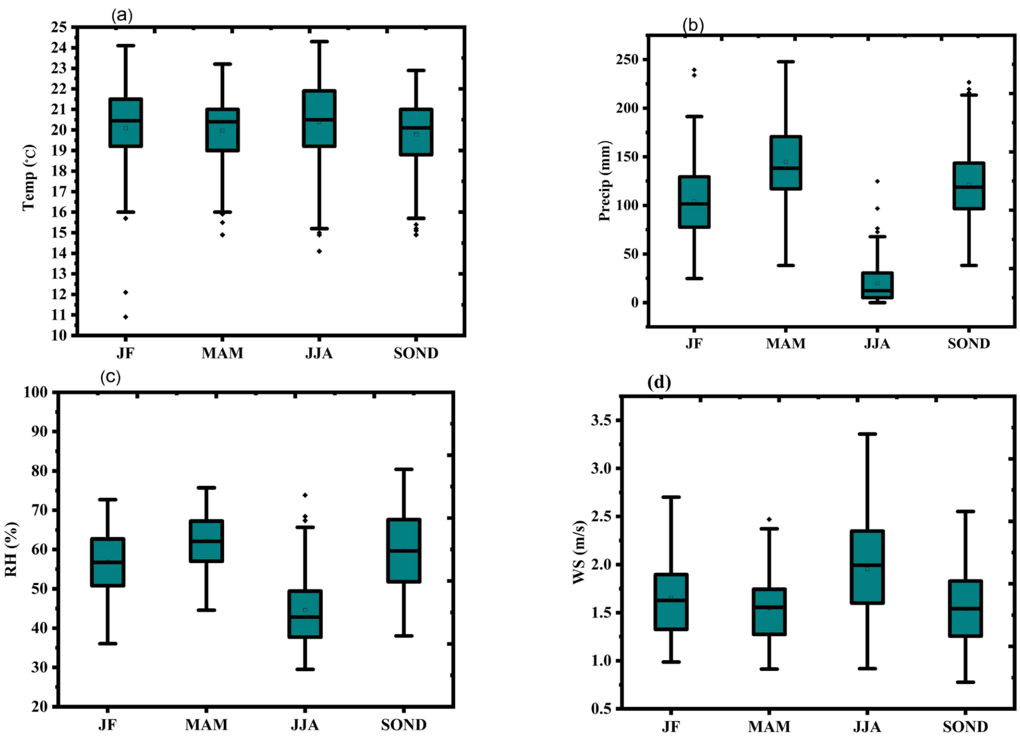

Figure 6. Seasonal variations in climatic variables across Rwanda (a) temperature, (b) precipitation, (c) relative humidity, and (d) wind speed). The values ranging from the 25th to the 75th percentile are represented by a central box. The vertical line is from the 10th percentile to the 90th percentile. The middle solid line is the median. The arithmetic average is represented by the small box inside the larger central box. Dots represent outliers.

speeds, occasionally exceeding 3.0 m/s, while SOND and JF share similar wind speed distributions. MAM exhibits a narrower range of wind speeds compared to the other seasons.

The relationship between air pollutants and wind patterns was analyzed using the bivariate Polar Plot function available, in the open-air R package. This approach enabled the identification of pollution sources, distinguishing between local contributions and long-range transport. Daily pollutant concentrations, including CO, $PM_{2.5}$, PM_{10}, O_3, NO_2, and SO_2, along with corresponding wind speed and direction data were analyzed for the JJA season of 2022 period characterized by elevated pollution levels during the above seasonal analysis. Data from five geographically distributed air quality monitoring stations Bugesera, Bugeshi-Rubavu, Byimana, Gacuriro, and Gicumbi, representing the Eastern (E), Western (W), Southern (S), and Northern (N) Provinces, as well as Kigali City, were analyzed to assess the influence of wind patterns on criteria air pollutant concentrations across the country. **Figure 7(a)**, & **Figure 7(b)**, **Figure S1**, **Figure S2** and **Figure S3** illustrate daily criteria air pollutants concentration behavior on wind speed and wind direction at the stations; Bugesera, Bugeshi_Rubavu, Byimana, Gacuriro, and Gicumbi respectively. At Bugesera Station (Eastern Province) CO (440 ppb), $PM_{2.5}$ (55 μg/m^3), PM_{10} (70 μg/m^3), NO_2 (14 ppb), and SO_2 (9 ppb) were transported from the SW direction at a wind speed of 4 m/s, while O_3 (25 ppb) was predominantly local under calm conditions (1 m/s). At Bugeshi-Rubavu Station (Western Province) CO (340 ppb), $PM_{2.5}$ (120 μg/m^3), PM_{10} (140 μg/m^3), O_3 and NO_2 of (28 ppb) were primarily local, with contributions from the E and SE directions. SO_2 was transported from the S direction at a wind speed of 4 m/s. At Byimana Station (**Figure S1**) in Southern Province all pollutant concentrations are transported from the W direction of the station with higher wind speed of (4 m/s) CO (700 ppb), $PM_{2.5}$ (70 μg/m^3), PM_{10} (80 μg/m^3), NO_2 (30 ppb), and SO_2 (15 ppb), in contrast, O_3 (33 ppb) concentration seems to be local at wind speed of 1 m/s. At Gacuriro Station (**Figure S2**) (Kigali City) CO (550 ppb), $PM_{2.5}$ (70 μg/m^3), and PM_{10} (110 μg/m^3) were transported from the W direction at wind speed of 3 m/s. O_3 (40 ppb) and NO_2 (42 ppb) were predominantly local at calm condition 1 m/s. while SO_2 (14 ppb) was transported from the N direction. At Gicumbi Station (**Figure S3**) (Northern Province) CO (430 ppb), NO_2 (46.5 ppb), and O_3 (32 ppb) were identified as local under calm conditions (1 m/s). $PM_{2.5}$ (50 μg/m^3) and PM_{10} (30 μg/m^3) were carried from NW direction at wind speed 4 m/s, while SO_2 (15 ppb) was transported from the N direction. The analysis indicates that the monitoring stations are largely affected by pollution transported over long distances from multiple directions. However, some stations are also significantly influenced by local emissions. For example, the Bugeshi-Rubavu station shows a strong influence of local emissions on pollutants such as CO, $PM_{2.5}$, and PM_{10}, while at the Gicumbi station, local emissions primarily impact CO, NO_2, and O_3 levels. Additionally, O_3 concentrations at all stations are notably influenced by local emissions, as it is formed through sunlight-driven chemical reactions involving precursor pollutants such as VOCs [5].

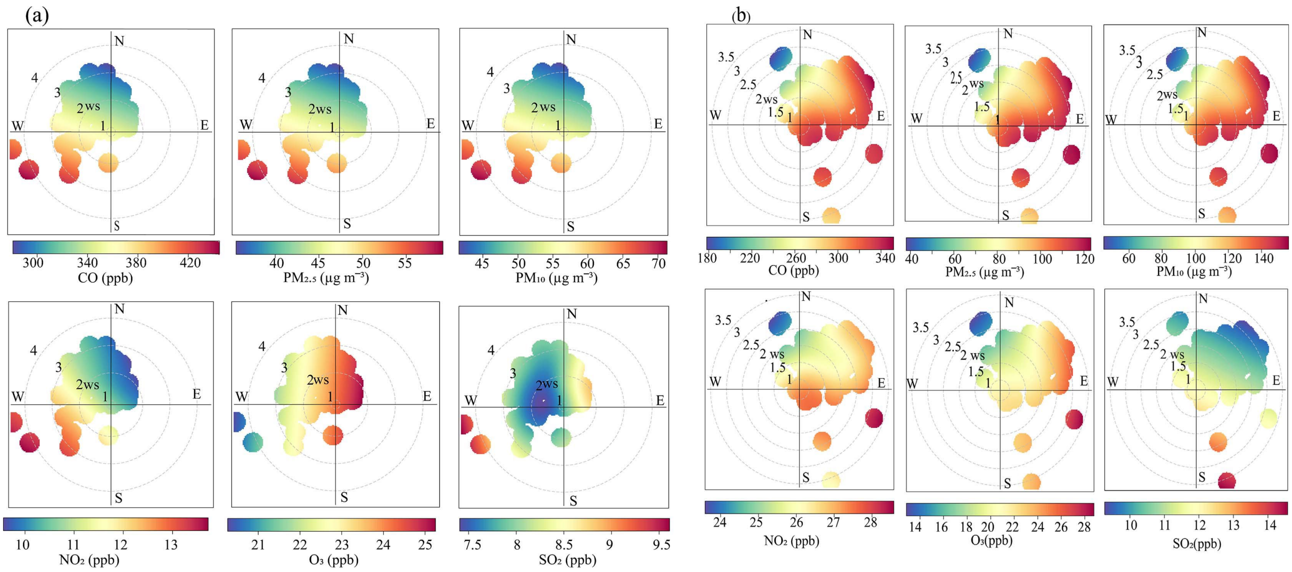

Figure 7. Bivariate polar plot of criteria air pollutants along with wind speed and wind direction from different stations (a) Bugesera and (b) Bugeshi_Rubavu during JJA season 2022.

3.4. Diurnal Variation of Criteria Air Pollutants during Dry Season (JJA)

Diurnal variations in pollutant concentrations provide valuable insights into local and regional emission sources [13]. These variations in air pollutant concentrations are influenced by the dynamics of the atmospheric boundary layer, local anthropogenic activities, meteorological conditions, and photochemical processes. During this study, the JJA season trend reveals notably higher air pollutant levels than other seasons. Figure 8 illustrates the diurnal variation of criteria air pollutants during the JJA season across five selected air quality monitoring stations representing four provinces and Kigali City and are categorized into rural and urban locations based on their geographic and socioeconomic characteristics to further investigate the main source contributor of criteria air pollutants across the study area. The rural stations include Bugesera, Byimana, and Gicumbi, while the urban stations comprise Bugeshi_Rubavu and Gacuriro, Figures 8(a)-(c) Bugesera, Gacuriro, and Byimana stations, respectively shows the same pattern of CO, $PM_{2.5}$, PM_{10}, SO_2, and NO_2 concentration peaks in the early morning (06:00-07:00) and evening (18:00-21:00), among this air quality monitoring stations. Byimana have higher hourly mean value for all pollutants (CO, $PM_{2.5}$, PM_{10}, NO_2, O_3, and SO_2) as 880 ppb, 180 μg/m^3, 210 μg/m^3, 55 ppb, 40 ppb, and 24 ppb. These peaks are influenced by morning and evening traffic rush hour emissions, domestic cooking stoves, and construction dust in urban cities while in rural is due to unpaved roads, agriculture biomass burning, local cooking methods using wood and charcoal, and charcoal-making as we saw on Figure 7 all those stations are primarily affected by cross-regional emission, midday dips are caused by sunlight-enhanced dispersion and photochemical conversion of NO_2 to O_3. Subramanian (2020) observed that $PM_{2.5}$ concentrations in Kigali exhibit a distinct diurnal pattern, with a morning peak between 08:00-10:00 am, likely attributed to increased traffic emissions. Concentrations decline during the day as the boundary layer height expands, facilitating pollutant dispersion, but rise again in the evening due to a combination of heightened emissions and the reduced boundary layer height. O_3 peaks in the afternoon (12:00-15:00) due to photochemical activity, while SO_2 remains stable with slight midday dips reflecting dispersion and reduced emissions. Gacuriro as an urban station is primarily influenced by vehicle traffic emissions and industrial activities, with pollutant concentrations peaking during morning and evening hours. According to the REMA (2018) report, the primary sources of $PM_{2.5}$ and PM_{10} emissions on busy urban roads in Rwanda are heavily influenced by domestic stoves and road traffic, highlighting the significant impact of these activities on urban air quality.

Figure 8(d) and **Figure 8(e)**: Bugeshi-Rubavu, and Gicumbi stations are located on the border of other countries, showed the same pattern of CO, PM_{10}, $PM_{2.5}$, SO_2, and NO_2 levels concentration rise steadily from 06:00, peaking sharply in the evening time (18:00-20:00) and its persist at night because of the low boundary layer trapping pollutants near the surface with a higher hourly mean concentration of PM_{10}, and $PM_{2.5}$, are 132 μg/m^3, and 170 μg/m^3 at Bugeshi-Rubavu station, as a result of an anthropogenic emission from industries, vehicle traffic emission, domestic stove and long-rage transport emission from DR Congo. REMA (2018) reported that air pollution levels in Rubavu City are significantly influenced by long-range transport pollution from the nearby city of Goma, located across the border in the Democratic Republic of Congo (DRC), which is known for its poor air quality. NO_2 and O_3 show an inverse diurnal pattern, with NO_2 peaking in the morning and O_3 in the afternoon, reflecting photochemical processes. SO_2 concentrations remain relatively stable throughout the day, with slight increases in the afternoon linked to traffic and industry fossil fuel combustion.

3.5. Seasonal Correlation of Criteria Air Pollutants and Meteorological Paraments

Figure 9 shows a correlation heatmap that indicates the relationship between various meteorological parameters on season timescale and criteria air pollutants. The color bar on the right side indicates the strength of the correlation, where the red color represents a positive correlation, the blue color represents a negative correlation and the white color represents no correlation. Temperature demonstrated a strong positive correlation with CO during MAM, r = 0.69 season. Studies conducted at observatories like the Rwanda Climate Observatory (RCO) have documented seasonal variations in pollutants, including CO, showing elevated levels associated with biomass-burning activities in MAM [13], PM_{10} and PM2.5 exhibit negative correlations with temperature across almost all seasonal except MAM shown a slightly positive correlation for PM10. It is known that higher temperature often promotes atmospheric mixing, which can disperse particulates and reduce their concentration near the ground, while cooler, stable conditions tend to

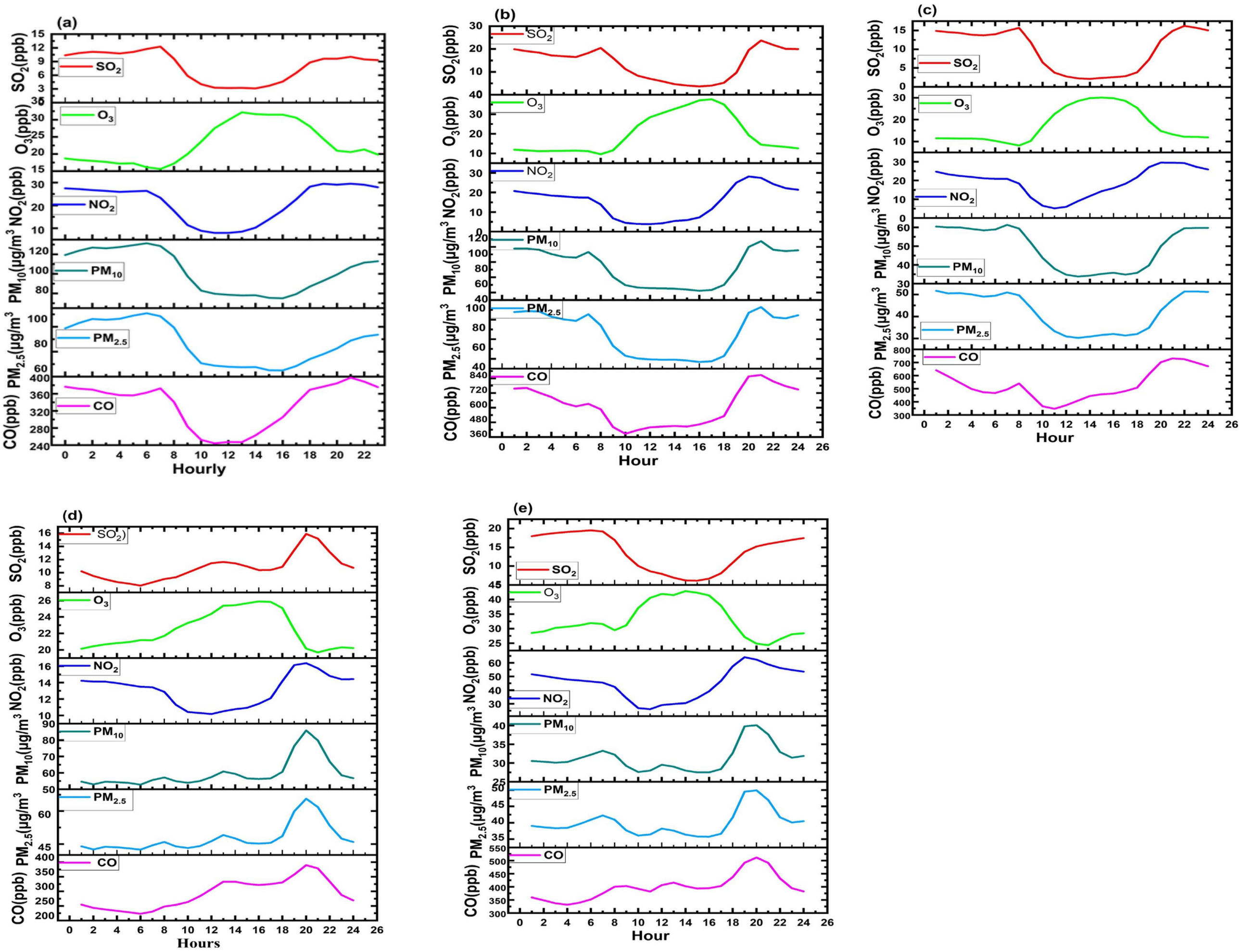

Figure 8. Diurnal variation (hourly) average of criteria air pollutants in JJA season during 2022 from ten different air quality monitoring stations across the country, (a) Bugesera, (b) Gacuriro, (c) Byimana, (d) Bugeshi_Rubavu, (e) Gicumbi respectively.

trap particulate matter close to the surface, leading to higher concentrations. The positive correlation during MAM is related to seasonal activities, such as biomass burning from agricultural and residential emissions. O_3 shows a consistent negative correlation with temperature, particularly strong during JJA ($r = -0.7$). Previous research on East Africa studied tropospheric O_3 especially over Nairobi city in Kenya highlighted how seasonal shifts influence O_3 distribution, indicating that JJA generally experiences high O_3 levels aloft, yet lower near-surface concentrations due to enhanced mixing and stratospheric intrusions. This effect is compounded by East Africa's relatively low background levels of O_3 precursors compared to other regions, resulting in distinct seasonal O_3 variability compared to areas with higher industrial emissions, where surface O_3 tends to increase with temperature [33]. NO_2 presented a slight negative correlation with temperature in JJA and a slight positive correlation in SOND and JF seasons. This caused biomass burning, especially from agriculture, to occur in this season in Rwanda. SO_2 is positively correlated with temperature in all seasons except for a negative correlation in JF, and it shows a particularly strong positive correlation in JJA ($r = 0.67$)

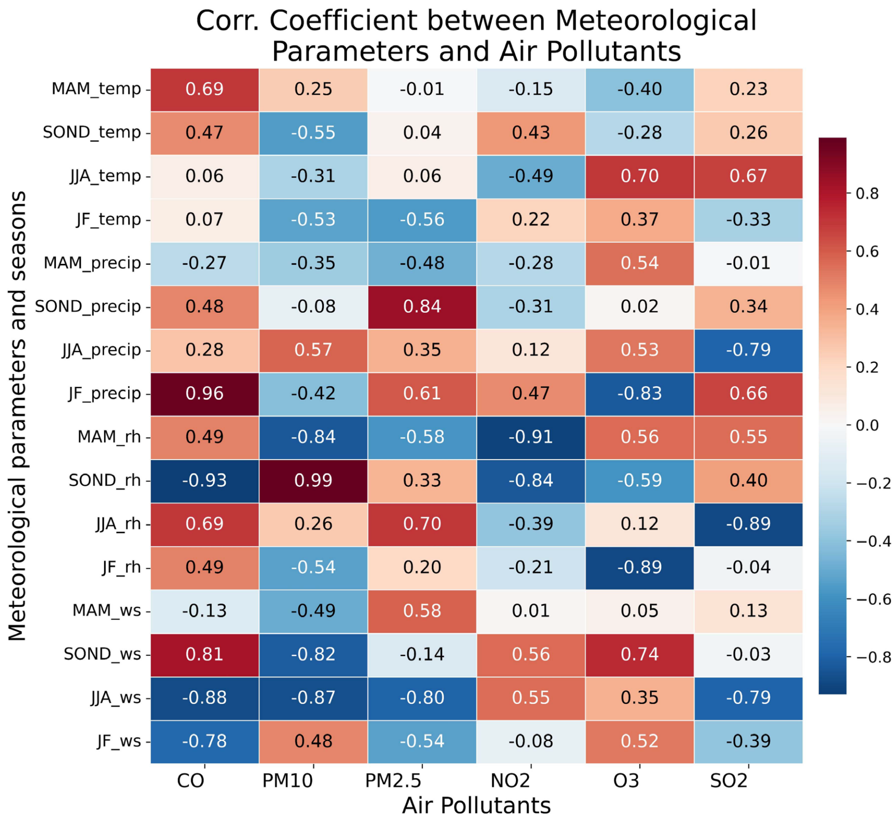

Figure 9. Correlation heatmap between Meteorological variables used in the study and criteria air pollutants.

due to emissions from industrial activities, especially from power plants, and transportation increase during dry seasons. [34] Precipitation is strongly positively correlated with CO during JF (r = 0.96) but shows a negative correlation in MAM. Opio *et al.*, 2021 [35] found that biomass burning is prevalent in Rwanda and surrounding East Africa, especially in rural areas where wood and charcoal are primary energy sources for heating and cooking. This phenomenon is also noted in urban areas, like Kigali, where localized cooking and waste-burning emissions become prominent during rainy seasons, contributing to CO and other pollutant levels close to the ground. PM_{10} is negatively correlated with precipitation in all seasons except for JJA, season while $PM_{2.5}$ exhibits a strong positive correlation during SOND (r = 0.84) and a slight negative correlation during MAM (r = −0.48), where a moderately strong positive correlation occurs caused by reduced rain in JJA season for PM_{10} while for $PM_{2.5}$ is due to secondary particulate formation driven by chemical reactions in moist conditions in Rwanda and surrounding regions, rainy periods often correspond with elevated $PM_{2.5}$ concentrations as aerosols form more readily in humid conditions [4]. NO_2 is strongly positively correlated with precipitation during JF and slightly negative in both SOND and MAM. O_3 has a significant negative correlation with precipitation in JF (r = −0.83), indicating that higher rainfall may lower ozone concentrations, while it shows positive correlations in other seasons. SO_2 is positively correlated with precipitation in JF (r = 0.66) and strongly negatively corrected in JJA (r = −0.79). CO shows a positive correlation with relative humidity (RH) during MAM, JJA, and JF, but exhibits a strong negative correlation in SOND (r = −0.93). $PM_{2.5}$ correlates positively with RH in all seasons, with a notable correlation in JJA (r = 0.7), while PM_{10} has a strong positive correlation in SOND (r = 0.99), and a strong negative correlation in MAM (r = −0.84), it is known that high RH favors the partition of semi-volatile species into the aerosol phase [36], thus leading to high PM concentrations. NO_2 is negatively correlated with RH across all seasons, particularly in MAM and SOND (r = −0.91, −0.84, respectively). O_3 has significant negative correlations with RH, especially during JF and JJA, suggesting that higher humidity reduces ozone levels. SO_2 shows mixed correlations with RH depending on the season, with positive correlations in MAM and SOND, and a strong negative correlation in JJA (r = −0.89). CO is negatively correlated with wind speed in MAM and JF, with a particularly strong negative correlation in JJA (r = −0.88), suggesting that higher wind speeds reduce CO concentrations. However, CO shows a strong positive correlation with wind speed in the SOND season with (r = 0.81) and is mainly influenced by westerly and southwesterly winds during the East African Monsoon carry pollutant-laden air masses from densely populated or biomass-burning areas in neighboring countries [37]. Most seasons showed a negative correlation between wind speed on $PM_{2.5}$ and PM_{10}, especially in JJA indicated (r = −0.80 and r = −0.87 respectively). On the other hand, $PM_{2.5}$ in MAM is positively correlated (r = 0.58). The significant negative correlation in JJA and SOND indicates that horizontal dispersion is essential for lowering particle concentrations during this season, and vertical dispersion increases the concentration of particulate matter in MAM. NO_2 shows positive correlations with wind speed in all seasons except JF. O_3 is positively correlated with wind speed in all seasons, with a particularly strong correlation in SOND (r = 0.74). SO_2 is positively correlated with temperature in all seasons except for a negative correlation in JF, and it shows a particularly strong positive correlation in JJA, indicating that higher wind speeds may help disperse SO_2 concentrations.

4. Conclusion and Implication

This study provides a comprehensive assessment of air pollution trends in Rwanda from 2019 to 2023, analyzing key pollutants (PM_{25}, PM_{10}, CO, NO_2, O_3, and SO_2) and their meteorological influences. The findings reveal significant regional and seasonal variations, with elevated pollutant levels in urban and industrial areas such as Kigali and Rubavu, driven by vehicular emissions, construction, and biomass burning. Despite a slight decline in PM concentrations, levels remain above national and WHO standards, posing ongoing health risks. Meteorological factors play a crucial role in pollutant dispersion, with wind speed negatively correlated with PM during dry seasons, while humidity enhances aerosol formation in wet periods. Long-range transport of pollutants also contributes to air quality challenges in some regions.

To mitigate air pollution, targeted interventions are needed, including stricter emission controls, expansion of air quality monitoring networks, and promotion of cleaner energy sources. Strengthening regional cooperation is essential, particularly in border areas affected by transboundary pollution. Finally, further research is needed to evaluate the long-term health impacts of air pollution in Rwanda and to assess the effectiveness of proposed mitigation strategies, such as cleaner fuels, improved waste management, and traffic regulations. By providing actionable insights into the spatial, temporal, and seasonal dynamics of air pollutants, this study contributes to the growing body of knowledge on air quality management in low- and middle-income countries, offering valuable guidance for policymakers and environmental managers aiming to improve air quality and safeguard public health.

Acknowledgements

The first author acknowledged the Chinese Scholarship Council (CSC), the World Meteorological Organisation (WMO), and the Rwanda Meteorology Agency for their support throughout her Master's studies at Nanjing University of Information Science and Technology. My gratitude to Prof Yu Mingyuan for supervising me as I accomplished my task. The authors thank the previous authors cited in the essay for their support, as well as the institutions that provided the data used in the analysis.

Data Availability

The datasets used in this study will be available upon request. Data for meteorological parameters can be requested through the Rwanda Meteorology Agency website: www.meteorwanda.gov.rw, and criteria air pollutants data can be ordered through the Rwanda Environmental Management Authority (REMA) website: http://www.rema.gov.rw/.

Author Contributions

Diane AKIMANA is the main author of the work, manuscript drafting, data analysis, methods, and analysis; Yu Mingyuan is the Supervisor, coordinates the work, and the Corresponding author; Jonah Kazora Contributed to research corrections and editing; Tizazu Geremew and Nyasulu Matthews assisted in the analysis; Gerverse Ebaju Kamukama and Genesis Magara contributed to the data part.

Conflicts of Interest

The authors state that they have no known competing financial interests or personal relationships that could have influenced the work presented in this study.

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Supplementary Materials

Table S1. Statistical summary of the monthly averaged concentration of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 during the study period. Units: µg/m^3, for $PM_{2.5}$ and PM_{10}; ppb for CO, NO_2, SO_2, and O_3.

STATIONS	TYPE OF STATION		PM_{10}	$PM_{2.5}$	CO	NO_2	SO_2	O_3
Bugeshi_Rubavu	urban	Average	128	90	273	37	28	26
		Max	164	116	360	53	99	32
		Min	105	74	216	30	2	18
		Stdv	14	10	31	5	18	4
Gacuriro	urban	Average	104	82	319	45	13	17
		Max	132	562	439	64	64	22
		Min	71	50	231	34	2	10
		Stdv	12	64	43	8	9	2
Gikondo-Mburabuturo	urban	Average	104	46	316	43	12	16
		Max	132	107	429	57	41	20
		Min	71	32	239	32	2	10
		Stdv	12	12	42	7	9	2
Kiyovu	urban	Average	112	73	320	41	10	22
		Max	223	95	441	57	47	28
		Min	21	50	239	30	7	13
		Stdv	64	9	43	6	31	3
Nyagatare	urban	Average	126	89	315	41	28	8
		Max	182	128	445	55	58	11
		Min	103	73	238	32	2	5
		Stdv	15	11	42	6	20	1
Rusizi	urban	Average	128	69	314	41	11	9
		Max	164	82	398	53	50	11
		Min	105	56	217	28	1	5
		Stdv	14	6	42	5	9	1
Rusororo	urban	Average	112	73	313	41	11	11
		Max	223	95	446	55	26	13
		Min	21	50	214	31	1	6
		Stdv	64	9	43	6	7	1
Rebero	urban	Average	103	48	288	39	7	11
		Max	130	73	397	51	24	13
		Min	66	36	217	31	2	6
		Stdv	10	7	35	5	5	1

Continued

Kirehe	suburban	Average	64	46	296	39	8	12
		Max	148	107	397	51	43	15
		Min	46	32	218	30	1	7
		Stdv	16	12	38	6	8	2
Lake-Kivu-Rubavu	rural	Average	128	90	313	40	25	22
		Max	164	116	395	54	116	29
		Min	105	74	225	31	5	14
		Stdv	14	10	36	5	25	4
Mont-Huye	rural	Average	112	73	303	41	8	12
		Max	223	95	402	53	61	15
		Min	21	50	219	28	1	7
		Stdv	64	9	38	6	7	2
Mont-Kigali	rural	Average	104	73	318	44	10	12
		Max	132	95	437	58	57	16
		Min	71	50	240	34	1	9
		Stdv	12	9	43	7	7	2
Mugogo	rural	Average	128	90	280	37	12	13
		Max	164	116	372	47	94	16
		Min	105	74	207	28	1	9
		Stdv	14	10	32	4	15	2
Bugesera	rural	Average	104	73	316	41	8	25
		Max	132	95	457	55	52	31
		Min	71	50	218	31	1	14
		Stdv	12	8	46	6	7	3
Byimana	rural	Average	104	73	347	40	12	18
		Max	132	95	467	52	54	23
		Min	71	50	252	30	1	11
		Stdv	12	9	44	6	8	3
Gicumbi	rural	Average	126	48	284	39	9	31
		Max	182	73	388	52	79	40
		Min	103	36	217	29	2	18
		Stdv	15	7	35	5	10	4
Gikomero	rural	Average	126	89	305	41	10	25
		Max	182	128	420	57	32	31
		Min	103	73	219	30	1	14
		Stdv	15	11	40	6	12	3
Jali	rural	Average	84	59	302	40	11	15
		Max	110	78	408	51	33	19
		Min	67	47	217	28	1	9
		Stdv	9	6	40	6	8	2

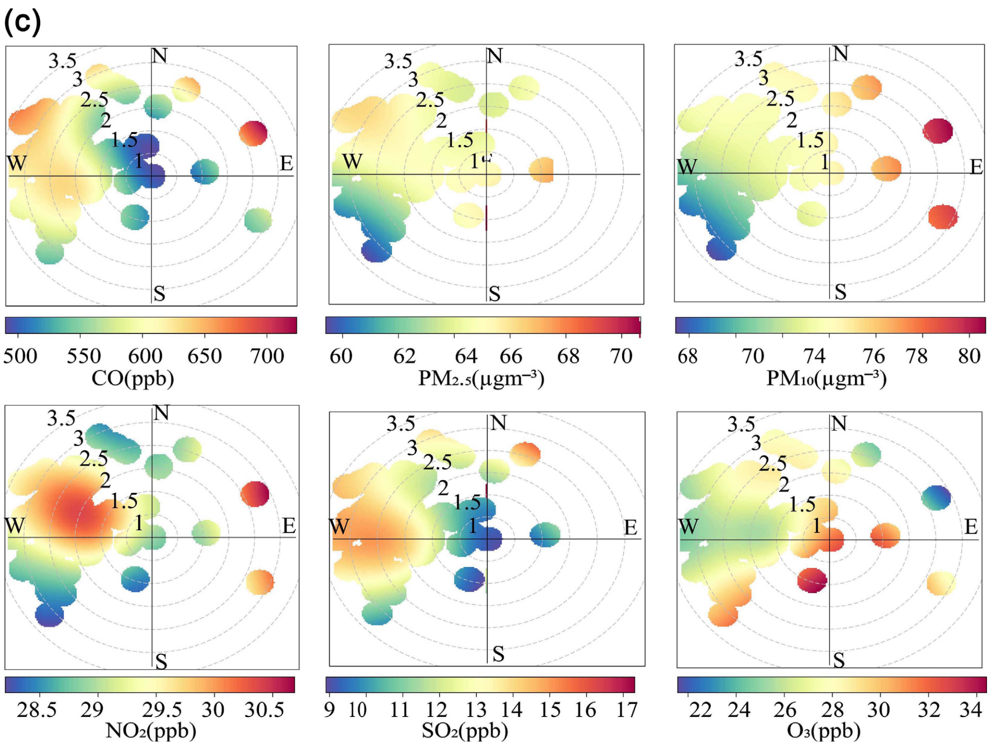

Figure S1. Bivariate polar plot of criteria air pollutants along with wind speed and wind direction from different stations (c) Byimana station during JJA season 2022.

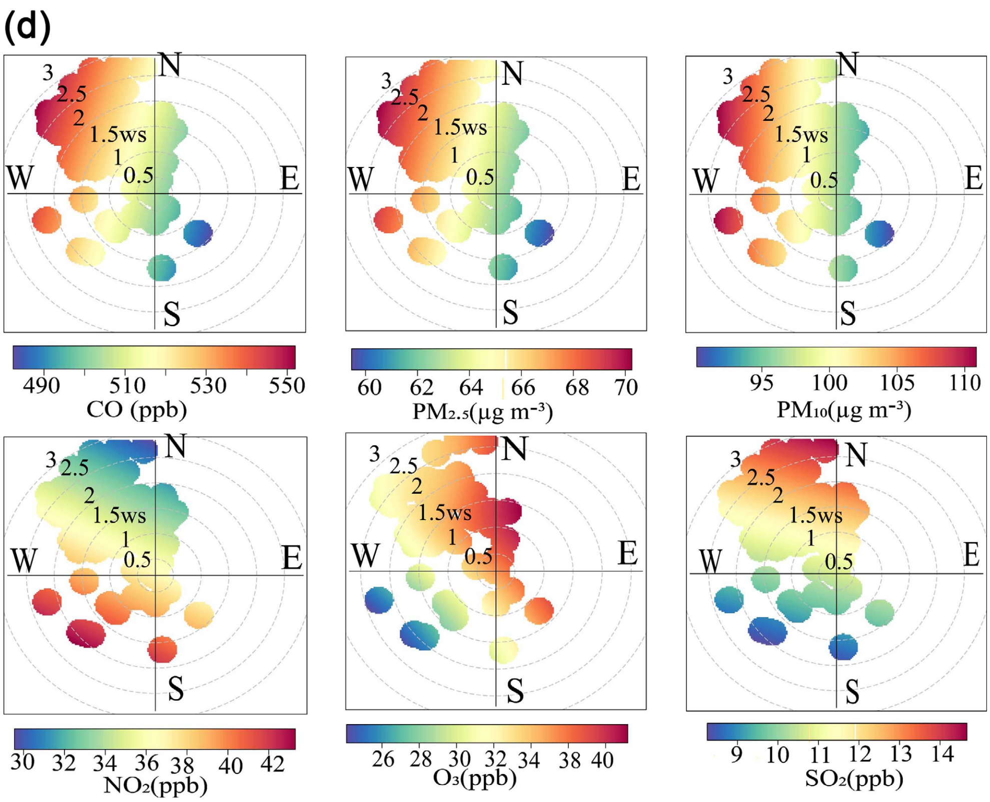

Figure S2. Bivariate polar plot of criteria air pollutants along with wind speed and wind direction from different stations (d) Gacuriro station during JJA season 2022.

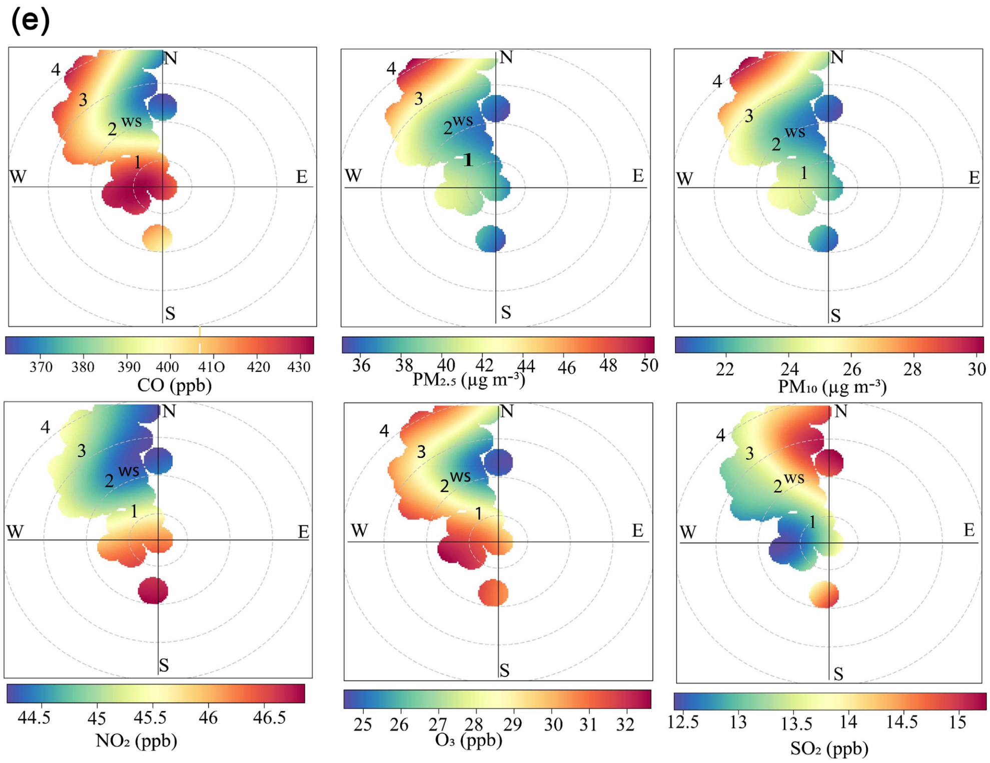

Figure S3. Bivariate polar plot of criteria air pollutants along with wind speed and wind direction from different stations (e) Gicumbi station during JJA season 2022.