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Ambient Air Quality, Pollutant Behavior, and Distribution Pattern in Rabigh City Using an Air Dispersion Model

Aljahdali Mohammed Othman[1]*, Alhassan Abdullahi Bala[1], Al-Ansari Ahmed Mohammed[2,3] and Albeladi Mutaz Naser[2]

[1]*Department of Biological Sciences, Faculty of Science, King Abdulaziz University, Jeddah 21598 P.O. Box 80203, Saudi Arabia.*

[2]*Environmental Affairs, The General Authority of Meteorology and Environmental Protection, Jeddah 1358, P.O. Box 21431, Saudi Arabia.*

[3]*Department of Environmental Sciences, King Abdulaziz University, Jeddah 21598, P.O. Box 80208, Saudi Arabia.*

**Corresponding Author Email: moaljahdali@kau.edu.sa*

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Abstract

The rise in industrial development and modern technology is one of the major causes of atmospheric pollution, which negatively affects human health. In this study, meteorological conditions and atmospheric pollution dispersion in Rabigh city and its catchments were analyzed using measured data and an air quality dispersion model. The Hybrid Single-Particle Lagrangian Integrated Trajectory model was used to simulate the dispersion of atmospheric pollutants. A dataset from 2018 was analyzed to clarify the seasonal distributions of atmospheric pollutant concentrations in Rabigh and other areas (Thuwal and Khulais). A significant variation in atmospheric pollutants was recorded across the seasons, which may be caused by changes in meteorological conditions. Variations in other anthropogenic sources related to high population density or heavy traffic in the nearby road may also be involved in these fluctuations. Predictions indicated that pollutants would impact the Thuwal area (>50 µg m^{-3}) and Khulais (>35 µg m^{-3}) during the winter season and affect Thuwal (>20 µg m^{-3}) and Rabigh (>20 µg m^{-3}) during the fall season. The concentrations of pollutants were mostly negatively correlated with wind speed, except for carbon monoxide. We established variations in the seasonal concentration of pollutants and the effect of meteorological conditions on atmospheric pollutants for the year 2018 in the study area. Policymakers and stakeholders must provide solutions to mitigate the environmental effect of atmospheric pollution in Rabigh city, Thuwal, and Khulais for the health of inhabitants.

Keywords*:* Source, Air pollution, Meteorological conditions, Dispersion model, Rabigh.

Introduction

The majority of economic activities involving the use and transformation of energy cause air pollutants, thereby contaminating the environment and harming human health [1]. The quality of air in urban environments is a critical aspect of urban health status. People living in urban settlements, especially megacities, face severe health problems because of conditions related to air pollution [2].

Air pollution has numerous sources; sources of air pollution can be natural, such as volcanos and earthquakes, or man-made, such as industrial and transportation activities [3]. The use of coal as a common fuel for heat and energy is one of the major sources of air pollution in industrial environments [4]. Various diseases, most of which are respiratory, are common in industrial towns because of air pollution. Furthermore, the

increase in the number of people exposed to air pollutants may engender large public health problems [5].

Outdoor air pollution is a primary environmental cause of the increase in mortality from heart and lung diseases [6] and of the occurrence of several diseases. In 2010, approximately 3.15 million reported deaths globally were associated with atmospheric pollution. In 2018, a study on the Global Burden of Disease estimated that 4.2 million deaths in 2015 were associated with outdoor air pollution [7].

The atmospheric pollution status of Saudi Arabia is a growing concern, which has led the government to establish several authorities and agencies to monitor and report the status of air pollution across the country. The scientific community is responsible for increasing public awareness of air pollution and investigating the quality of air in major cities where industrial activities and modern lifestyles are increasing [8]. Several companies contribute substantially to atmospheric pollution in Saudi Arabian cities. For instance, in Jeddah City, oil refineries and cement companies have played a major role in atmospheric pollution for years, which poses a threat to the residence of this city [9, 10].

Several potential air pollution sources far from Jeddah can affect and contribute to its air quality. For instance, Rabigh city (approximately 150 km to the north of Jeddah) contains numerous sources of pollution, such as the Petro-Rabigh refinery, desalination plant, power plant, cement company, and plastic company. These sources affect the air quality status and the intensity of air pollution in Rabigh through gaseous discharges that contribute significantly to atmospheric pollution in this region. This region is mostly affected by particulate pollution and Saharan dust, and an increase in their levels causes a decrease in the life span of about 1.48 years in Saudi Arabia [11].

Generally, sulfur dioxide (SO_2), hydrogen sulfide (H_2S), NO_x (e.g., nitric oxide [NO] and nitrogen dioxide [NO_2]), carbon monoxide (CO), and ozone (O_3) are pollutants that represent the largest proportions of discharged gases into the air surrounding industries such as refineries, sewage plants, and power plants [11]. This study aimed to evaluate the air quality status and predict pollutant behaviors and distributions using an air dispersion model. The use of a dispersion model is crucial to understand the behavior of pollutants and the detrimental effects on subjected neighborhood areas in Rabigh city.

Materials and Methods

Site Description and Initial Survey

Rabigh (Fig. 1) is an industrial city situated on the eastern coast of the Red Sea, Kingdom of Saudi Arabia. Extreme heat is experienced during the summer, with another rise in temperature during the winter season. The high relative humidity, especially during the summer season, is a key characteristic of Rabigh that has been attributed to limited rain showers. Several industries, such as the Petro-Rabigh oil refinery, a power plant, and Arabian Cement, are located in Rabigh. These three industries are considered the three major sources of air pollution. The closeness of these industries to residential areas could expose inhabitants to risks associated with produced air pollutants.

Data on the atmospheric pollutants and meteorological conditions of the study area (Rabigh city: 22°47′57.37″ N and 39°02′00.83″ E) from December 2017 to November 2018 were obtained from the General Authority of Meteorology and Environmental Protection (GAMEP) during the initial survey and pre simulation. Site

selection was based on the possibility or probability that these sites had been affected by existing emission sources. Settlements refer to receptors were also put into consideration during the selection of sites. The possible wind directions of the area and sites and year-round variations were also considered. Receptors considered in this study were Rabigh (22°47′57.37″ N and 39°02′00.83″ E), Thuwal (22°16′59.85″ N and 39°06′00.06″ E), and Khulais (22°09′22.08″ N and 39°20′05.57″ E) (Fig. 1 and 2). Data collected for the whole year was later grouped by season (i.e., winter, spring, summer, and fall).

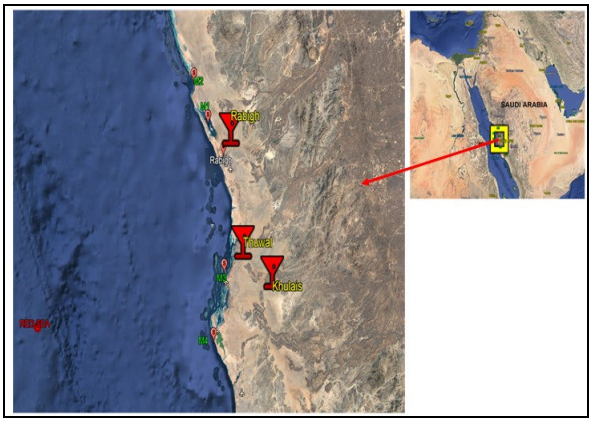

Figure 1. **Map showing rabigh city with other settlements refer to as receptors.**

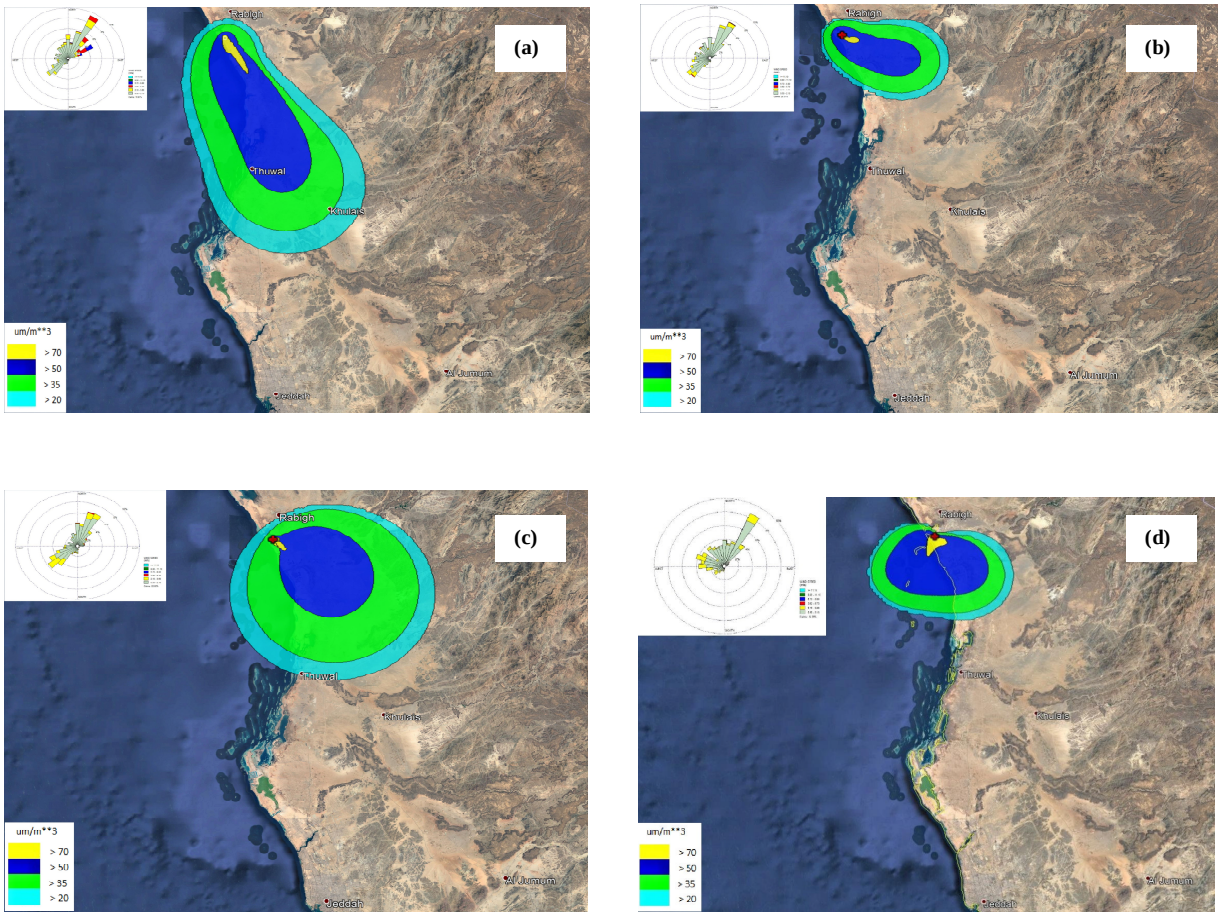

Figure 2. **Modeled seasonal dispersion of pollutants in a) winter b) spring c) summer and d) fall**

Data on atmospheric pollutants, such as SO_2, H_2S, NO_x (NO and NO_2), CO, and O_3, and meteorological conditions, such as atmospheric temperature, relative humidity, and wind speed, were utilized. These measurements followed the standard GAMEP methods [11], which adhere to US EPA protocols for ambient air quality monitoring. It involved biweekly calibrations, span verifications, repetitive and preventative maintenance, and regular inspection of site activities every 3 to 6 weeks.

Air Quality Dispersion Modeling

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) [11] model was used to simulate the dispersion of atmospheric pollutants. HYSPLIT is a tool used to investigate the movement of pollutants by using mathematical and numerical methods. These methods simulate both physical and chemical processes affected by pollutants' dispersion into the atmosphere. Meteorological and source information is required for this model. Puff or particle approaches are used in the HYSPLIT model to calculate the dispersion trajectories of atmospheric pollutants and their depositions. Calculations of dispersion could also be based on the composition of air or particle movement, aided by wind and turbulence.

The simulation of dispersion of atmospheric pollutants was achieved using a horizontal resolution of 0.005° × 0.005° (approximately 50 × 50 m) and ten vertical levels: 10, 50, 75, 100, 200, 400, 500, 750, 1000, and 3000 m above ground level. Seasonal variations in the pollutant emission and the emission from the source were considered when assigning the mass of pollutants to each simulated particle represented in the HYSPLIT model. The model allowed a maximum of 10000 particles to be transported for the period of simulation, and approximately 500 particles or puffs were released at 30-min intervals. The mixing of turbulence and turbulent speed per unit time was calculated using a short-range diffusivity method from stability parameters. Ground-level concentrations were calculated for a minimum of 50 m in each grid cell in a horizontal pattern [10, 11].

A sequence of simulations for dispersion was performed using a successive integration technique with seasonal initialization. The continuous release of emissions was recorded from the source during the entire period of simulation, and the simulated concentrations of atmospheric air quality collected were used to prepare a series of data for analysis regarding the atmospheric concentration [11].

Data Analysis

One-way analysis of variance (ANOVA) was used to determine seasonal variations in meteorological and atmospheric pollutants in the study area. A Duncan multiple range post hoc test was used to separate means if a significant difference was observed. Before the one-way ANOVA, the data generated were subjected to normality assessment using the Shapiro-Wilk test and were later grouped into dependent and independent variables. The four seasons (winter, spring, summer and fall) were the independent variables. At the same time, the atmospheric pollutants (SO_2, H_2S, NO_x, CO, and O_3) and meteorological parameters (temperature, relative humidity and wind speed WS) were classified as the dependent variables. The Pearson correlation coefficient was used to determine the correlation between meteorological data and atmospheric pollutants. The principal component analysis (PCA) was used to assess the effect of meteorological data on atmospheric pollutants' dispersion and identify possible key sources.

Data analysis was performed using IBM SPSS v.22.0 and Minitab v.17.0 Statistics Software Packages.

Results and Discussion

Air Pollutant Concentrations and Meteorological Conditions

The seasonal concentrations of SO_2, H_2S, NO_x, CO, and O_3 for the four seasons (i.e., winter, spring, summer, and fall) were recorded for the period of the study. The mean concentration ranges were 341.13 ± 57.19–763.79 ± 95.44, 17.30 ± 6.10–43.92 ± 15.73, 19.87 ± 6.70–52.91 ± 5.25, 933.83 ± 115.57–3682.50 ± 448.31, and 83.57 ± 18.71–308.09 ± 61.24 µg m^{-3} for SO_2, H_2S, NO_x, CO, and O_3 respectively (Fig. 3). Pollutants exhibited marked differences between the minimum and maximum concentrations recorded in a particular season. However, ANOVA ($p < 0.05$) revealed significant variations in the concentrations of atmospheric pollutants across the four seasons. SO_2 and NO_x recorded the minimum and maximum concentrations in winter and fall, respectively. The minimum concentration of H_2S was recorded in summer, and the maximum value was recorded during the winter. The minimum concentrations of CO and O_3 were recorded in spring and summer, respectively, whereas the maximum values were recorded in summer and spring.

Significant variations in pollutants across the seasons may have resulted from seasonal changes in meteorological conditions or variations in other anthropogenic sources related to high population density and heavy traffic in roads close to the source of pollution [12, 13]. Changes in the emission policy also play a major role in the temporal distribution of pollutants in the atmosphere; for instance, this could be observed after reducing crude oil supply, replacing coal with gas, or industrial upgrading of structure, occurring at a particular time [14, 15]. Our results accord with other findings [12, 16] that indicated seasonal dependence.

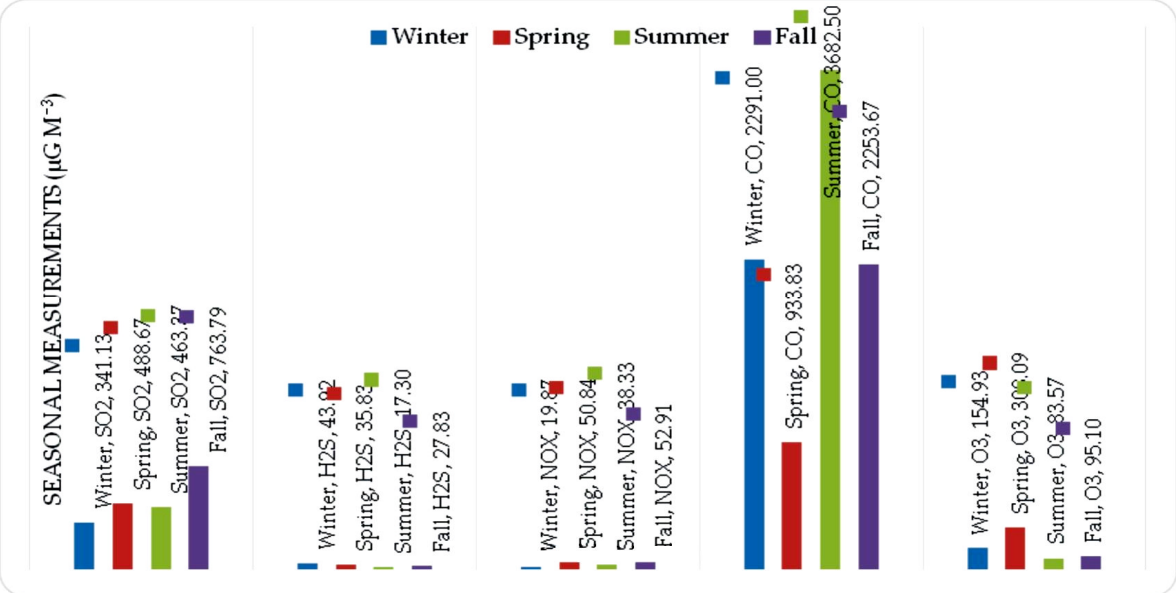

Figure 3. Seasonal variation in air pollutants of rabigh city and its environs, SO_2 (µg m^{-3}), H_2S (µg m^{-3}), NO_x (µg m^{-3}), CO (µg m^{-3}) and O_3 (µg m^{-3})

The increased concentration of NO_x during the fall season can be linked to the longer lifetime of NO_x in the fall relative to other seasons, such as winter [17]. SO_2 in the atmosphere may have been converted to secondary particulates through photochemical reactions [1, 18]. In high moist conditions, NO_x has the potential to react with OH radicals to yield HNO_3, which is subsequently removed from the atmosphere in that form [19]. Furthermore, increases in NO_x and SO_x concentrations in the atmosphere may also be associated with increased burning activities in crude oil production processes, residential heating, and vehicle emissions [20, 11]. Similar findings were reported by Zeb *et al.* [21] in a study assessing seasonal behaviors of tropospheric trace gases by using satellite observations.

The high concentration of H_2S recorded in the winter may be associated with an increased emission from the source point caused by the addition of sulfur-containing odorants to natural gases to detect leaks. The presence of active wastewater treatment plants in winter and the effects of stagnant meteorological conditions could also be a major reason for the increasing concentration of H_2S [22, 13]. CO is a colorless and odorless gas that is present in the atmosphere at increasingly large concentrations. The presence of CO is reportedly caused in part by an increased level of road traffic and other industrial activities, such as fuel combustion [3]. The increase in concentration during the summer may be caused by the reason above [15].

The high concentration of O_3 recorded during the spring season can be attributed to the increased ambient temperature and sunlight over several days and the presence of relatively stagnant air [23, 24]. These conditions have been reported to cause the buildup of ozone and its precursors, causing ozone formation that would typically be formed during high-temperature days in a season [7, 24].

The Gaussian HYSPLIT model seasonal average pollutant concentrations were used to create contour maps illustrating emission sources and areas affected (Fig. 2). The seasonal dispersion of pollutants from the source to three areas with high concentrations of pollutants (Rabigh, Thuwal, and Khulais) was displayed.

During the winter season, when the wind speed was the highest in the northeast direction, the highest levels of pollutants were predicted to affect the Thuwal area (>50 µg m^{-3}), followed by Khulais (>35 µg m^{-3}), with no effect on the Rabigh area despite its proximity to the source point. The dispersion of pollutants during the spring and summer seasons was minimal. The wind speed was the highest in the northeast direction but remained lower than the wind speed recorded in winter, and the dispersion of pollutants in the two seasons did not affect the three areas. Predictions for the fall revealed dispersion of pollutants to Thuwal (>20 µg m^{-3}) and Rabigh (>20 µg m^{-3}) because the wind was blowing more in the northeast and southwest directions. The corresponding wind speed and wind direction frequency distributions affecting pollutant dispersion are represented as a wind rose in Fig. 4.

Generally, wind speed plays a key role in the dispersion or spread of air pollutants from sources or hot spots to other environments [25, 26]. The effect of wind speed was evident in this study. It may be responsible for the high effect of pollution on areas further from the source, such as the Thuwal and Khulais areas in the northeastern direction during the winter. However, the lower effect in Khulais compared with Thuwal may be attributed to a gradual reduction in pollution levels over distance, as the Khulais area was further from the source point.

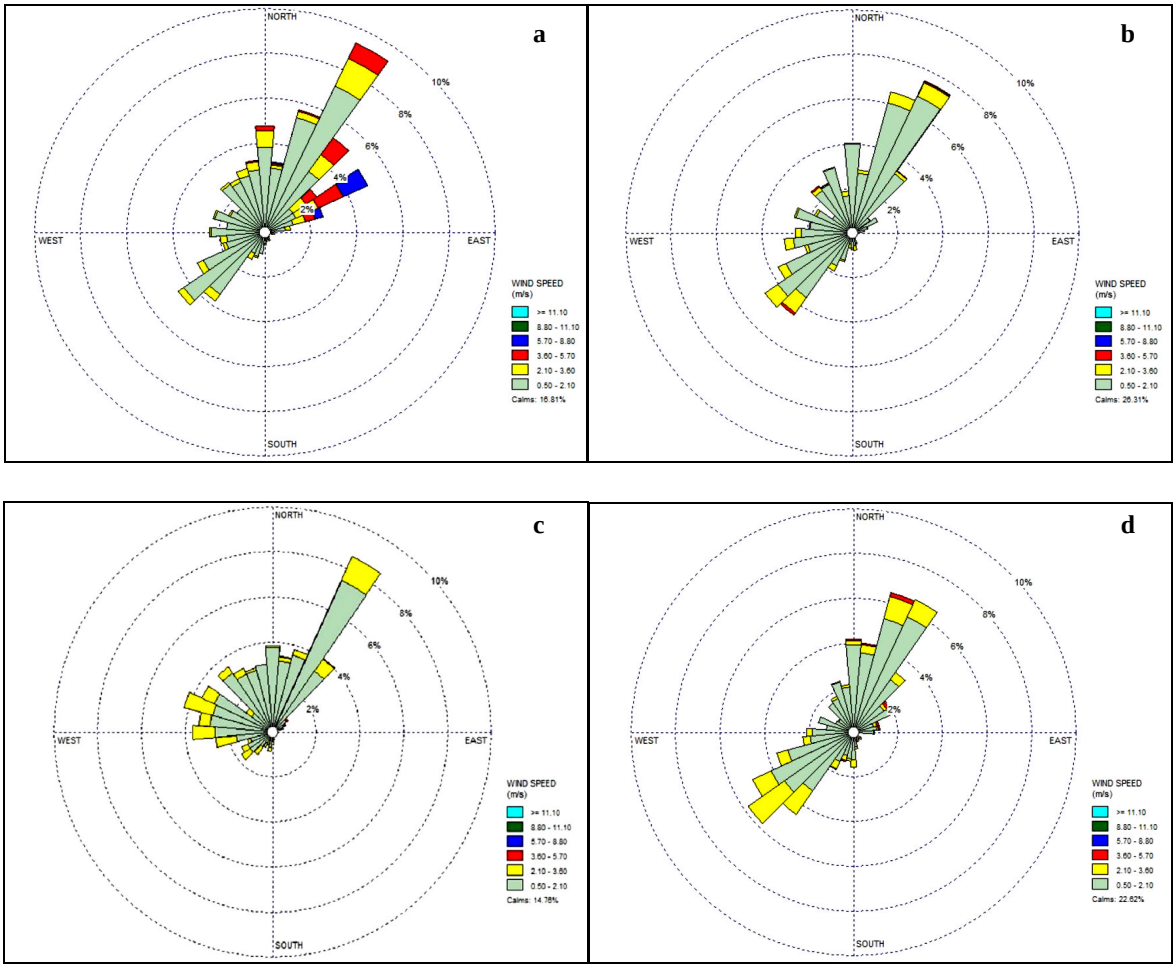

Figure 4. **Rate distribution of wind speed and wind direction represented as the wind rose for a) winter b) spring c) summer and d) fall**

The slight southwestern wind direction explains the lower concentrations in the Rabigh area during the fall season compared with the concentration in the Thuwal and Khulais areas resulting from the northeastern wind during the winter [27]. The wind drift phenomenon could also be a major reason for the spread of pollutants to Rabigh from the source [26]. The high-intensity north westerlies experienced during the winter are attributed to the breeze formed from the Red Sea; this breeze is toward the northwest [26, 28].

Seasonal variations in meteorological conditions, such as temperature (T), relative humidity (H), and wind speed (WS), are presented in Fig. 5. The recorded mean temperature range was 24.73 ± 2.51–34.62 ± 5.07 °C, relative humidity was 53.33 ± 4.42–55.67 ± 7.36%), and wind speed was 1.92 ± 1.52–2.98 ± 1.43 ms^{-1}). The maximum values were recorded in summer, spring, and winter for temperature, relative humidity, and wind speed, respectively. ANOVA ($p < 0.05$) revealed significant variation in meteorological conditions across the four seasons (winter, spring, summer, and fall).

Meteorological conditions are key factors in the dispersion of air pollutants. Temperature, relative humidity, and wind speed are major meteorological conditions measured in this study.

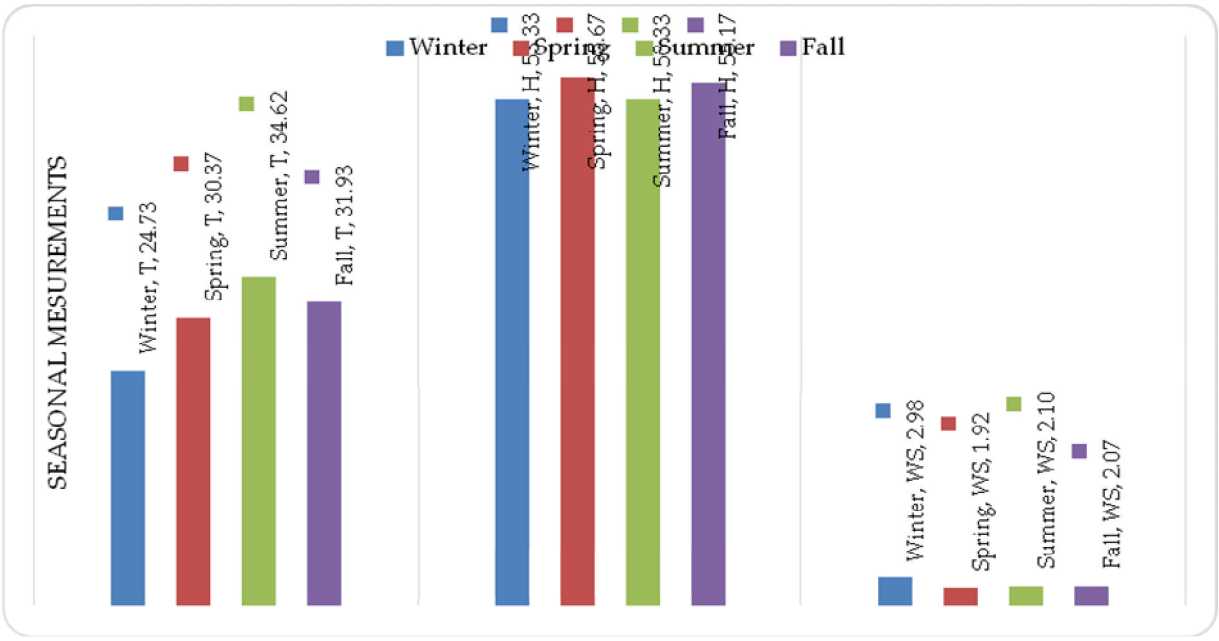

Figure 5. **Seasonal variation in meteorological conditions of rabigh city and its environs T = Temperature (°C), H = Humidity (%), WS = Wind Speed (ms^{-1})**

An increase in the temperature recorded during the summer can be attributed to the location of the pollution source and the unique characteristic of the coastal areas of the Red Sea, which cause higher atmospheric temperatures than in inland areas. Higher temperatures increase atmospheric turbulence, pollutant dispersion, and warm advection, which could be crucial reasons for increased pollutant concentrations. Similar findings were reported by Patlakas et al. [26] regarding the rise in temperature in the summer season. They reported an increase in the variation of regional features based on the climatic conditions of the Arabian Peninsula. However, our results contrast with findings by Almazroui [29].

The rise in relative humidity established in this study during the spring season may be caused by the warm sea close to the study area. Radiation properties and temperature are also reported to play a role in the percentage of relative humidity in the atmosphere [26, 30]. These findings have provided a deeper understanding of the relationship between seasonal atmospheric temperature and relative humidity [5, 30].

Correlation between Air Pollutants and Meteorological Conditions

To further understand the effect of meteorological conditions (T, H, and WS) on pollutants (SO_2, H_2S, NO_x, CO, and O_3) and the relationship between pollutants and meteorological conditions, a Pearson correlation analysis was performed. The Pearson correlation matrix (Table 1) revealed that most concentrations of pollutants were negatively correlated with wind speed except for CO. The negative correlation with NO_x was significant ($p < 0.05$). However, significant positive correlations were observed among temperature, relative humidity, and NO_x. Positive correlations were also observed between humidity and all pollutants, with a significant positive correlation between humidity and NO_x. A positive correlation was

established between temperature and pollutants, except for H_2S and O_3, which were negatively correlated with temperature. A significant positive correlation between temperature and NO_x was revealed.

Table 1. **Correlation matrix for meteorological data and air pollutants.**

	Temp	Hum	WS	SO_2	H_2S	NO_x	CO	O_3
Temp	1							
Hum	.337	1						
WS	-.280	-.260	1					
WD	.157	-.278	-.150					
SO_2	.259	.399	-.252	1				
H_2S	-.256	.499	-.062	.614*	1			
NO_x	.581*	.649*	-.583*	.442	.109	1		
CO	.304	.143	.336	.247	.157	.011	1	
O_3	-.329	.340	-.466	.316	.685*	.314	-.112	1

*. Correlation is significant at the 0.05 level (2-tailed).

The negative correlation between most pollutants and wind speed may be attributable to the effectiveness of wind speed in pollutant removal or the reduction in the concentration because of pollutants being increasingly dispersed as wind speed increases and for further locations. We observed that locations further away from the source were less affected by pollutants. Gaseous pollutants always have more prospects and the ability to undergo dilution or react with other elements, which has led to significant correlations between wind speed and pollutants in a gaseous state [30]. The absorption of semivolatile species by aerosols may cause an increase in the particulate matter concentration, which engendered a significant positive correlation between humidity and NO_x [13]. The significant positive correlation between temperature and NO_x may result from the role of temperature in combustion processes, causing the emission of NO_x into the atmosphere [13]. Valentim et al. [31] reported a positive effect of temperature on NO_x formation.

The PCA results for pollutants and meteorological conditions revealed that components 1 and 2 accounted for 61.75% of the total variation (Fig. 6a). The score plot reveals the data structure since the first two components account for most of the variance in the data, and the existence of the data in four groups was established to reveal the distribution of the data. The random distribution of points on the score plot near zero indicates standardization and normal distribution of the seasonal values of pollutants and meteorological data (Fig. 6b).

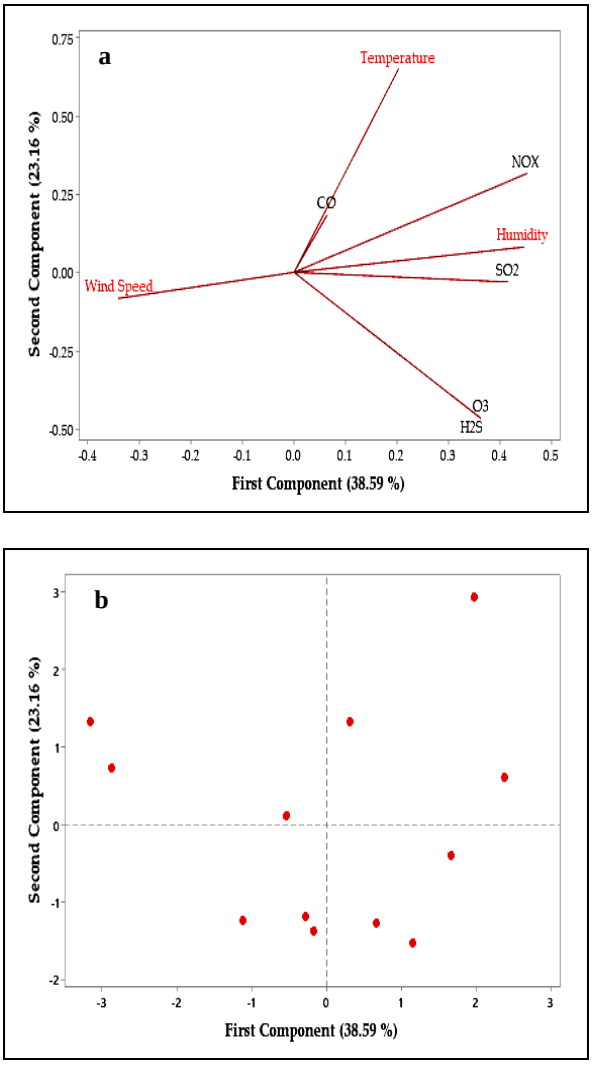

Figure 6. **a) PCA loading plot for meteorological data and air pollutants b) PCA score plot for mean meteorological data and air pollutants**

The values for PCA loadings for components 1 and 2 are presented in Table 2. High eigenvalues indicated the pattern and extent of the spread of data, which informed the choice of high eigenvalue as the principal component. The highest eigenvalue was recorded in Component 1 (PC1), which accounted for 38.59% of the total variation. PC1 accounted for considerably more variation than other components. PC1 also exhibited positive loadings for all variables except wind speed. PC1 was a measure of humidity, SO_2, H_2S, NO_x, CO, and O_3. Component 2 (PC2) accounted for 23.16% of the total variation and displayed positive loadings for all variables except wind speed, SO_2, H_2S, and O_3. PC2 appeared to be a measure of temperature, H_2S, and O_3.

Table 2. Principal component analysis (PCA) loadings on the first and second components.

Variable	PC1	PC2
Temperature	0.203	0.648
Humidity	0.446	0.08
Wind Speed	-0.34	-0.083
SO_2	0.416	-0.031
H_2S	0.362	-0.464
NO_X	0.452	0.315
CO	0.065	0.183
O_3	0.363	-0.466
Eigenvalue	3.0871	1.853
Variance	3.0871	1.853
% Var	0.386	0.232

PCA reveals the possible sources of pollution and the effect of meteorological data on the dispersion or spread of pollutants. Positive loadings in PC 1 in all variables except wind speed indicated a unique effect of possible dilution of pollutants as the wind speed increased. PC1 is a measure of humidity, SO_2, H_2S, NO_x, CO, and O_3. This finding indicates that the source may be gasoline combustion or crude oil refining, which is significantly affected by relative humidity. PC2 is a measure of temperature, H_2S, and O_3 and can thus be attributed to a wastewater source. Photochemical phenomena are affected by temperature in O_3 formation [32].

Conclusion

In this study, seasonal pollutant dispersion concentrations, meteorological conditions, and the effect of meteorological conditions on atmospheric pollutants in 2018 were investigated. There was a significant variation in atmospheric pollutants (SO_2, H_2S, NO_x, CO, and O_3) and meteorological conditions (temperature, relative humidity, and wind speed) across the four seasons. However, during the winter season, the Thuwal area, followed by the Khulais area, was most affected by high levels of pollutants, whereas no effect was observed in the Rabigh area. By contrast, the effect of pollutant dispersion was observed in the Rabigh and Thuwal areas during the fall season.

Our results revealed that most pollutants were negatively correlated with wind speed, indicating that wind speed was effective for pollutant removal or reducing the concentration as pollutants were dispersed to further locations. The PCA revealed a significant positive correlation between NO_x and humidity and NO_x and temperature. SO_2, H_2S, NO_x, and CO originated primarily from crude oil refining and gasoline combustion, whereas O_3 was attributed to photochemical phenomena that require high temperatures for formation. Policymakers and stakeholders must provide solutions to mitigate the effects of atmospheric pollution in Rabigh, Thuwal, and Khulais to protect the health of inhabitants.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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