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Estimation of short-lived climate forced sulfur dioxide in Tehran, Iran, using machine learning analysis

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Abstract

This paper presents a time-series analysis of SO_2 air concentration and the effects of particulates (either $PM_{2.5}$ and PM_{10}) concentrations and meteorological conditions (relative humidity and wind speed) on SO_2 trend in Tehran for the period from 2011 to 2020. The source data were obtained from 21 monitoring stations of Air Quality Control Company and meteorological stations in Tehran. To predict the status of future concentration of SO_2, $PM_{2.5}$ and PM_{10}, a Box–Jenkins ARIMA approach was used to model the monthly time series. Considering the whole period of ten years, a somewhat downward trend was noted for SO_2 air concentration, even though a slight rising trend was observed in 2020 year. Monthly sulfur dioxide concentrations showed the lowest value in June and the highest value in January. Seasonal concentrations were lowest in spring and highest in winter. Then, in the ArcGIS software, the IDW method was used to obtain air pollution zoning maps. As a result, the highest average concentration of SO_2 occurred in the north and southwest of Tehran. In the last step, Relations between the SO_2 concentration and particulate matters and relative humidity and wind speed were calculated statistically using the daily average data. We finally concluded that the combined effect of particulate matters and relative humidity with the increasing role of Sulfur dioxide overcomes the decreasing role of wind speed. This study can contribute to a better understanding of the SO_2 air pollution in Tehran affected by meteorological conditions and the rapid urbanization and industrialization, followed by the possible combustion of fuel oil in power plants and health problems.

Keywords Sulfur dioxide · Short-lived climate pollutants · Meteorological parameters · Air pollution · Machine learning · ARIMA forecasting

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1 Introduction

Atmospheric Sulfur dioxide (SO_2), emitting from anthropogenic and natural sources, is one of the most important air pollutants leading to climate change, environmental problems and health risks (Braga et al. 2006; Gonçalves et al. 2005; Krotkov et al. 2016; Mallik and Lal 2014; Pereira et al. 2009; Hoveidi et al. 2017; Borhani and Noorpoor 2020). Sulfur dioxide can cause a number of harmful effects on the lungs, (i.e., Wheezing, breathing problems, chest tightness) (EPA 2008; Yun et al. 2015). While $PM_{2.5}$ (Particulate Matter with 2.5 μm or less in aerodynamic diameter) is deposited on the surface of the deeper parts of the lungs and PM_{10} (Particulate Matter with 10 μm or less in aerodynamic diameter) on the surface of the larger airways in the upper part of the lungs. Particulate matter deposited on the lung surface can lead to tissue

damage and lung inflammation (Wei and Tang 2018; Losacco and Perillo 2018; Happo 2009). SO_2 is one of the five main pollutants that together account for more than 90% of air pollution in the world (Sharma 2001). Sulfur oxides in combination with particulate matter and moisture (e.g. humidity) in ambient air produce the most harmful effects associated with atmospheric air pollution (Dutkiewicz et al. 2000; Moldan et al. 2001). Numerous studies to show that exposure to SO_2, $PM_{2.5}$, and PM_{10} Periodontitis increases the risk of respiratory diseases in adults, during the COVID-19 pandemic (Borhani et al. 2021a; Zoran et al. 2020; Zou et al. 2020; Wu et al. 2020). Sulfur dioxide (SO_2) is one of the Short-lived climate forcers (SLCF). Short-lived climate forcers (SLCF) are also known to as short-lived climate pollutants (SLCP) (Randall et al. 2008; Retama et al. 2015; Stohl et al. 2015; Kindbom et al. 2019). SO_2 remains in the air for an average of 2 to 4 days (Turalıoğlu et al. 2005). SO_2, $PM_{2.5}$, PM_{10} are precursors of aerosols (Wang et al. 2015).

Although the relationships between meteorological conditions and SO_2 air pollution have been investigated, such as, Kalkstein and Corrigan (1986) examined a synoptic climatological approach to assessing the effects of climate on sulfur dioxide concentrations. Elminir (2005) mentioned dependence of air pollutants on meteorological conditions over Cairo in Egypt. And Several works have been carried out to study SO_2 air pollution in Iran. Such as, Geravandi et al. (2015) investigated the effects of nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) exposure related to health and increased premature deaths in Ahvaz, the capital of Khuzestan province, Iran. The results showed that about 5.6% of respiratory mortality and chronic obstructive pulmonary disease cases occurred when nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) concentrations were above 20 μg m^{-3}. Masoudi et al. (2018) studied the effects of meteorological factors on the prediction of SO_2 and the relationships between air pollutants and some meteorological parameters in Tehran from 2009 to 2010. Shen et al. (2020) proposed a machine learning-based extreme learning model to predict the concentration and ratio of air pollutants (O_3, CO, NO_2, SO_2, $PM_{2.5}$, PM_{10}) in Seoul, the capital of South Korea. Bhatti et al. (2021) analyzed the relationship between pollutants (CO, NO, O_3, SO_2) using a time series model to predict subsequent concentrations. Naseem et al. (2018) used an autoregressive integrated moving average (ARIMA) model to predict air quality time series data and then evaluated its application in air quality management decision making.

We still have very little information on the dependence of sulfur dioxide emissions on the geographic and meteorological conditions of the city and the emission rate from stationary and mobile sources. This study aimed to examine the relationship between SO_2, PM_{10} and $PM_{2.5}$

concentrations in ambient air and meteorological conditions in Tehran using the auto-regressive integrated moving average (ARIMA) method and statistical tools of analysis. we tried to make a time series model to forecast the environmental air quality time series data. Therefore, first, exhibits monthly, seasonal and annual variations of concentration of sulfur dioxide and particulates (either PM_{10} and $PM_{2.5}$) in the Tehran air over ten years (2011–2020). In the second step, the effect of particulate matter (i.e., PM_{10} and $PM_{2.5}$), wind speed, WS, and relative humidity, (RH in %)) on variations of sulfur dioxide concentration based on Pearson correlations between sulfur dioxide and its precursors were also analyzed. In the third step, the concentration distribution of the air pollutants in 21 air quality monitoring stations of the regions were zoned based on the measurements with the ArcGIS software using Inverse distance weighting (IDW) interpolation method. Finally, we use a time series model for the prediction of sulfur dioxide and particulate matter concentrations and wind speed and relative humidity. Figure 1 shows a flowchart of the steps followed during the research.

2 Materials and methods

2.1 The study area

Tehran, the largest metropolitan center in Iran, is located at about 35° 41′ 21″ N and 51° 23′ 20″ E (see Fig. 2). The total area covered by the city is about 751 km^2. The average annual precipitation amounts to 245.8 mm. The highest temperature in Tehran is 43 °C and the lowest temperature is − 15 °C. The average relative humidity is about 40%. The prevailing wind is West Tehran (270°) and its average speed is 5.5 m/s. Tehran city has a population of 8.7 million approximately. There are a number of reasons for air pollution in Tehran, some of which are in the industrial sector, the transportation sector, and the geographical location of the city, with the large Alborz Mountains in the north of the city contributing to pollution levels. Tehran is thus one of the most polluted cities in Iran, which is why an analysis of air quality in this city must be conducted.

2.2 Field measurement

In Tehran city, the automatic measurement of air quality is performed by 21 measuring stations of Air Quality Control Company (AQCC 2020). Figure 2 shows the location of the air pollution monitoring stations. The paper presents the analysis of SO_2, PM_{10} and $PM_{2.5}$ concentrations measurements collected at 21 stations which provided the information for a database covering a period of ten years:
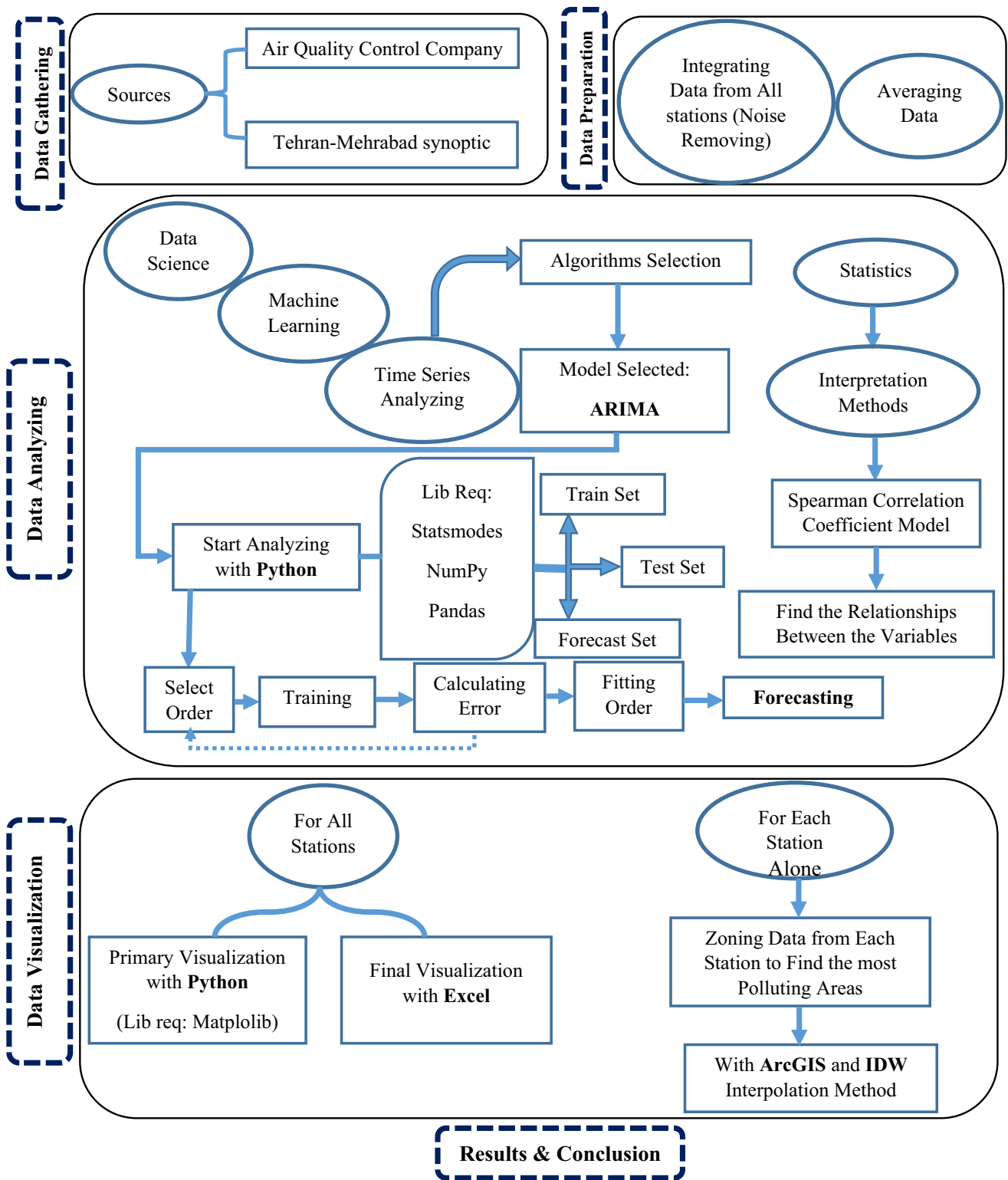
Fig. 1 Flow chart of research methodology

2011–2020 (Table 1). all air quality monitoring stations with > 75% of the hourly data over the year were used for further calculations, as less than 0.1% of the SO_2 data for each station was removed from the data set and subsequent calculations. The incoming information was converted into standard concentrations based on the Clean Discussion Guidelines issued by the US Natural Security Organization
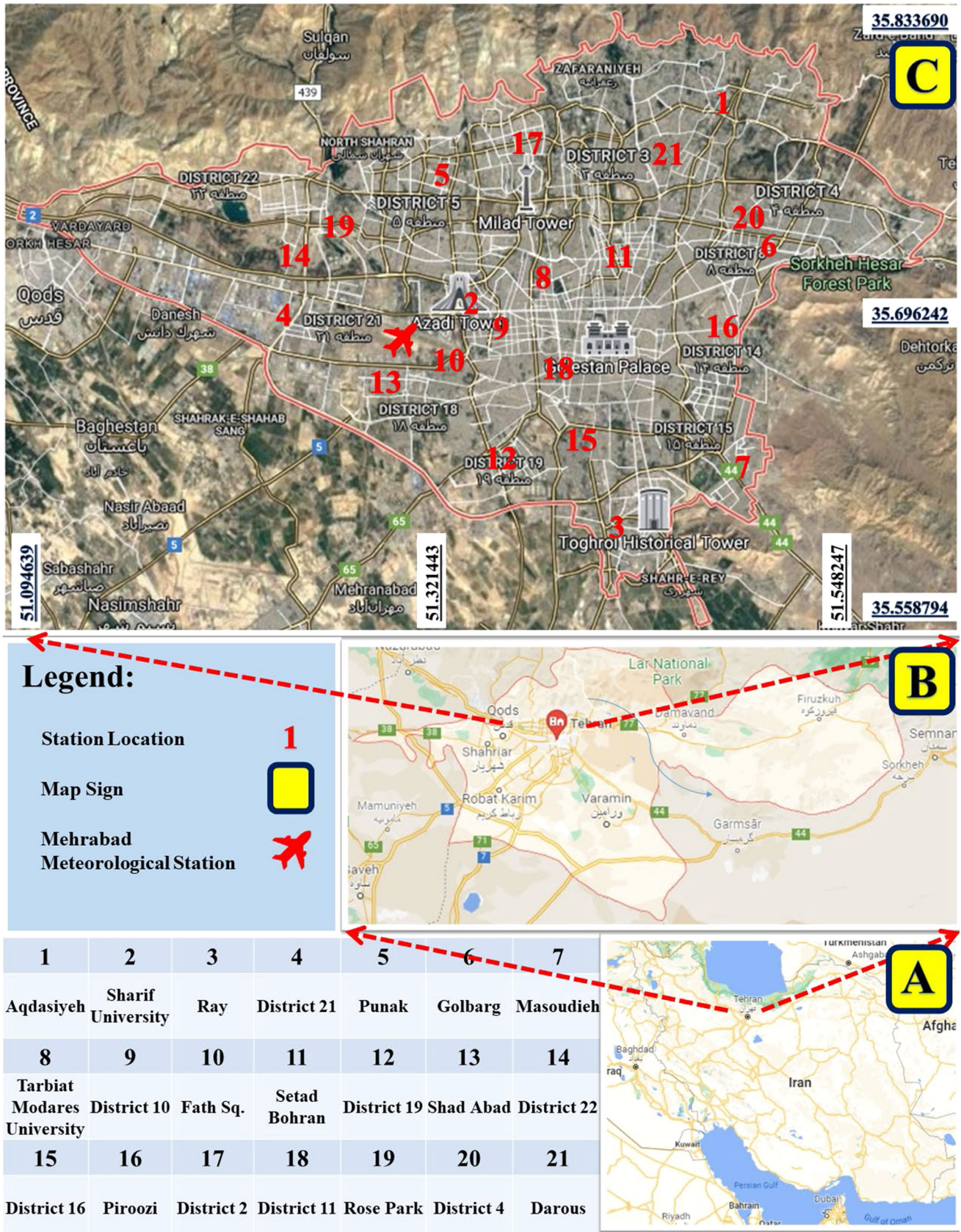
Fig. 2 The locations of the air quality monitoring stations and the Mehrabad synoptic station in Tehran. **a** Iran, **b** Tehran Province, **c** Tehran City

Table 1 Annual average of SO_2, $PM_{2.5}$, PM_{10} and RH and WS recorded from 2011 to 2020 in Tehran

Year	Parameters	Dataset											
		Winter			Spring			Summer			Autumn		
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011	SO_2 (ppb)	26.50	18.73	19.00	18.93	18.47	18.64	17.57	18.50	25.40	21.25	20.69	22.94
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	38.67	27.67	32.33	44.50	41.50	37.75	35.75	42.25	45.25	39.00	34.50	43.50
	PM_{10} ($\mu g\ m^{-3}$)	96.36	62.43	60.07	103.71	95.21	111.61	96.85	106.85	93.71	93.13	80.27	105.33
	RH (%)	58.95	48.36	45.58	26.74	27.62	19.17	17.10	26.87	23.90	45.00	66.28	52.88
	WS (Knot)	4.63	7.41	5.81	7.71	8.60	7.90	6.58	6.50	5.34	6.22	5.00	3.96
2012	SO_2 (ppb)	29.91	26.00	22.09	17.38	16.71	18.57	21.61	18.93	19.23	19.77	18.23	21.77
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	34.33	33.33	34.00	33.00	41.56	32.90	38.64	31.15	32.36	36.50	35.14	44.50
	PM_{10} ($\mu g\ m^{-3}$)	75.50	73.30	63.50	72.08	108.00	79.23	84.31	77.87	83.60	80.00	71.06	90.94
	RH (%)	48.66	52.74	32.14	38.75	23.79	21.67	23.06	18.41	24.43	33.39	52.34	64.96
	WS (Knot)	5.88	6.08	8.69	6.54	8.59	6.31	6.15	5.48	5.51	5.23	4.22	4.27
2013	SO_2 (ppb)	24.60	22.00	17.27	18.00	19.20	20.18	15.27	16.75	15.67	16.00	16.64	17.73
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	43.60	35.71	31.40	24.92	23.54	37.46	37.83	33.27	33.70	36.91	33.67	35.46
	PM_{10} ($\mu g\ m^{-3}$)	100.18	80.41	76.53	67.19	68.25	106.87	112.20	97.57	90.57	101.60	84.56	79.73
	RH (%)	45.63	44.34	35.15	30.54	28.37	20.77	21.93	24.08	18.67	31.50	53.52	50.79
	WS (Knot)	5.85	6.07	7.49	7.11	8.57	8.00	6.78	6.32	6.38	5.57	4.27	5.61
2014	SO_2 (ppb)	19.89	19.89	15.22	19.50	21.00	14.12	11.69	14.91	16.91	15.78	17.50	18.60
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	38.62	35.85	24.85	21.90	22.80	34.33	36.00	29.00	34.45	32.09	29.50	37.91
	PM_{10} ($\mu g\ m^{-3}$)	78.40	85.57	64.28	57.21	64.13	94.46	95.21	86.17	94.36	84.00	69.60	86.33
	RH (%)	54.36	44.68	36.58	32.38	24.73	18.48	19.34	16.08	19.04	37.65	49.23	53.61
	WS (Knot)	5.26	5.07	8.18	7.44	7.72	8.00	6.78	6.16	6.21	6.57	4.58	4.39
2015	SO_2 (ppb)	21.29	18.00	15.94	13.00	13.22	14.05	14.88	17.37	16.23	17.71	14.56	13.88
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	33.07	29.75	25.00	22.69	26.25	38.06	27.82	26.91	25.00	25.75	37.00	41.23
	PM_{10} ($\mu g\ m^{-3}$)	79.53	76.23	65.28	68.61	77.39	107.56	89.47	101.33	89.06	111.00	82.40	84.14
	RH (%)	42.41	47.34	41.90	23.20	20.51	16.02	18.96	21.18	26.18	38.57	50.11	61.62
	WS (Knot)	5.07	6.00	6.89	8.29	7.61	6.93	5.98	5.65	5.42	5.78	4.89	4.51
2016	SO_2 (ppb)	13.87	15.44	11.07	8.36	9.00	8.27	13.91	9.54	10.00	10.87	12.38	11.93
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	27.71	32.08	23.38	22.43	25.50	30.14	35.20	35.21	31.33	29.50	42.00	42.00
	PM_{10} ($\mu g\ m^{-3}$)	72.46	87.53	64.36	59.13	68.27	95.78	102.53	92.43	110.36	94.93	101.43	83.50
	RH (%)	46.98	37.46	35.89	36.48	26.39	19.23	22.31	18.00	21.43	28.15	41.48	52.64
	WS (Knot)	5.76	6.04	8.75	7.57	8.47	8.14	7.03	5.19	6.66	4.71	4.61	5.14
2017	SO_2 (ppb)	12.46	9.50	7.00	6.11	5.62	5.59	5.94	6.40	8.75	7.76	6.75	9.50
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	42.69	31.37	23.44	22.87	28.81	27.87	28.87	29.56	30.69	34.00	37.31	52.81
	PM_{10} ($\mu g\ m^{-3}$)	84.71	69.73	56.53	69.87	77.87	78.00	82.50	90.07	95.78	97.20	102.27	105.73
	RH (%)	49.88	47.25	46.32	37.73	24.26	16.87	18.65	19.12	20.41	27.98	32.39	40.00
	WS (Knot)	5.21	5.87	6.91	6.81	7.21	7.63	5.70	5.62	5.26	5.32	5.43	4.31
2018	SO_2 (ppb)	8.50	7.07	6.13	4.88	3.00	3.87	4.86	4.80	5.07	5.26	5.40	6.27
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	40.33	43.47	30.60	25.06	25.00	26.14	32.29	25.86	25.07	24.57	29.93	33.80
	PM_{10} ($\mu g\ m^{-3}$)	81.07	93.21	85.57	58.47	71.20	70.40	85.93	89.81	84.06	68.31	62.63	79.56
	RH (%)	47.00	55.95	27.15	37.08	37.46	22.26	14.09	20.00	21.17	40.36	59.14	51.50
	WS (Knot)	5.34	5.15	8.38	6.25	7.18	6.30	5.65	6.00	5.58	5.69	4.29	4.71
2019	SO_2 (ppb)	6.07	5.64	5.07	3.47	3.78	4.33	4.78	4.88	5.18	5.23	6.47	7.18
	$PM_{2.5}$ ($\mu g\ m^{-3}$)	33.43	27.36	19.00	17.00	22.53	27.07	29.67	27.50	26.81	27.06	45.69	47.94
	PM_{10} ($\mu g\ m^{-3}$)	85.81	59.75	46.25	46.50	64.44	72.81	95.25	85.37	91.62	75.50	85.19	88.50
	RH (%)	51.86	44.44	43.09	34.07	25.34	18.13	18.42	20.52	24.53	40.02	57.45	56.81
	WS (Knot)	5.81	6.35	7.11	7.12	7.96	5.84	7.24	6.12	6.20	5.03	4.36	4.42

Table 1 (continued)

Year	Parameters	Dataset											
		Winter			Spring			Summer			Autumn		
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2020	SO$_2$ (ppb)	7.00	6.22	4.72	3.39	3.83	4.53	4.33	6.05	6.56	5.78	6.33	9.67
	PM$_{2.5}$ (µg m^{-3})	38.75	26.44	21.56	18.62	22.75	26.25	27.75	24.37	24.50	31.62	30.94	49.50
	PM$_{10}$ (µg m^{-3})	73.69	68.88	52.37	44.44	65.44	75.57	71.75	78.00	78.19	79.94	62.63	89.12
	RH (%)	57.95	46.75	41.37	48.37	26.28	17.46	21.02	26.46	23.60	32.71	57.20	67.71
	WS (Knot)	5.11	7.90	6.21	6.86	7.47	7.65	6.27	6.78	5.27	4.42	4.42	4.08

(USEPA 1997). In this standard, a maximum concentration of 24 h was used for SO$_2$, PM$_{10}$, and PM$_{2.5}$.

The instruments used to measure the concentrations of SO$_2$, PM$_{10}$ and PM$_{2.5}$ were continuous automatic analyzers manufactured by Thermo Fisher Scientific Inc. (Waltham, MA, USA) and Teledyne API Inc. (San Diego, CA, USA). The PM monitor was used to measure the concentrations of both PM$_{10}$ and PM$_{2.5}$ in ambient air based on light scattering and β-ray attenuation. The SO$_2$ analyzer employed pulse fluorescence detection to determine the SO$_2$ concentration in the ambient air. Data must be evaluated in the wider context of the checks and calibrations employed during their use and in the production of published data, a process usually known as quality assurance and quality control (QA/QC). Recording Air Quality Control Company systems follows QA/QC (2008/50/EC). Then, in the ArcGIS software, the IDW method was used to obtain air pollution zoning maps. As a result, spatial analysis of distribution of SO$_2$, PM$_{2.5}$ and PM$_{10}$ contaminants in Tehran was made. Also, the Spearman correlation coefficient model was used to examine the relationship between sulfur dioxide and PM$_{10}$, PM$_{2.5}$, RH, and WS (Ozbay 2012). Correlation coefficients (r) significant at the 0.05 level (P value $\leq$ 0.05) are identified with a single asterisk (significant).

$$r = \frac{\sum (\hat{y}_i - \overline{\hat{y}_i})(y_i - \overline{y_i})}{\sqrt{\sum (\hat{y}_i - \overline{\hat{y}_i})^2 \sum (y_i - \overline{y_i})^2}} \tag{1}$$

2.3 ARIMA model

Time series forecasts including automatic ARIMA modeling was carried out using the 'forecast' package. A differenced process that depends upon the p lags of the series values and q lags of the error terms is termed as ARIMA (p = autoregressive, d = differencing, q = moving average). we apply these processes on this series to find out the best and most appropriate ARIMA model. The ARIMA model can be considered as a "cascade" of the two models. The first part of this model is suitable for non-stationary conditions, the equation of which is as follows:

$$Y_t = (1 - L)^d X_t. \tag{2}$$

The second part is wide-sense stationary, the equation of which is as follows:

$$\left(1 - \sum_{i=1}^{p} \varphi_i L^i\right) Y_t = \left(1 + \sum_{i=1}^{q} \theta_i L^i\right) \varepsilon_t. \tag{3}$$

The variables of this equation are: L is the lag operator, θ_i the parameters of the moving average part, ε_t is error term, and the three variables p, d, q mentioned earlier.

The values of the p and q variables can be found by one of the functions: autocorrelation function (ACF), or partial autocorrelation function (PACF). We used both of these functions here to find the most suitable order (Agrawal et al. 2017). To establish whether an ARIMA model qualifies to predict the concentration of sulfur dioxide, PM$_{2.5}$ and PM$_{10}$ and wind Speed and relative humidity parameters in Tehran, statistical errors through determination coefficient (R^2), mean square error (MSE) and root mean square error (RMSE) were applied as follows (Beckerman et al. 2013; Elavarasan et al. 2018; Goap et al. 2018):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \overline{y_i})}{\sum_{i=1}^{n}(y_i - \overline{y})} \tag{4}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{5}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{6}$$

where y_i and $\hat{y}_i$ are the forecasted and observed i values of y, $\overline{y_i}$ and $\overline{\hat{y}_i}$ represent the mean y values of the forecasted and observed in the tested sample set and n denotes the number of datum points in the set.

Table 2 The average monthly SO_2, $PM_{2.5}$ and PM_{10} concentration and RH and WS in the city Tehran from 2011 to 2020

Month	SO_2 (ppb)	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	RH (%)	WS (Knot)
Jan	17.01	37.32	82.77	50.37	5.39
Feb	14.84	32.30	75.70	46.93	6.19
Mar	12.35	26.55	63.47	38.52	7.44
Apr	11.30	25.30	64.72	34.53	7.17
May	11.38	28.02	76.02	26.47	7.94
Jun	11.21	31.79	89.23	19.00	7.27
Jul	11.48	32.98	91.60	19.49	6.42
Aug	11.81	30.51	90.55	21.07	5.98
Sep	12.89	30.92	91.13	22.34	5.78
Oct	12.54	31.71	88.56	35.53	5.45
Nov	12.49	35.52	80.20	51.91	4.61
Dec	13.94	42.86	89.29	55.25	4.54

In this study, Meteorological data from the Mehrabad synoptic station in Tehran during a period of 10 statistical years (2011–2020) was used to recorded wind speed and relative humidity. Mehrabad Meteorological Station is located at 35° 41′ N and 51° 19′ E. The average annual temperature, average annual relative humidity, average annual precipitation, and annual sunshine hours are 17.7 °C, 41%, 238.9 mm, and 3025 h, respectively. The prevailing wind is from the west, as calculated at three times of record (morning, noon, and evening) at a speed of 5.5 m/s (IRIMO 2020).

3 Result and discussion

3.1 Sampling data analysis

The results show that the trend of changes in $PM_{2.5}$, PM_{10}, and sulfur dioxide in Tehran decreased from 2011 to 2020 (Fig. 4a–c) (Skrobacki et al. 2019). Torbatian et al. (2020) investigated air pollution variations in Tehran. Their results show that the $PM_{2.5}$ and sulfur dioxide concentrations decreased from 2005 to 2016. The average concentrations of SO_2, $PM_{2.5}$, and PM_{10} during the last 10 Years, are 12.77 ppb, 32.14 $\mu g\ m^{-3}$ and 81.94 $\mu g\ m^{-3}$, respectively. In December and January 2019 and 2020, the concentrations of $PM_{2.5}$, PM_{10}, and sulfur dioxide increased (Table 1). It was found that the maximum concentration for the examined period was recorded in January 2012 with an average value of 29.91 ppb and the lowest average monthly concentration for SO_2 was in 2018 (3.00 ppb) (Table 1). Sulfur dioxide pollutants also cause the formation of secondary suspended particles in the atmosphere. in winter and autumn, inversion is often observed in the city, which leads to an increase in the concentration of pollutants in the city. Kaushik and Melwani (2007), observed high SO_2 concentrations during the colder months in Delhi.

However, in another study in Kerman, Iran, SO_2 concentrations were shown to have a stable trend (Mansouri et al. 2013).

In this study, PM_{10} also showed a decreasing trend. The highest average monthly concentration for PM_{10} was in 2013 (112.2 $\mu g\ m^{-3}$) and the lowest in 2020 (44.44 $\mu g\ m^{-3}$) and maximum values are seen in summer (Table 2). The results described in the present study are consistent with several earlier investigations (Draxler et al. 2001; Shahsavani et al. 2012). According to Fig. 3b, the highest amounts of PM_{10} were recorded in the Shad Abad station.

The highest average monthly concentrations for $PM_{2.5}$ were in 2017 (52.81 $\mu g\ m^{-3}$) and the lowest in 2019 (17.00 $\mu g\ m^{-3}$). $PM_{2.5}$ reaches its maximum concentration in Tehran in December and January (Table 2). Zhang et al. (2021) examining the trend of $PM_{2.5}$ concentration, they also concluded that the average $PM_{2.5}$ concentration reaches its maximum in December and January. The zoning map shows that in regions 3 and 18 (Darrous and Shadabad monitoring stations), concentrations of $PM_{2.5}$ are high and in the central regions is less (Fig. 3a).

Two monitoring stations, Darrous and Aqdasiyeh, are located in the north of the city, and higher sulfur dioxide concentration is observed at these sites. After that, the District 16 monitoring station (in the southwest of Tehran) shows the highest sulfur dioxide concentration (Fig. 3c). The primary and secondary standard for sulfur dioxide according to the NAAQS for 24 h was 140 ppb (Goudarzi et al. 2014; WHO 2003; US EPA 2011). Table 3 shows that the annual average concentration of sulfur dioxide in air quality monitoring stations in Tehran was below the NAAQS standards from 2011 to 2020. One of the factors that can be effective in the heterogeneous distribution of pollutants in the city of Tehran is the rapid population growth and development of construction activity in some areas compared to other areas. This means that

Fig. 3 Distribution of annual average concentration in air quality monitoring stations in Tehran from 2011 to 2020, **a** PM$_{2.5}$, **b** PM$_{10}$, **c** SO$_2$
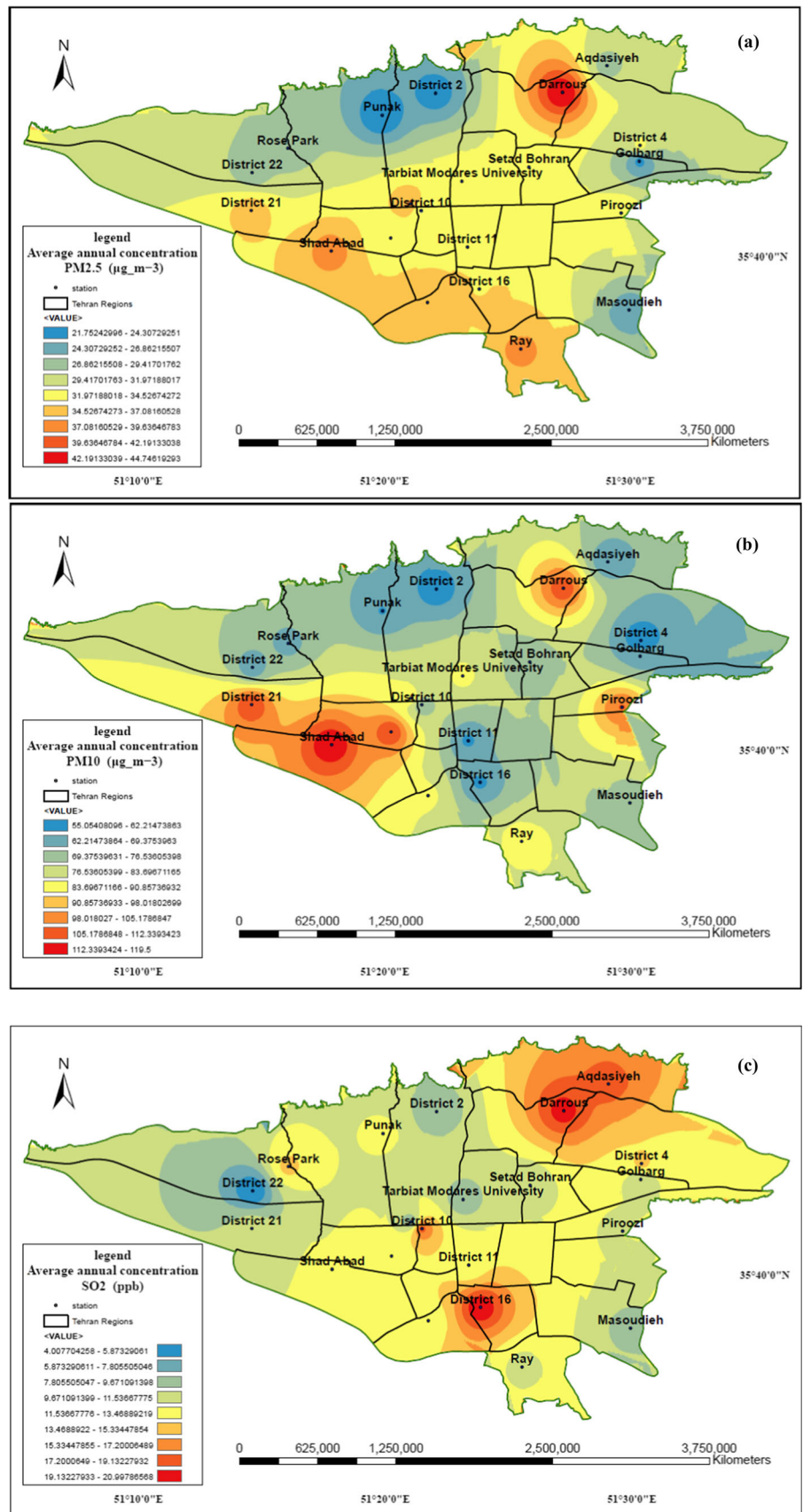
Table 3 Detailed information on AQMSs and the hourly average of SO$_2$, PM$_{2.5}$ and PM$_{10}$ data recorded from 2011 to 2020 in Tehran

No	District	Air Quality Monitoring Stations (AQMSs)	Latitude	Longitude	*SO$_2$ (ppb)	*PM$_{2.5}$ (µg m^{-3})	*PM$_{10}$ (µg m^{-3})
1	1	Aqdasiyeh	35.7958	51.4841	18.00	28.50	64.50
2	2	Sharif University	35.7022	51.3509	8.00	37.50	88.00
3	20	Ray	35.6036	51.4257	11.00	37.50	87.00
4	21	District 21	35.6977	51.2431	11.00	36.50	111.50
5	5	Punak	35.7623	51.3316	12.00	21.75	62.00
6	8	Golbarg	35.7310	51.5061	10.00	23.50	68.00
7	15	Masoudieh	35.6300	51.4990	9.00	25.75	73.00
8	6	Tarbiat Modares University	35.7175	51.3859	8.00	32.75	85.50
9	10	District 10	35.6974	51.3580	18.00	31.75	71.00
10	9	Fath.Square	35.6788	51.3375	13.00	32.75	112.00
11	7	Setad Bohran	35.7270	51.4312	10.00	32.25	72.00
12	19	District 19	35.6352	51.3625	12.00	36.50	85.00
13	18	Shad Abad	35.6700	51.2973	12.00	38.50	119.50
14	22	District 22	35.7233	51.2436	4.00	27.50	64.00
15	16	District 16	35.6445	51.3976	21.00	34.50	61.00
16	13	Piroozi	35.6959	51.4937	11.00	33.75	105.50
17	2	District 2	35.7770	51.3681	8.00	22.75	58.00
18	11	District 11	35.6729	51.3897	12.00	34.25	61.00
19	22	Rose Park	35.7398	51.2678	14.00	27.75	67.00
20	4	District 4	35.7418	51.5064	14.00	32.75	55.00
21	3	Darrous	35.7777	51.4541	20.00	44.75	110.00

*Air Quality Monitoring Stations with less than 75% valid hourly data available were excluded from the next analysis

Table 4 Spearman's rank correlations between SO$_2$, PM$_{2.5}$, PM$_{10}$ and RH, WS data from 2011 to 2020

	SO$_2$ (ppb)	PM$_{2.5}$ (µg m^{-3})	PM$_{10}$ (µg m^{-3})	RH (%)	WS (Knot)
SO$_2$ (ppb)	1				
PM$_{2.5}$ (µg m^{-3})	0.5787	1			
PM$_{10}$ (µg m^{-3})	0.0648	0.5611	1		
RH (%)	0.6845	0.5679	− 0.2986*	1	
WS (Knot)	− 0.5186*	− 0.8083*	− 0.4960*	− 0.5873*	1

*$P \leq 0.05$

Table 5 Square root of the MSE for Algorithm test the average monthly SO$_2$, PM$_{2.5}$ and PM$_{10}$ concentration and RH and WS in Tehran from January 2020 to December 2020

No	Models (p, d, q)	RMSE SO$_2$	RMSE PM$_{2.5}$	RMSE PM$_{10}$	RMSE WS	RMSE RH
1	ARIMA (1, 1, 1)	3.6331	8.6379	15.0551	2.1165	Error
2	ARIMA (2, 1, 2)	3.7908	7.1540	17.9815	1.4282	8.9558
3	ARIMA (3, 1, 3)	3.8052	8.4443	14.6274	0.7193*	Error
4	ARIMA (3, 2, 3)	1.9937	20.8813	14.4223*	2.8032	Error
5	ARIMA (4, 1, 4)	1.5600	7.6312	16.9547	Error	Error
6	ARIMA (3, 1, 4)	1.5172*	7.8734	14.8090	Error	8.6740*
7	ARIMA (2, 1, 4)	3.7239	7.7383	14.5312	0.9204	8.7141
8	ARIMA (2, 1, 3)	Error	7.0851*	14.5628	1.3185	Error

MSE Mean squared error, *RMSE* Square root of the MSE, *Error* The algorithm has not reached convergence

*Minimum square root of the MSE

Table 6 Comparison of model predictions and actual values for average monthly SO$_2$, PM$_{2.5}$ and PM$_{10}$ concentration and RH and WS in Tehran from January 2020 to December 2020 (Algorithm test)

Month	SO$_2$ (ppb)		PM$_{2.5}$ (μg m^{-3})		PM$_{10}$ (μg m^{-3})		WS (Knot)		RH (%)	
	AV	PV	AV	PV	AV	PV	AV	PV	AV	PV
Jan	7.00	6.08	38.75	39.59	73.69	85.31	5.11	5.56	57.95	51.37
Feb	6.22	5.15	26.44	29.46	68.88	79.06	7.90	6.10	46.75	48.88
Mar	4.72	4.78	21.56	23.56	52.37	77.73	6.21	6.71	41.37	42.45
Apr	3.39	4.84	18.62	24.63	44.44	76.61	6.86	7.12	48.37	33.81
May	3.83	5.15	22.75	28.30	64.44	77.51	7.47	7.22	26.28	25.25
Jun	4.53	5.53	26.25	30.20	75.57	77.49	7.65	7.00	17.46	19.05
Jul	4.33	5.83	27.75	29.57	71.75	78.05	6.27	6.50	21.02	16.85
Aug	6.05	6.01	24.37	28.12	78.00	77.93	6.78	5.87	26.46	19.23
Sep	6.56	6.03	24.50	27.39	78.19	78.17	5.27	5.26	23.60	25.57
Oct	5.78	5.91	31.62	27.57	79.94	78.09	4.42	4.85	32.71	34.15
Nov	6.33	5.70	30.94	28.01	62.63	78.27	4.42	4.74	57.20	42.70
Dec	9.67	5.45	49.50	28.16	89.12	78.27	4.08	4.97	67.71	48.93

AV Actual value, *PV* Predicted value

development has not been continuously distributed throughout the city during these ten years.

3.2 Correlation analysis

Table 4 shows the relationships between sulfur dioxide and PM$_{2.5}$, PM$_{10}$, RH, WS using the average Pearson correlation coefficient (r). The results indicated that the Sulfur oxides, in combination with particulate matter and relatively high relative humidity, have the strongest negative impact on the environment (P value > 0.05) (Schwartz 1996; Asadifard 2013). While the concentration of sulfur oxides decreases with increasing wind speed (P value < 0.05) (Unal et al. 2000). Venners et al. (2003) also investigated the concentration of sulfur oxides in Chongqing, China, showing that there is a positive correlation between sulfur dioxide concentrations and particulates (either PM$_{2.5}$ and PM$_{10}$) concentrations. wind speed (WS) has a negative correlation with PM$_{2.5}$ and PM$_{10}$ concentrations ($r = -0.808$ and -0.496 respectively). In addition, a significant positive correlation was observed between PM$_{2.5}$ and PM$_{10}$, which shows that PM$_{2.5}$ and PM$_{10}$ have the same origin ($r = 0.561$).

3.3 Results of the ARIMA model

For the purpose of time series modelling in this study, the first 12 observations (January 2020 to December 2020) were used to fit the ARIMA model while the subsequent 7 observations (from January 2021 to July 2021) were kept for the post sample forecast accuracy check. As presented in Table 5, the value of SO$_2$ is decreases till the ARIMA (3,1,4) but at ARIMA (2,1,4) it again increases. So, the smallest significant value of SO$_2$ for the ARIMA process is

at ARIMA (3,1,4). So, we may conclude that the ARIMA (3, 1, 4) gives better results on forecasting the concentration of sulfur dioxide. Pohoata and Lungu (2017) also used the ARIMA model to forecast SO$_2$ concentration in Ploiesti, Romania, showing that the best result was obtained with ARIMA (3, 1, 3). Das et al. (2019) also showed the best fitted ARIMA (p, d, q) was selected on the basis of the maximum value of R^2 and minimum value of RMSE. Similarly, ARIMA (2, 1, 3), ARIMA (3, 2, 3), ARIMA (3, 1, 4) and ARIMA (3, 1, 3) are the best model for predicting the concentration of PM$_{2.5}$, PM$_{10}$, relative humidity and wind speed, respectively. The ARIMA model was able to predict the 7 months from 2021 relatively accurately, with only 1 year (2020) of data (Table 6). The ARIMA statistical forecasting method did not provide satisfactory results to predict PM$_{10}$ concentrations in 2021, the relative errors are bigger than 10% (Fig. 4c). The forecasting of the PM$_{10}$ concentrations is difficult because of the uncertainties in describing the meteorological conditions and emission variability (Zhang et al. 2017). This error rate may be associated with a rapid change in wind direction. The prevailing wind flows from the west in Tehran. main winds from west, south and southwest which are industrial places are the main sources of Tehran air pollution (Borhani et al. 2017, 2021b). The increasing error in forecasting is due to the unpredictability of new trends that may occur in the future. In April 2021 prediction for SO$_2$ concentration, the Actual Value was 4.68 ppb, while the Predicted Value was 4.61 ppb, a difference of 0.07 ppb. For the data corresponding to SO$_2$, PM$_{2.5}$, WS and RH time series, the determination coefficient (R^2) and RMSE equal to (0.74, 2.18), (0.73, 9.49), (0.88, 0.67) and (0.82, 9.66), respectively (as can be seen in Fig. 4a–e and
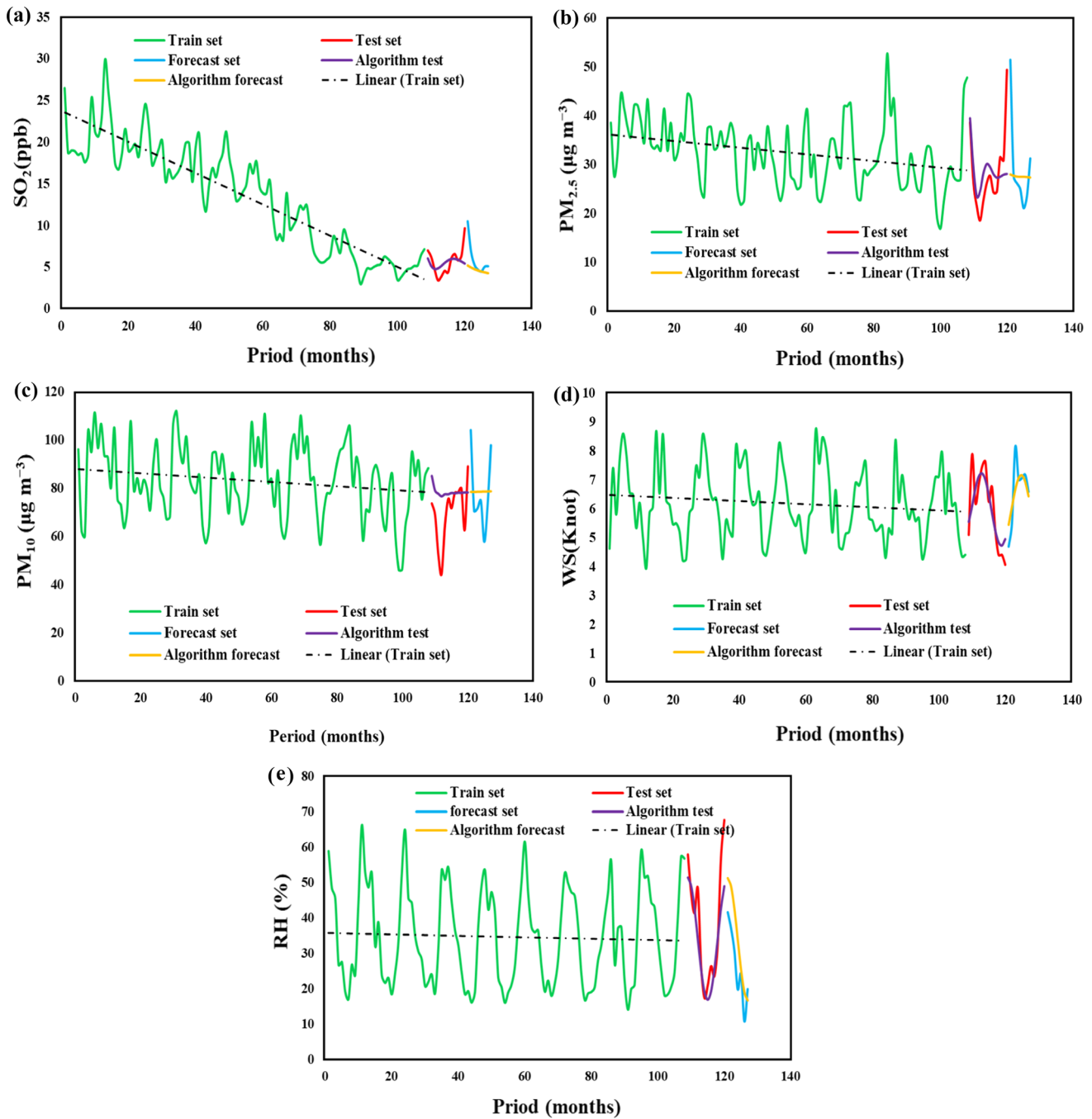
Fig. 4 Time-series analysis (Train set,Forecast set, Algorithm forecast, Test set and Algorithm test) model in air quality monitoring stations in Tehran from 2011 to 2020, **a** SO₂, **b** PM₂.₅, **c** PM₁₀, **d** WS, **e** RH

Table 7). Therefore, the ARIMA model provided satisfactory results.

In general, the ARIMA model is the most suitable model for predicting unexpected values, but drastic changes in the data and, of course, the monthly step and averaging have caused a high error for some pollutants, even when the noise has been removed.

4 Conclusion

The paper presents the results of comparative analysis of measuring and monitoring the concentration of sulfur dioxide, based on, the changes in sulfur dioxide concentration due to changes in particulates (either PM_{10} and $PM_{2.5}$) concentrations and meteorological conditions (relative humidity and wind speed) in the air in the city of

Table 7 Comparison of model predictions and actual values for average monthly SO$_2$, PM$_{2.5}$ and PM$_{10}$ concentration and RH and WS in Tehran from January 2021 to July 2021 (Algorithm forecast)

Month	SO$_2$(ppb)		PM$_{2.5}$ (μg m^{-3})		PM$_{10}$ (μg m^{-3})		WS (Knot)		RH (%)	
	AV	PV	AV	PV	AV	PV	AV	PV	AV	PV
Jan	10.53	5.19	51.47	27.98	104.12	78.41	4.70	5.46	41.60	51.18
Feb	6.84	4.96	27.65	27.72	70.63	78.44	5.51	6.08	37.00	48.84
Mar	5.26	4.76	26.23	27.58	71.75	78.56	8.15	6.68	30.70	42.54
Apr	4.68	4.61	25.00	27.56	74.81	78.61	7.02	7.09	19.80	33.95
May	4.47	4.49	21.18	27.55	57.81	78.71	7.07	7.18	24.20	25.35
Jun	5.05	4.39	23.67	27.51	72.69	78.77	7.18	6.94	10.70	19.03
Jul	5.10	4.29	31.33	27.42	97.94	78.86	6.59	6.44	19.90	16.67
R^2	0.74		0.73		0.10		0.88		0.82	
RMSE	2.18		9.49		15.22		0.67		9.66	

AV Actual value, *PV* Predicted value, *R^2* Determination coefficient

Tehran from 2011 to 2020. In this study used an ARIMA modelling approach for short-term forecasting Sulfur dioxide (SO$_2$), Particulate Matter (PM$_{10}$ and PM$_{2.5}$) concentrations, and meteorological conditions (relative humidity and wind speed). According to the measurements results of SO$_2$, PM$_{10}$ and PM$_{2.5}$ concentrations from 21 monitoring stations of Air Quality Control Company in Tehran and the data of Mehrabad Meteorological Station (RH and WS), it can be deduced, average SO$_2$, PM$_{10}$, and PM$_{2.5}$ concentrations have decreased significantly over the past decade. And as for the seasonal concentrations, SO$_2$ concentrations in the air are increased in the winter, which is affected not only by weather but also by other pollutants (production of thermal energy for city heating, combustion of fuel oil in power plants, small boiler rooms for certain economic entities, companies, old vehicles, etc.). The results show that the monthly concentration of sulfur dioxide is lowest in June and highest in January. The distribution of annual average concentration in air quality monitoring stations shows that the highest average SO$_2$ concentration in zoning map is related to the north and southwest of Tehran. The Correlations of SO$_2$ with PM$_{2.5}$ and PM$_{10}$ and with relative humidity and wind speed were examined using Pearson correlation. The results showed that SO$_2$ has a positive and significant correlation with PM$_{2.5}$, PM$_{10}$ and relative humidity and a negative correlation with relative wind speed. These results come from the fact that more than 80% of sulfur oxides are produced by burning fossil fuels from stationary pollution sources, followed by the most important cause of particulate matter emissions, the high volume of traffic in Tehran. The Alborz Mountains have made Tehran's climate very humid and as a result, sulfur oxides combined with suspended particulate matter and humidity have the most harmful effects on air pollution in Tehran.

However, for quality improvement, it is necessary to take many additional measures, such as the expansion of the public transport system, especially the metro system, the establishment of technical control centers and the obligation of technical inspection of vehicles, the control and monitoring of car traffic, especially in the last hours of the night, the change of fuel consumption of suburban power plants and the monitoring of pollution standards, and better distribution of fuel for intercity buses, because without this update, no concrete measures can be taken to reduce SO$_2$.

In addition, relatively accurate prediction of air pollutant concentrations, both short and long term, is an important step in mitigating the damage causes of poor air quality. For example, public and private institutions can plan for the economic, health and environmental impacts of air pollution by predicting the period when air pollution levels may be particularly high.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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