Asian Journal of Water, Environment and Pollution, Vol. 15, No. 2 (2018), pp. 79–87.
DOI 10.3233/AJW-180020

Air Pollution Effects on Climate and Air Temperature of Tehran City Using Remote Sensing Data

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Received August 10, 2017; revised and accepted January 19, 2018

Abstract: It is difficult to demonstrate air pollution spatial distribution as it is related to weather conditions, location, topography, and the area. Air pollution is studied by remote sensing techniques less than other techniques due to lack of sensors capable of detecting emissions, and hence, Aerosol Optical Depth (AOD) method is used for investigation. Aerosol optical depth is a measure of the extinction of the solar beam by dust and haze. In this study, the linear regression analysis was used to develop a relationship between AOD measures by MODIS and daily air pollution (CO, O_3, NO_2, SO_2 and $PM_{2.5}$) in six consecutive years (2011-2016) at 22 stations in Tehran. Matrix correlation between AOD values and air pollution parameters indicated a significant relationship for O_3 and NO_2 with regression squared from 0.631 to 0.764, respectively. Linear regression between AOD and the parameters was separately developed and pollution maps were produced for CO, O_3, NO_2 and $PM_{2.5}$ parameters within 2011-2016. Spatial distribution map of the aforementioned gases revealed that NO_2 and CO were higher than the regular standards in the studied region during 2011-2016; $PM_{2.5}$ was desirable in the northern areas; however, its concentration was larger than the standard level in southern and central regions. Comparison of pollution maps and land surface temperature (LST), picked up by MODIS satellite, indicated that the correlation between $PM_{2.5}$ and temperature is $R = 0.55$; in addition, it largely influences higher air pollution increases in Tehran comparing other gases.

Key words: Air pollution, aerosol optical depth (AOD), MODIS satellite, $PM_{2.5}$.

Introduction

One of the most important environmental risk parameters to human life is air pollution (WHO, 2013). Some green-house gases and particulate pollution with diameters less than 2.5 μm ($PM_{2.5}$) is not only dangerous to human life, but also impacts visibility and contributes to climate change (Feng et al., 2016).

According to analyzed aerosol optical and physical properties in Kolkata as an urban environment during winter monsoon pollution transport, the values of low temperature and wind speed, and a strong downdraft of air mass, indicated weak dispersion and inhibition of vertical mixing of aerosols. A comparison of ground-based observations with MODIS data indicated an underestimation of MODIS AOD and Angstrom parameter (α) values for most of the days (Verma et al., 2014).

Objective of this study is to estimate air quality parameters in Tehran (CO, O_3, NO_2, SO_2 and $PM_{2.5}$) using optical depth information of particle sensor MODIS (MODIS-AOD) and creating regressions between air quality parameters (as dependent variables) and AOD parameter (as independent variable), and to analyze the impact of air pollution in Tehran temperature. To achieve this goal, according to

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information of Tehran air pollution, polluted days were selected. By selecting AOD images of these days, air quality and AOD regressions were established; then, spatial distribution map of air pollution was developed through regression equations. Finally, the relationship between air pollution parameters and land surface temperature (LST) of MODIS images were examined to investigate air pollution effects in Tehran temperature.

Methodology

Case Study

The area studied in this paper is Tehran with about 730 square kilometres. Industrial development, population growth, urban development, as well as transportation development caused Tehran air pollution as one of the most critical challenges. Accordingly, there were 21 clean days (6%), 233 healthy days (64%), 105 unhealthy days for sensitive groups of society (29%), five unhealthy days for general population (over 1%), and one very unhealthy day (less than 1%) in Tehran in 2015. Figure 1 shows location of Tehran, measurement stations, and air monitoring in Tehran used in this study.

Data Measured for Air Pollutants

The study used Tehran air pollution data in 2011-2016 measured at 22 active air monitoring stations. Table 1 represents average monthly parameters at intervals of 2011 to 2016.

Aerosol Optical Depth Data of MODIS Sensor (MODIS-AOD)

Two sensors of MODIS were installed on EOS-Terra and EOS-Aqua satellites in December 1999 and 2002. Both sensors collected AOD data with a spatial resolution of 10 km. The amount of existing AOD in the atmosphere obtained by the help of MODIS particle algorithm over oceans (Tanré et al., 1997) and over land surfaces (Gopal et al., 2016; Levy et al., 2010). In recent years, existing algorithms were more accurate; numerous studies revealed that MODIS-AOD products are more accurate than AOD measured on ground (You et al., 2016; Wang and Christopher, 2003; Li, 2016). Terra and Aqua satellites are passing over Tehran at 10:30 and 13:30 local time, respectively. The study used the data collected by the two MODIS sensors during

Table 1: Average monthly parameters at intervals of 2011 to 2016

	Month											
Parameters	*March*	*April*	*May*	*June*	*July*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*
CO (ppm)	34	35	34	39	39	36	45	40	44	43	41	37
O_3 (ppb)	31	34	38	48	56	43	31	23	20	22	24	30
NO_2 (ppb)	57	58	52	62	69	60	60	53	60	66	65	56
SO_2 (ppb)	22	22	22	25	26	25	23	22	25	27	25	21
$PM_{2.5}$ (μg/m^3)	58	82	100	100	80	88	84	84	111	108	89	84

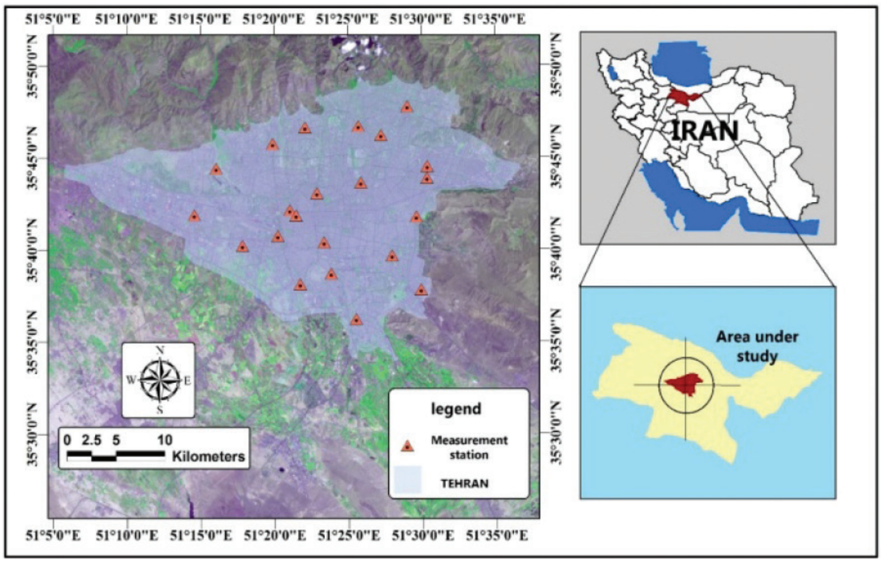

Figure 1: Location of Tehran in Iran, measurement stations, and air monitoring in Tehran.

the day. AOD (MOD04) product was also used at a wavelength of 550 nm.

MODIS Sensor (MOD11A2) Land Surface Temperature (LST)

Daily land surface temperature (LST) data of MODIS sensor (MOD11A1) with a spatial resolution of 1 km was used to investigate Tehran temperature changes in comparison to air pollution changes in the polluted days.

Development of Regression Models

Once the required data including satellite images and information of measurement stations were collected, it was necessary to individually calculate each pollution parameter map and to investigate the pollution effect on temperature changes. To achieve this purpose and to provide air pollution parameters' map, the regression relationship between pollution parameters and MODIS-AOD was used; moreover, the regression relationship between air pollution data at measurement stations and MODIS-AOD images of that day was developed, too. Information gathered on pollution measurement stations included CO, O_3, NO_2, SO_2 and $PM_{2.5}$. Components of air pollution in the first phase were considered as dependent variables in the regression analysis and independent variables in the second phase. Therefore, multiple regression equation is as follows:

1. Linear relationship between AOD as dependent variable and CO, O_3, NO_2, SO_2, $PM_{2.5}$ air pollution as independent variable.
2. The relationship between CO parameter as dependent variable and AOD as independent variable.
3. The relationship between O_3 parameter as dependent variable and AOD as independent variable.
4. The relationship between NO_2 parameter as dependent variable and AOD as independent variable.
5. The relationship between SO_2 parameter as dependent variable and AOD as independent variable.
6. The relationship between $PM_{2.5}$ parameter as dependent variable and AOD as independent variable.

Regression equations were separately developed for each parameter and eventually air pollution map was prepared for each parameter based on the developed relationship. Accuracy of developed regression equations was verified using correlation coefficient (R^2); furthermore, other statistical parameters including standard error of the estimate, *f*-statistics, and *t*-significance were also evaluated.

Results

Selecting the Polluted Days

Air Quality Index (AQI) was applied to select the polluted days used in regression models. Regarding mentioned air pollution standards, whenever air quality index exceeds 150, the air quality is unhealthy and the values of 301 to 500 imply dangerous air quality condition. Accordingly, from 2011 to 2016, days with air quality index above 150 were selected as polluted days. Table 2 illustrates data of downloaded images.

Table 2: The characteristics of downloaded data for 11 selected days (spatial resolution 10 km and image dimension (Pixels)203×135)

11 selected days with air quality index above 150										
14.04.2011	04.06.2011	13.06.2011	14.03.2012	22.04.2012	16.05.2012	26.05.2012	05.12.2015	08.10.2013	01.07.2014	01.09.2015

Developing Regression Models

This section describes how to develop the relationship between Aerosol Optical Depth (AOD) and the collected air pollution data. To do this, the linear regression between the measured amounts of pollution parameters' time series on the same days with AOD images downloaded within 2011-2016 was used to find the relationship between the measured information and AOD. The information gathered on pollution measurement stations including CO, O_3, NO_2, SO_2 and $PM_{2.5}$ in the first phase were considered as dependent variables in the regression analysis and as independent variables in the second phase.

Linear Relationship between AOD and Air Pollution Parameters

The relationship between air pollution data as the independent variables and AOD as the dependent variable was examined. Several methods were studied to find the best fit between air pollution parameters and AOD. Independent variables were verified through using stepwise regression method. In the first phase, all five parameters (CO, O_3, NO_2, SO_2 and $PM_{2.5}$) were considered together. According to evidences, there was not any relation between SO_2, and AOD and other parameters; therefore, SO_2 was eliminated and stepwise regression was performed for the four remaining parameters. Table 3 shows summarized stepwise regression results statistically. As seen, any increase in variable stepwise regression model intensifies R^2 and R^2-adjusted values. Changes in F-statistic, which is less than 0.05 at different stages of stepwise regression, indicates that the parameters entered into the regression model are well able to express changes in dependent variable (AOD).

Table 4 indicates coefficients and constants of air pollution and AOD obtained by different regression models through stepwise regression. T-statistic values in all models with an absolute value larger than 2.33 and the significance level of less than 0.05 reflected statistically significant effect of all independent variables on changes in the dependent variable. Finally, the fourth model in Table 4 with $R^2_{adjusted} = 0.88$ was selected as the best relationship between air pollution and AOD (Eq. 1).

$$AOD = 0.005 \times NO_2 + 0.002 \times PM_{2.5} + 0.004 \times CO + 0.002 \times O_3 - 0.534 \quad (1)$$

AOD Relationship with Other Parameters

Tables 5 and 6 summarize linear regression models fitted between AOD as independent variable and air pollution parameters (CO, O_3, NO_2, SO_2 and $PM_{2.5}$) as dependent

Table 3: Summarized stepwise regression results statistically

Model	*R*	*R^2*	*$R^2_{Adjusted}$*	*Std. error of the estimate*	*Change statistics*				
					R^2 change	*F change*	*df1*	*df2*	*Sig. F change*
1	0.764[a]	0.584	0.563	0.14797121	0.584	28.057	1	20	0.000
2	0.911[b]	0.830	0.812	0.09716978	0.246	27.379	1	19	0.000
3	0.937[c]	0.878	0.858	0.08442907	0.049	7.167	1	18	0.015
4	0.954[d]	0.910	0.888	0.07480153	0.032	5.932	1	17	0.026

[a]Predictors: (Constant), NO_2
[b]Predictors: (Constant), NO_2, $PM_{2.5}$
[c]Predictors: (Constant), NO_2, $PM_{2.5}$, CO
[d]Predictors: (Constant), NO_2, $PM_{2.5}$, CO, O_3

Table 4: Coefficients and constants of air pollution parameters and AOD

	Model	*Unstandardized coefficients*		*Standardized coefficients*	*t*	*Sig.*
		B	*Std. error*	*Beta*		
1	(Constant)	-0.264	0.109		-2.414	0.026
	NO_2	0.008	0.002	0.764	5.297	0.000
2	(Constant)	-0.489	0.084		-5.842	0.000
	NO_2	0.006	0.001	0.589	5.857	0.000
	$PM_{2.5}$	0.003	0.000	0.526	5.233	0.000
3	(Constant)	-0.530	0.074		-7.129	0.000
	NO_2	0.006	0.001	0.537	5.999	0.000
	$PM_{2.5}$	0.002	0.000	0.400	4.032	0.001
	CO	0.004	0.002	0.267	2.677	0.015
4	(Constant)	-0.534	0.066		-8.106	0.000
	NO_2	0.005	0.001	0.432	4.795	0.000
	$PM_{2.5}$	0.002	0.000	0.363	4.076	0.001
	CO	0.004	0.001	0.271	3.063	0.007
	O_3	0.002	0.001	0.214	2.435	0.026

variable and models' coefficients, respectively. According to Table 5, the developed regression model between AOD and CO estimates CO through $R^2 = 0.65$. The results of AOD values and O_3 regression model imply that AOD is able to obtain the amounts of ozone through $R^2 = 0.57$. The coefficient of determination between AOD and NO_2 is also equal to $R^2 = 0.58$. However, there was seen no significant relationship between AOD and SO_2; therefore, AOD developed regression model fails to estimate SO_2 ($R^2 = 0.36$). The results of fitting AOD and $PM_{2.5}$ linear regression model reveal that AOD accurately approximates the values of these parameters ($R^2 = 0.59$).

Table 5: Summarize linear regression models fitted between AOD and air pollution parameters

Model	*R*	*R square*	*Adjusted R square*	*Std. error of the estimate*
1	0.8065[a]	0.650	0.647	8.23256
2	0.7586[b]	0.575	0.571	10.28956
3	0.7637[c]	0.583	0.579	17.78831
4	0.6018[d]	0.361	0.353	9.96230
5	0.7729[e]	0.596	0.590	26.31823

[a]Dependent variable: CO
[b]Dependent variable: O_3
[c]Dependent variable: NO_2
[d]Dependent variable: SO_2
[e]Dependent variable: $PM_{2.5}$

Thus, the following relationships are computed between AOD and air pollution parameters with the highest correlation:

$$CO = 58.491 \times AOD + 9.172 \quad (2)$$

$$O_3 = 63.922 \times AOD + 12.819 \quad (3)$$

$$NO_2 = 104.360 \times AOD + 12.792 \quad (4)$$

$$PM_{2.5} = 188.958 \times AOD + 68.551 \quad (5)$$

The relations between AOD and other parameters have been shown in Figure 2.

Spatial Distribution of Pollution Parameters

Pollution maps extracted by MODIS-AOD display more detailed information about spatial distribution of air pollution parameters comparing measurements of measuring stations merely providing point information of air pollution. Therefore, the linear regression equations fitted between AOD and air pollution parameters were used to estimate the spatial distribution of each parameter. Figure 3 represents spatial distribution of pollution parameters from 2011 to 2016. The results indicated that Tehran during this period had an unhealthy condition (at a standard of 9.4 ppm) with minimum and maximum amount of carbon monoxide emissions of 32.18 ppm and 38.32 ppm, respectively. In general, central and northern regions of Tehran experienced the largest concentration of the pollutants gradually reduced in terms of severity moving to the south (Figure 3a).

Table 6: The coefficients of stepwise regression models between AOD and air pollution parameters

		Unstandardized coefficients		*Standardized coefficients*		
	Model	*B*	*Std. Error*	*Beta*	*t*	*Sig.*
1	(Constant)	9.172	1.808		5.074	.000
	AOD	58.491	3.935	.806	14.862	.000
2	(Constant)	12.819	2.126		6.028	.000
	AOD	63.922	5.337	.758	11.978	.000
3	(Constant)	12.792	3.592		3.561	.001
	AOD	104.360	8.270	.763	12.620	.000
4	(Constant)	16.984	2.031		8.364	.000
	AOD	29.633	4.410	.601	6.719	.000
5	(Constant)	68.551	9.735		7.042	.000
	AOD	188.958	18.992	.772	9.949	.000

1. Dependent Variable: CO
2. Dependent Variable: O_3
3. Dependent Variable: NO_2
4. Dependent Variable: SO_2
5. Dependent Variable: $PM_{2.5}$

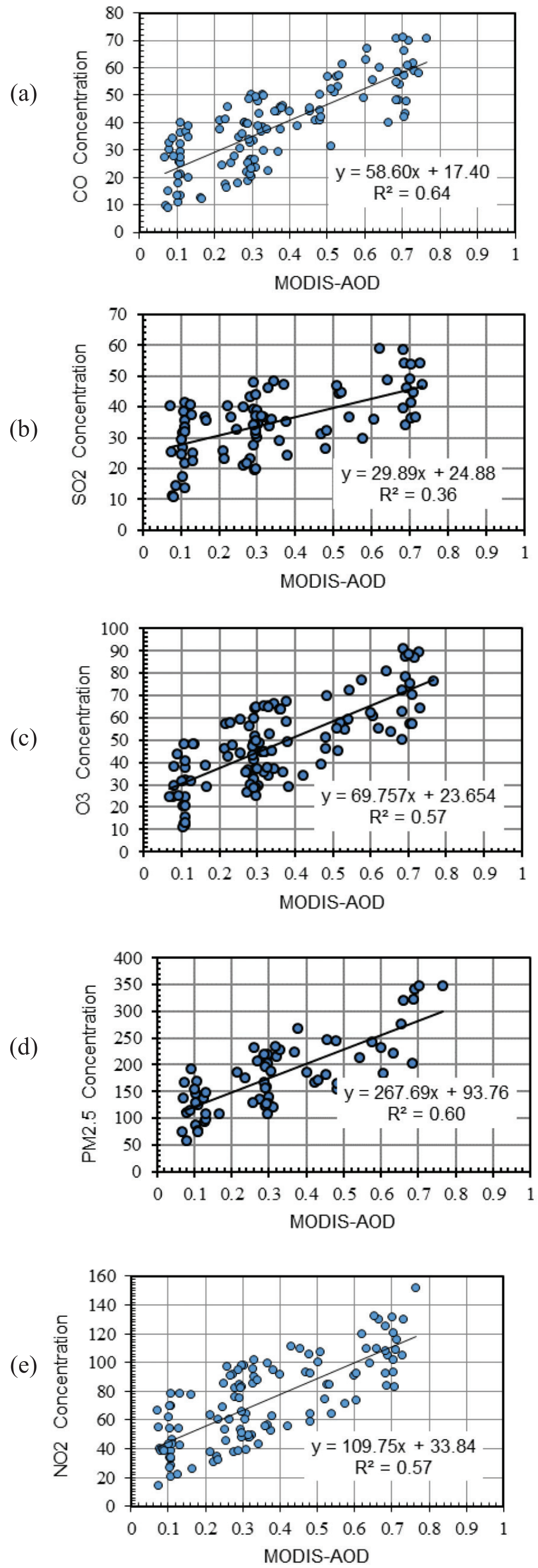

Figure 2: The relation between MODIS-AOD and pollution parameters (a: CO, b: SO_2, c: O_3, d: $PM_{2.5}$, e: NO_2).

Respecting to NO_2 pollutants, unlike the situation in CO pollutant, the minimum concentration is seen in the northern regions; whereas, southern regions showed the maximum. But overall, according to the standard for this gas (annual standard of 21 ppb), the pollutant concentration with minimum and maximum of 34.93 ppb and 49.52 ppb, respectively was in unhealthy conditions for all regions (Figure 3b). Ozone gas concentration is quite different from other air pollution parameters in terms of the place so that it decreases from east to west. It was in standard conditions with the minimum and maximum concentration of 29.38 ppb and 31.97 ppb and according to the existing standard limit of 75 ppb (Figure 3c). According to Figure 4d showing concentration of $PM_{2.5}$ floating aerosols and also considering the standard limit of this gas (35 µg/m^3), it is observed that concentration of this pollutant in northern areas was less than the standard; whereas, it exceeded the standard in southern and central areas of Tehran. According to Figure 2, it concluded that central and southern regions of Tehran are more affected by pollutants such as NO_2 and $PM_{2.5}$ because of higher traffic and industrial estates mainly located in this area of Tehran. However, CO_2 concentration was higher in northern regions unlike the other two mentioned pollutants signifying complexity of studying the pollutants that are influenced by factors such as weather conditions and regional transportation. Thus, further research is needed to allow better examination of air pollution parameters. To do this, it is better to combine AOD concentration with other climate parameters to develop better models for studying pollution parameters. Overall, the model presented in this study provides acceptable accuracy for estimating the pollution parameters and their distribution, which can be used in areas with no measurement stations.

Mutual Relationship between Temperature and Pollution Parameters

Daily land surface temperature (LST) of MODIS sensor (MOD11A1) with a spatial resolution of 1 km was used to investigate the effect of pollution on climate change in Tehran. For this purpose, air pollution maps were used in the most polluted days in 2011 to 2016 (April 13th, 2012 with AQI 278). Thus, April 13th LST map was downloaded and the relation between LST map pixels was plotted for any pollution parameter. Then, spatial variation pollution trend was compared to global spatial variation of surface temperatures. Fig. 4 shows plotted distribution graphs.

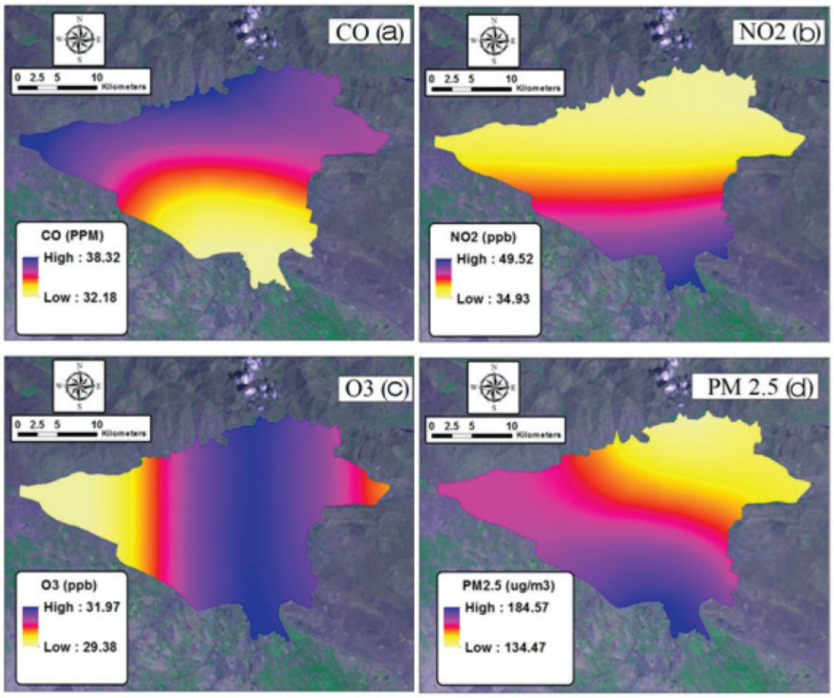

Figure 3: Spatial distribution of average pollution parameters during 2011-2016 (a: CO, b: NO_2, c: O_3, d: $PM_{2.5}$).

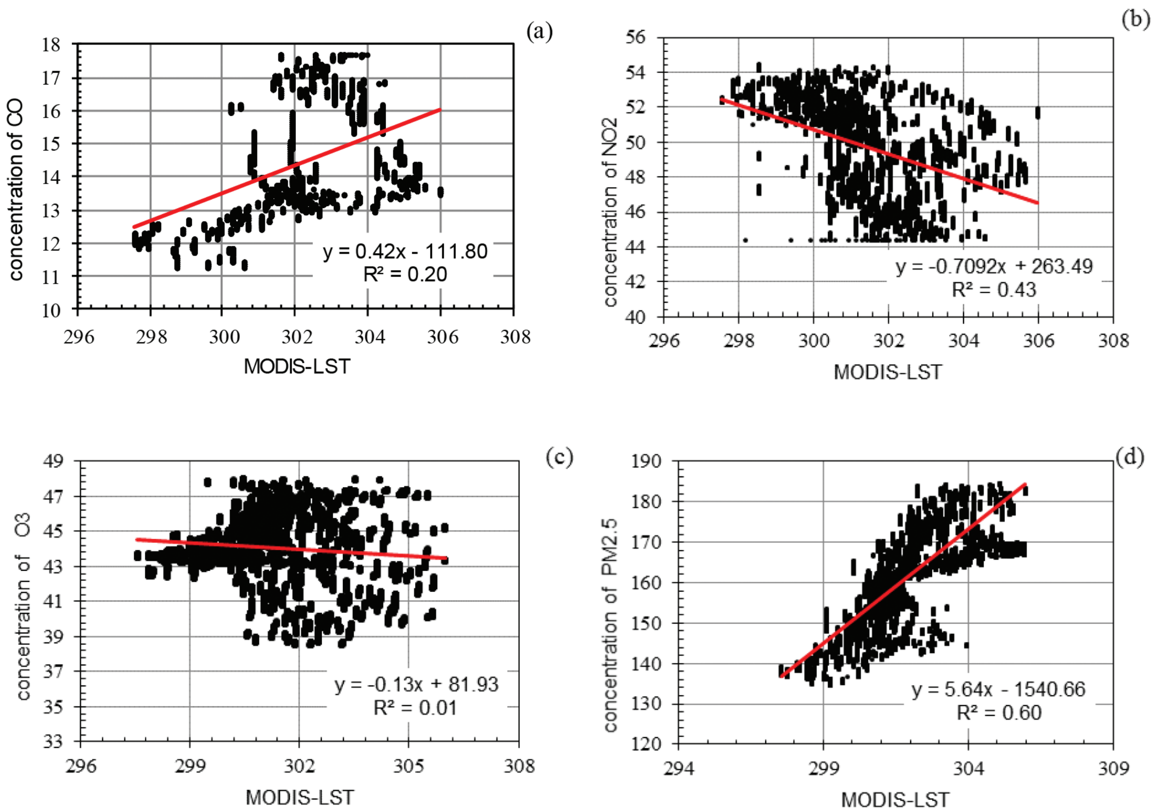

Figure 4: Plotted distribution graphs between LST and air pollution parameters (a: LST and CO, b: LST and NO_2, c: LST and O_3, d: LST and $PM_{2.5}$).

As seen in Figure 4, CO and $PM_{2.5}$ showed a positive relationship with the temperature measured by MODIS sensor as $R^2 = 0.45$ and $R^2 = 0.55$. Conversely NO_2 and O_3 with correlation values of $R^2 = 0.43$ and $R^2 = 0.01$, respectively, are negatively correlated with LST. According to R^2 square parameter, particulate matter $PM_{2.5}$ revealed the greatest impact on air temperature playing a significant role in increasing Tehran temperature. In contrast, increasing ozone concentration showed no obvious effect on air temperature. Negative relationship between NO_2 concentrations and air temperature denoted that this gas is increased by cooling and temperature reduction. This can happen due to inversion phenomenon. The results of the spatial distribution of air pollution parameters in Tehran showed that maps derived from regression equations developed by AOD (for the computation of pollution) can be carefully used for spatial variation of pollution changes as well as changes in temperature.

Discussion and Conclusion

Satellites are increasingly used for studying air pollution parameters. The main objective of this study was to assess air pollution in Tehran through satellite imagery and to introduce pollution parameter maps to develop regressions between satellite images and measured information in measuring stations. To this end, MODIS-AOD data and the measured concentrations of various pollutants (CO, O_3, NO_2, SO_2 and $PM_{2.5}$) in Tehran pollution monitoring stations were used within 2011-2016. Altogether, 11 polluted days in the given interval were selected and MODIS-AOD images were used on the 11-day download to develop regression models. The results of the correlation matrix between listed pollutants and AOD values showed that air pollution parameters have a positive significant correlation with AOD at confidence level of 0.001; meanwhile NO_2 and O_3 with $R^2 = 0.764$ and $R^2 = 0.631$, showed the highest and lowest correlation with AOD values, respectively. For further analysis of the relationships between pollutants and AOD values, stepwise multiple regression models were used to find the best fit between air pollution parameters as independent variables and AOD as the dependent variable. Research findings demonstrated that if AOD values depend on the amount of gas pollutants, SO_2 may impose no effect on the relationship between AOD and other parameters; further, AOD as dependent variable is simultaneously connected to just four other parameters (CO, O_3, NO_2 and $PM_{2.5}$).

In the next step, linear regression models between any single pollutant as the dependent variable and MODIS-AOD values as independent variables were developed and each model was evaluated by correlation coefficient (R^2), *f*-statistics, and *t*-significance. The results of this work exhibited that AOD is enabled to accurately estimate the values of CO, O_3, NO_2, and $PM_{2.5}$, as the lowest coefficient of determination is corresponding to O_3 with $R^2 = 0.57$ and the highest to CO with $R^2 = 0.64$. A separate linear relationship was established between AOD values and pollutants; then, the relationship was used for pollution map. The spatial distribution of pollution parameters was mapped within 2011-2016. The results described much higher concentrations of NO_2 and CO in this period at all regions of Tehran than the standard and unhealthy conditions. $PM_{2.5}$ particulate matter concentration in northern areas was less than standard; while, in southern and central areas, it exceeded standard limits and just ozone was in standard conditions in Tehran.

Comparison of air pollution parameters with maps of land surface temperature (LST) measured by MODIS on the most polluted day (13 April 2012) in the studied period showed that $PM_{2.5}$, among the pollutants, with the correlation coefficient of $R^2 = 0.55$ had the greatest effect on air temperature in Tehran. CO with a correlation coefficient $R^2 = 0.20$ has the greatest impact on rising temperatures after the particulate matter. Increased NO_2 and O_3 were inversely related to changes of temperature rise. O_3 with a correlation coefficient $R^2 = 0.01$ was the only parameter showing no impact in temperature increasing or decreasing.

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Asian Journal of Water, Environment and Pollution

Volume 15 Number 1 **January – March, 2018**

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