Human, Forest and vegetation health metrics of ground-level ozone (SOMO35, AOT40f and AOT40v) in Tehran Human, Forest and vegetation health metrics of ground-level ozone (SOMO35, A...

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RESEARCH ARTICLE

Human, Forest and vegetation health metrics of ground-level ozone (SOMO35, AOT40f and AOT40v) in Tehran

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Abstract

Purpose We aimed to investigate the spatial O_3 indices (SOMO35: annual sum of maximum daily 8-h ozone means over 35 ppb, AOT40: the accumulated exposure over an hourly threshold of 40 ppb during daylight hours between 8:00 and 20:00 in the growing seasons of plants) in Tehran (2019–2020).

Methods The data of ambient O_3 concentrations, measured at twenty-three regulatory ambient air quality monitoring stations (AQMSs) in Tehran, were obtained.

Results The annual mean O_3 concentrations were found to be 15.8–25.7 ppb; the highest and lowest annual mean concentration of ambient O_3 were observed in Shahrdari 22 and Shahr-e-Rey stations, respectively. Spatial distribution of exposure to O_3 across Tehran was in the range of 1.36–1.64; the highest O_3 concentrations were observed in the northern, west and south-western parts of Tehran, while the central and south areas of Tehran city experienced low to moderate concentrations. The indices of SOMO35, AOT40f and AOT40v across AQMSs in Tehran was in the range of 1830–6437 ppb. Days, 10,613–39,505 ppb.h and 4979–16,804 ppb.h, respectively. For Tehran city, the indices of SOMO35 and AOT40f were 4138 ppb. days and 27,556 ppb.h respectively. Our results revealed that the value of SOMO35 across AQMSs of Tehran was higher than the recommended target value of 3000 ppb. days.

Conclusions To reduce O_3 pollution and its effects on both human and plants health, the governmental organizations should take appropriate sustainable control policies.

Keywords Ground-level ozone · Ozone-exposure metrics · SOMO35 · AOT40 · Tehran

Introduction

As a powerful oxidizing and phytotoxic air pollutant, ground-level ozone (O_3) is widely known with detrimental effects on the human health, forest trees and crops [1, 2]. Global background tropospheric O_3 level has doubled during the twentieth century following the increased production of its precursors (e.g. nitrogen oxides and volatile organic compounds) [3–5]. Unlike fine particulate matter, ambient O_3 air pollution is invisible and may be exist when the sky is blue and clear [6]. As O_3 concentration incredibly increases within spring and summer seasons, this secondary major air pollutant is pronounced an important environmental issue in urban areas [2, 6–8]. In 2015, the Global Burden of Diseases (GBD) study estimated that ambient O_3 caused 254,000 deaths globally, making it the 33rd ranking risk factor for premature deaths [7, 9]. However, Malley et al., (2017) estimated the long-term health effects of O_3 with updated risk factor and reported that previous analyses have underestimated this value; the true premature deaths

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could be over one million cases per year globally [9]. In addition, previously conducted studies in Tehran have reported that the number of respiratory premature deaths attributable to ambient O_3 in Tehran was ranged from 85 (95% CI: 31, 144) in 2006 to 54 (95% CI: 20, 92) in 2015 [7]. The study of Hadei and colleagues estimated the number of deaths attributed to ambient O_3 was 1363 over March 2013–March 2016 in Tehran [10]. Furthermore, it has been reported that long- and short-term exposures to the high concentration of this important environmental risk factor may lead to the irritation of eyes, adverse impacts on respiratory system including declining lung capacity, difficulty in breathing, aggravation of asthma, cough, and even various respiratory infections [11, 12]. The adverse effects of O_3 on forest and agricultural crops consist of accelerated crop senescence, increased stomatal resistance, decreased photosynthesis rata and crop yields [13]. To better estimate the risk assessment of O_3, several indices have been suggested by previous studies for human (SOMO35: annual sum of maximum daily 8-h ozone means over 35 ppb), forest trees and vegetation/crops (AOT40: the accumulated exposure over an hourly threshold of 40 ppb during daylight hours between 8:00 and 20:00 in the growing seasons) [3, 14, 15]. To date, numerous studies have been carried out in Tehran investigating various issues of ambient air pollution [16, 17]. Little, however, is known about the aforementioned O_3 indices in Tehran. Therefore, this study designed for the first time, to investigate the spatial O_3 indices (SOMO35, AOT40f and AOT40v) in Tehran during the period March 21, 2019 to March 19, 2020.

Materials and methods

Ambient O_3 monitored data

We obtained (https://airnow.tehran.ir/home/DataArchive.aspx) the real-time hourly data of ambient O_3 concentrations over the period March 21, 2019 to March 19, 2020 from all the twenty-three ambient air quality monitoring stations (AQMSs) throughout different districts of Tehran (Fig. 1) belonging to Tehran Air Quality Control Company (TAQCC). In order to remove the outlier air quality data at temporal level by using z-scores approach, only AQMSs with more than 75% completeness of the total hours over a year (≥ 6570 recorded data) were pre-processed [7, 16, 18]. As listed in Table 1, 17 stations have recorded more than 75% of hourly O_3 concentrations for the year 2019–2020. The hourly ambient O_3 data were transformed into standard z-scores and removed when the following three conditions met: (1) having an absolute z score larger than 4 ($|Z_t| > 4$), (2) the increment from the previous value being larger than 6 (Z_t - $Z_{t-1} > 6$), (3) the ratio of the value to its centered rolling mean of order 3 (RM3) being larger than 2 (Z_t / RA3 $(Z_t) > 2$) [18–22]. After the screening, all AQMSs with >75% of the hourly data over the year were used for further calculation because less than 0.1% of O_3 data for each station was removed from the dataset and subsequent calculations.

Calculation of O_3 metrics

Human health metrics

Based on the epidemiological studies and recommended by World Health Organization (WHO), SOMO35 (Sum of Ozone Means Over 35 ppb) is considered as a relevant metric for health effect assessment of long-term exposure to ambient O_3 [7, 14, 23]. As mentioned below, SOMO35 (in ppb. days) is defined as the annual sum of maximum daily 8-h O_3 means over 35 ppb [7, 14, 23]. The following equations is used to calculate SOMO35 metric [7, 24]:

$$\mathrm{SOMO35}_{\mathrm{uncorrected}} = \sum_{i=1}^{N_{\mathrm{total}}} \max[0, (C_i - 35\mathrm{ppb})]$$

$$\mathrm{SOMO35} = \mathrm{SOMO35}_{\mathrm{uncorrected}} \frac{N_{\mathrm{total}}}{N_{\mathrm{Valid}}}$$

where $[C_i]$ is the maximum daily 8-h running mean O_3 concentration (ppb); N_{total} and N_{Valid} represent the number of days over a year (365 or 366) and the number of valid daily concentrations ($N_{\mathrm{Valid}} > 273$), respectively [7]. It is important to note that the maximum daily 8-h running mean O_3 concentrations exceeding 35 ppb are taken into calculation [23].

Vegetation health metrics

To quantitatively estimate the effect of O_3 on forest trees and other vegetation (for example crops including wheat, rice, and maize, etc.), AOT40f and AOT40v are widely used, respectively [1, 25, 26]. These metrics (expressed in ppb. hours) represent the accumulation of ambient O_3 over 40 ppb between 8 a.m. and 8 p.m. during plants growing seasons [25, 27]. It should be highlighted that the months of April to September (6 months) is considered as the growing season for the forest trees and calculation of AOT40f, whereas the months of May to July (3 months) are proposed for any other kind of vegetation/crops and the computation of AOT40v [23, 27]. The following equations is used to calculate AOT40 metrics [23]:

$$\mathrm{AOT40} = \sum_{i=1}^{n} \max\left([O_3]_i - 40\right), \text{ for } O_3 > 40 \text{ ppb}$$

where, $[O_3]_i$ represents the hourly average O_3 concentration during the daytime hours between 8:00 and 20:00 and n is the number of hours in the growing seasons for forest trees and crops [15, 27].

Table 1 Detailed information on AQMSs and the hourly O_3 data coverage throughout AQMSs of Tehran

No.	Air Quality Monitoring Stations (AQMSs)	Latitude	Longitude	Hourly O_3 data coverage (%)*
1	Park-e-Roz	35.739	51.267	0.0
2	Poonak	35.762	51.331	94.5
3	Golbarg	35.731	51.506	94.9
4	Setad-e-Bohran	35.727	51.431	92.5
5	Sharif	35.702	51.350	90.9
6	Tarbiat Modares	35.717	51.385	94.2
7	Piroozi	35.695	51.493	77.8
8	Fath	35.678	51.337	97.2
9	Shad Abad	35.670	51.297	90.1
10	Masoudiyeh	35.630	51.499	84.7
11	Shahr-e-Rey	35.603	51.425	90.3
12	Shahrdari 2	35.777	51.368	91.3
13	Shahrdari 4	35.741	51.506	0.0
14	Shahrdari 10	35.697	51.358	0.0
15	Shahrdari 11	35.672	51.389	57.6
16	Shahrdari 16	35.644	51.397	0.7
17	Shahrdari 19	35.635	51.362	83.3
18	Shahrdari 21	35.697	51.243	94.0
19	Shahrdari 22	35.723	51.243	85.8
20	Mahalati	35.661	51.466	81.0
21	Aghdasiyeh	35.795	51.484	97.1
22	Sadr	35.778	51.428	95.3

*AQMSs with less than 75% valid hourly data available were excluded from the next analysis

Results and discussion

Overview of O_3 concentrations

The station-specific boxplot of ambient O_3 concentrations in Tehran during was illustrated in Fig. 1. Additionally, the map of spatial distribution of annual mean concentration of ambient O_3 concentration was generated by using a Geographic Information System (Fig. 2). As shown in Fig. 1, the hourly and annual mean O_3 concentrations measured in selected AQMSs ranged from 1 to 178 ppb and 15.8 to 25.7 ppb, respectively. The highest annual mean concentration of

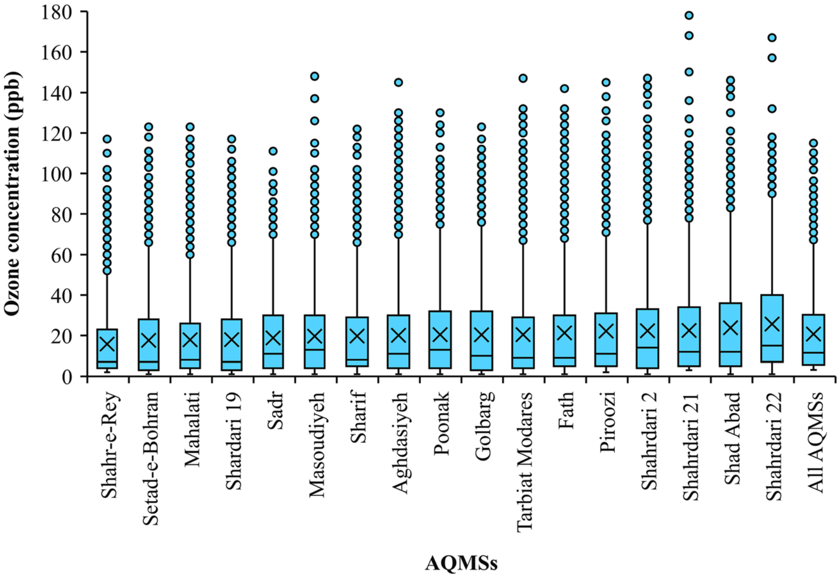
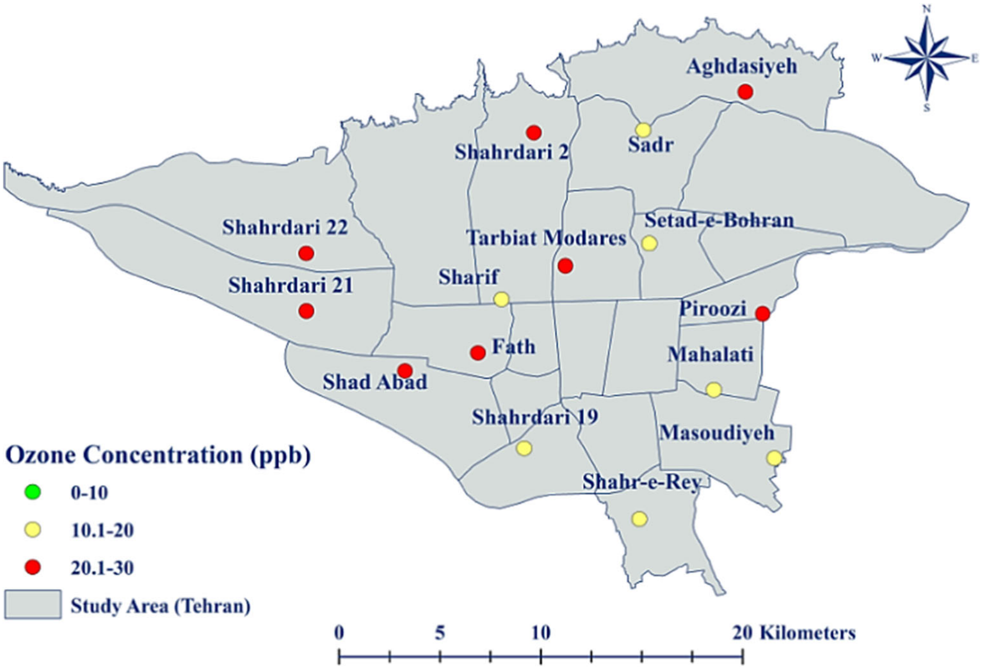


Fig. 1 The station-specific boxplot of ambient O_3 concentrations in Tehran (Multiplication sign (X) in each box is the annual mean concentration of ambient O_3 at each AQMS)

Fig. 2 Spatial distribution of annual mean concentration of ambient O_3 across Tehran (2019–2020)



ambient O_3 was observed in Shahrdari 22 station (25.7 ppb), followed by Shad Abad (23.9 ppb) station, whereas the lowest annual mean concentration of ambient O_3 was recorded in Shahr-e-Rey (15.7 ppb) and Setad-e-Bohran (17.6 ppb) stations for the year 2019–2020. On the other hand, population who live around Shahrdari 22 and Shad Abad stations were exposed to annual mean concentration of ambient O_3 approximately 1.36 to 1.64 times higher compared with those in Shahr-e-Rey and Setad-e-Bohran stations. A glance at the Fig. 2 provided reveals that the highest annual mean ambient O_3 concentrations were observed in the northern, west and south-western parts of Tehran; while the central and south areas of Tehran city experienced low to moderate concentrations during the study period. The aforementioned results on the spatial variability of O_3 concentrations are in agreement with the previously conducted studies in Tehran city [4, 18, 28]. There are several main reasons for the spatial variation in ambient O_3 concentrations. The changes of ambient air temperature across Tehran, the patterns of most important precursor and destroyer of O_3 (ambient NO_2), the speed and direction of local winds, meteorological events (such as local circulations) and topographic features are the most significant reasons [4, 18, 28]. Also, Jahangir and Moghim more recently depicted the urban heat island (UHI) in the city of Tehran using reliability methods [29]. They reported that ambient air temperature has an interesting spatiotemporal pattern across different districts of Tehran. Based on their findings, the northern part of Tehran city which is more elevated has a lower ambient air temperature relative to the western, southern, and south-western parts of Tehran [29]. Therefore, spatial distribution of ambient O_3 concentration across Tehran has an interesting variation.

We compared the daily maximum 8-h mean of O_3 across stations in Tehran with World Health Organization Air Quality Guideline (WHO AQG: 51 ppb). In fact, the number of days with the daily maximum 8-h mean of ambient O_3 more and less than the WHO AQG as well as the number of days without valid data across AQMSs in Tehran during the study period was showed in Fig. 3. As shown in Fig. 3, the daily maximum 8-h mean of ambient O_3 exceeded in 45 to 151 days of the year 2019–2020. We compared the daily maximum 8-h mean of O_3 across AQMSs in Tehran with World Health Organization Air Quality Guideline (WHO AQG: 51 ppb). As can be seen from Fig. 3, 10 out of 17 AQMSs were in areas of Tehran with >100 non–attainment days a year. Tarbiat Modares (142 days), Setad-e-Bohran (131 days) and Fath (131 days) AQMSs experienced the highest number of exceedances in comparison to the WHO AQG, whereas the lowest number of exceedances was found in Shahr-e-Rey (45 days), followed by Mahalati (53 days), Masoudiyeh (69 days) and Piroozi (76 days).

To better show the most polluted months in Tehran, monthly concentrations of ambient O_3 at hourly-level were investigated during the study period 2019–2020 (Fig. 4). As shown in Fig. 4, the ambient O_3 concentrations demonstrated remarkable monthly changes in

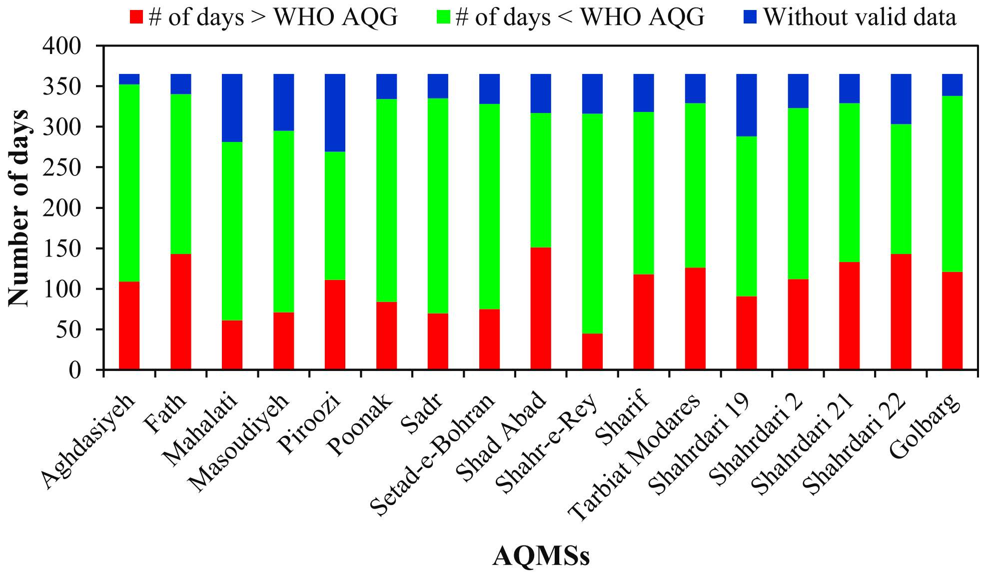
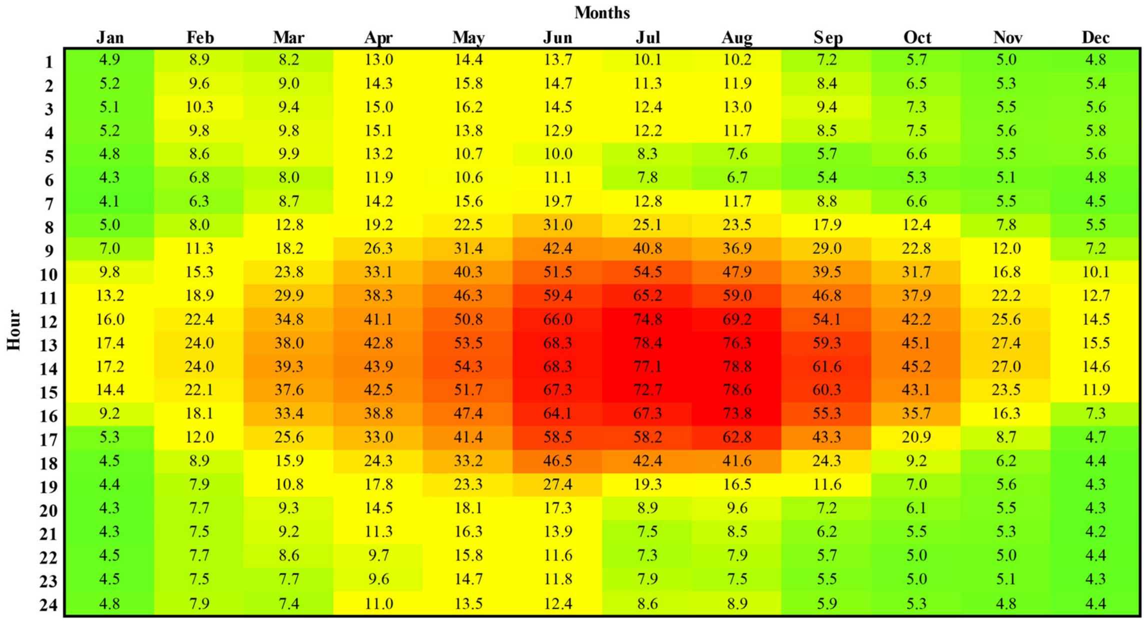


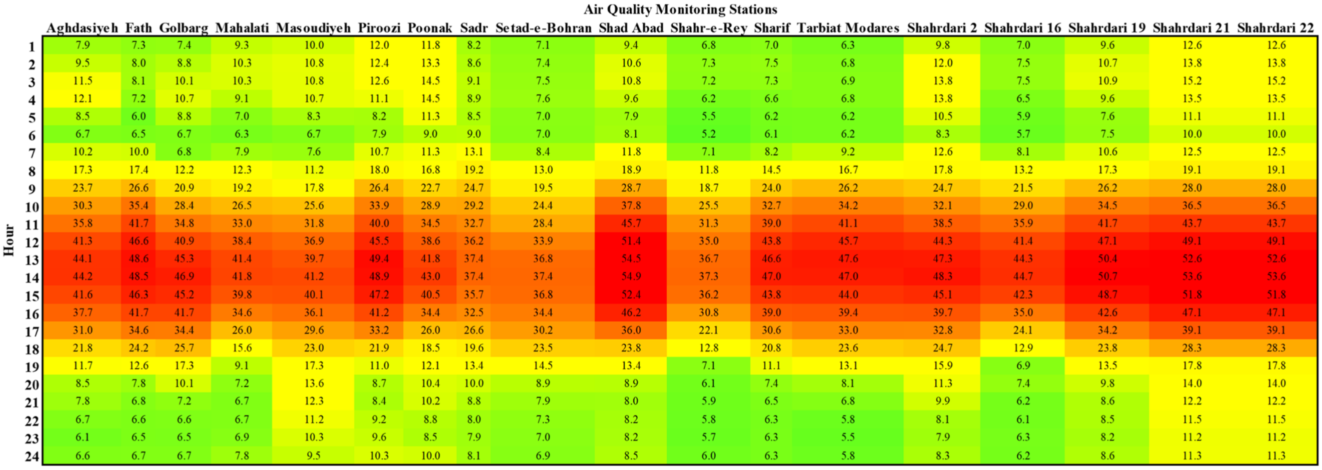
Fig. 3 Daily maximum 8-h mean of O_3 in Tehran compared to WHO AQG (51 ppb)

which the highest mean concentrations were recorded during the summer and spring months, especially July, August and June, whereas the lowest mean concentrations of ambient O_3 were observed during the wintertime months, specifically January and December. Compared to other months, the higher ambient O_3 concentrations during the months of spring and summer result from the increase of photochemical reactions to form O_3 from its precursor due to longer daylight hours, higher surface temperatures (Figure S2) as well as higher concentration of hydroxyl radical as the most notable oxidant species for the production of ambient O_3 during these seasons [4, 7, 16, 28, 30]. By contrast, lower O_3 concentrations occurred during the winter and autumn months most likely owing to decreased sunshine duration and lower surface temperatures over these months could be the main reasons for lower concentrations [4, 7, 16, 28, 30]. In addition, Fig. 5 reveals the



Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	4.9	8.9	8.2	13.0	14.4	13.7	10.1	10.2	7.2	5.7	5.0	4.8
2	5.2	9.6	9.0	14.3	15.8	14.7	11.3	11.9	8.4	6.5	5.3	5.4
3	5.1	10.3	9.4	15.0	16.2	14.5	12.4	13.0	9.4	7.3	5.5	5.6
4	5.2	9.8	9.8	15.1	13.8	12.9	12.2	11.7	8.5	7.5	5.6	5.8
5	4.8	8.6	9.9	13.2	10.7	10.0	8.3	7.6	5.7	6.6	5.5	5.6
6	4.3	6.8	8.0	11.9	10.6	11.1	7.8	6.7	5.4	5.3	5.1	4.8
7	4.1	6.3	8.7	14.2	15.6	19.7	12.8	11.7	8.8	6.6	5.5	4.5
8	5.0	8.0	12.8	19.2	22.5	31.0	25.1	23.5	17.9	12.4	7.8	5.5
9	7.0	11.3	18.2	26.3	31.4	42.4	40.8	36.9	29.0	22.8	12.0	7.2
10	9.8	15.3	23.8	33.1	40.3	51.5	54.5	47.9	39.5	31.7	16.8	10.1
11	13.2	18.9	29.9	38.3	46.3	59.4	65.2	59.0	46.8	37.9	22.2	12.7
12	16.0	22.4	34.8	41.1	50.8	66.0	74.8	69.2	54.1	42.2	25.6	14.5
13	17.4	24.0	38.0	42.8	53.5	68.3	78.4	76.3	59.3	45.1	27.4	15.5
14	17.2	24.0	39.3	43.9	54.3	68.3	77.1	78.8	61.6	45.2	27.0	14.6
15	14.4	22.1	37.6	42.5	51.7	67.3	72.7	78.6	60.3	43.1	23.5	11.9
16	9.2	18.1	33.4	38.8	47.4	64.1	67.3	73.8	55.3	35.7	16.3	7.3
17	5.3	12.0	25.6	33.0	41.4	58.5	58.2	62.8	43.3	20.9	8.7	4.7
18	4.5	8.9	15.9	24.3	33.2	46.5	42.4	41.6	24.3	9.2	6.2	4.4
19	4.4	7.9	10.8	17.8	23.3	27.4	19.3	16.5	11.6	7.0	5.6	4.3
20	4.3	7.7	9.3	14.5	18.1	17.3	8.9	9.6	7.2	6.1	5.5	4.3
21	4.3	7.5	9.2	11.3	16.3	13.9	7.5	8.5	6.2	5.5	5.3	4.2
22	4.5	7.7	8.6	9.7	15.8	11.6	7.3	7.9	5.7	5.0	5.0	4.4
23	4.5	7.5	7.7	9.6	14.7	11.8	7.9	7.5	5.5	5.0	5.1	4.3
24	4.8	7.9	7.4	11.0	13.5	12.4	8.6	8.9	5.9	5.3	4.8	4.4

Fig. 4 Monthly cycle of 1-h ozone concentrations over AQMSs in Tehran (observational data in the period 2019–2020)



Hour	Air Quality Monitoring Stations																	
	Aghdasiyeh	Fath	Golbarg	Mahalati	Masoudiyeh	Piroozi	Poonak	Sadr	Setad-e-Bohran	Shad Abad	Shahr-e-Rey	Sharif	Tarbiat Modares	Shahrdari 2	Shahrdari 16	Shahrdari 19	Shahrdari 21	Shahrdari 22
1	7.9	7.3	7.4	9.3	10.0	12.0	11.8	8.2	7.1	9.4	6.8	7.0	6.3	9.8	7.0	9.6	12.6	12.6
2	9.5	8.0	8.8	10.3	10.8	12.4	13.3	8.6	7.4	10.6	7.3	7.5	6.8	12.0	7.5	10.7	13.8	13.8
3	11.5	8.1	10.1	10.3	10.8	12.6	14.5	9.1	7.5	10.8	7.2	7.3	6.9	13.8	7.5	10.9	15.2	15.2
4	12.1	7.2	10.7	9.1	10.7	11.1	14.5	8.9	7.6	9.6	6.2	6.6	6.8	13.8	6.5	9.6	13.5	13.5
5	8.5	6.0	8.8	7.0	8.3	8.2	11.3	8.5	7.0	7.9	5.5	6.2	6.2	10.5	5.9	7.6	11.1	11.1
6	6.7	6.5	6.7	6.3	6.7	7.9	9.0	9.0	7.0	8.1	5.2	6.1	6.2	8.3	5.7	7.5	10.0	10.0
7	10.2	10.0	6.8	7.9	7.6	10.7	11.3	13.1	8.4	11.8	7.1	8.2	9.2	12.6	8.1	10.6	12.5	12.5
8	17.3	17.4	12.2	12.3	11.2	18.0	16.8	19.2	13.0	18.9	11.8	14.5	16.7	17.8	13.2	17.3	19.1	19.1
9	23.7	26.6	20.9	19.2	17.8	26.4	22.7	24.7	19.5	28.7	18.7	24.0	26.2	24.7	21.5	26.2	28.0	28.0
10	30.3	35.4	28.4	26.5	25.6	33.9	28.9	29.2	24.4	37.8	25.5	32.7	34.2	32.1	29.0	34.5	36.5	36.5
11	35.8	41.7	34.8	33.0	31.8	40.0	34.5	32.7	28.4	45.7	31.3	39.0	41.1	38.5	35.9	41.7	43.7	43.7
12	41.3	46.6	40.9	38.4	36.9	45.5	38.6	36.2	33.9	51.4	35.0	43.8	45.7	44.3	41.4	47.1	49.1	49.1
13	44.1	48.6	45.3	41.4	39.7	49.4	41.8	37.4	36.8	54.5	36.7	46.6	47.6	47.3	44.3	50.4	52.6	52.6
14	44.2	48.5	46.9	41.8	41.2	48.9	43.0	37.4	37.4	54.9	37.3	47.0	47.0	48.3	44.7	50.7	53.6	53.6
15	41.6	46.3	45.2	39.8	40.1	47.2	40.5	35.7	36.8	52.4	36.2	43.8	44.0	45.1	42.3	48.7	51.8	51.8
16	37.7	41.7	41.7	34.6	36.1	41.2	34.4	32.5	34.4	46.2	30.8	39.0	39.4	39.7	35.0	42.6	47.1	47.1
17	31.0	34.6	34.4	26.0	29.6	33.2	26.0	26.6	30.2	36.0	22.1	30.6	33.0	32.8	24.1	34.2	39.1	39.1
18	21.8	24.2	25.7	15.6	23.0	21.9	18.5	19.6	23.5	23.8	12.8	20.8	23.6	24.7	12.9	23.8	28.3	28.3
19	11.7	12.6	17.3	9.1	17.3	11.0	12.1	13.4	14.5	13.4	7.1	11.1	13.1	15.9	6.9	13.5	17.8	17.8
20	8.5	7.8	10.1	7.2	13.6	8.7	10.4	10.0	8.9	8.9	6.1	7.4	8.1	11.3	7.4	9.8	14.0	14.0
21	7.8	6.8	7.2	6.7	12.3	8.4	10.2	8.8	7.9	8.0	5.9	6.5	6.8	9.9	6.2	8.6	12.2	12.2
22	6.7	6.6	6.6	6.7	11.2	9.2	8.8	8.0	7.3	8.2	5.8	6.3	5.8	8.1	6.1	8.5	11.5	11.5
23	6.1	6.5	6.5	6.9	10.3	9.6	8.5	7.9	7.0	8.2	5.7	6.3	5.5	7.9	6.3	8.2	11.2	11.2
24	6.6	6.7	6.7	7.8	9.5	10.3	10.0	8.1	6.9	8.5	6.0	6.3	5.8	8.3	6.2	8.6	11.3	11.3

Fig. 5 Diurnal cycle of 1-h O_3 concentrations over AQMSs in Tehran (observational data in the period 2019–2020)

hourly O_3 concentrations at station-level in 2019–2020. Our findings related to hourly concentrations at monthly- (Fig. 4) and station-level (Fig. 5) showed that ambient O_3 experienced the highest concentrations between 11:00 and 16:00, particularly at 14:00, whereas the lowest hourly O_3 concentration was found in the late night and after midnight. These results are more likely due to higher solar radiation intensity and photochemical reactions in the early afternoon and the absence of photochemical reactions in the late night and after midnight [4, 7, 16, 28, 30]. A more recently study conducted by Jahangir and Moghim investigated urban heat island (UHI) in the city of Tehran using reliability methods [29]. The pattern of hourly ambient O_3 concentrations in our study was exactly similar to the reported UHI at hourly level by Jahangir and Moghim [29].

O_3 metrics

Figure 6 illustrates the spatial distribution of O_3 metrics (SOMO35, AOT40f and AOT40v) in Tehran during the study period. As a metric for the protection of human health, SOMO35 across AQMSs in Tehran was in the range of 1830–6437 ppb. days. The SOMO35 value for Tehran city (all stations) was 4138 ppb. days. The highest SOMO35 value was found at Shahrdari 22 AQMS, followed by Shad Abad (5556 ppb. days) and Golbarg (4904 ppb. days) stations, whereas the lowest value of SOMO35 metric was calculated for Shahr-e-Rey (1830 ppb. days), Sadr (1938 ppb. days) and Masoudiyeh (2549 ppb. days) stations. Although there is not established any target value for SOMO35, the critical level equal to 3000 ppb. days has been stated by P. Sicard et al. [23] that is consistent with European air quality limits. A glance at the figure provided (Fig. 6) reveals that the SOMO35 value at all AQMSs across Tehran, except for Shar-e-Rey, Sadr and Masoudiyeh stations, was higher than the recommended target value (3000 ppb. days). The AOT40f and AOT40v across AQMSs in Tehran ranged from 10,613 to 39,505 ppb.h and 4979 to 16,804 ppb.h, respectively. Additionally, the AOT40f and AOT40v for Tehran (all stations) was 27,556 ppb.h and 9610 ppb.h, respectively. The highest AOT40f and AOT40v metrics were calculated for Fath AQMSs with 39,505 and 16,804 ppb.h, whereas the lowest AOT40f and AOT40v was found in Shahr-e-Rey (10,613 ppb.h) and Aghdasiyeh (4979 ppb.h) stations. As can be seen from Fig. 6, the AOT40f metric at all AQMSs of Tehran city was higher than the target value (5000 ppb.h) recommended by previous studies. Detailed information on the SOMO35, AOT40f and AOT40v is presented in Table S1. To date, numerous studies have been conducted in Tehran megacity that have focused on different issues of ambient air pollution, including investigation of spatiotemporal variations of ambient air pollutants [7, 16–18, 20, 31], chemical and biological characterization of ambient air pollutants and their effects [32–35], source apportionment of ambient particulate matter [36–38] and health effects related to ambient air pollutants [22, 39–41]. Because of the paucity of studies on investigation of O_3 indices in Tehran and other cities of Iran, we only compared our results with two studies; one study in Tehran [7] and another study in Ahwaz [24]; which have reported only SOMO35. The study of Faridi and colleagues have stated that the value of SOMO35 in Tehran was in the range of 739–10,521 ppb. days during the period 2006–2015 [7]. Moreover, Karimi et al. have reported that the SOMO35 metric in Ahwaz ranged from 471 to

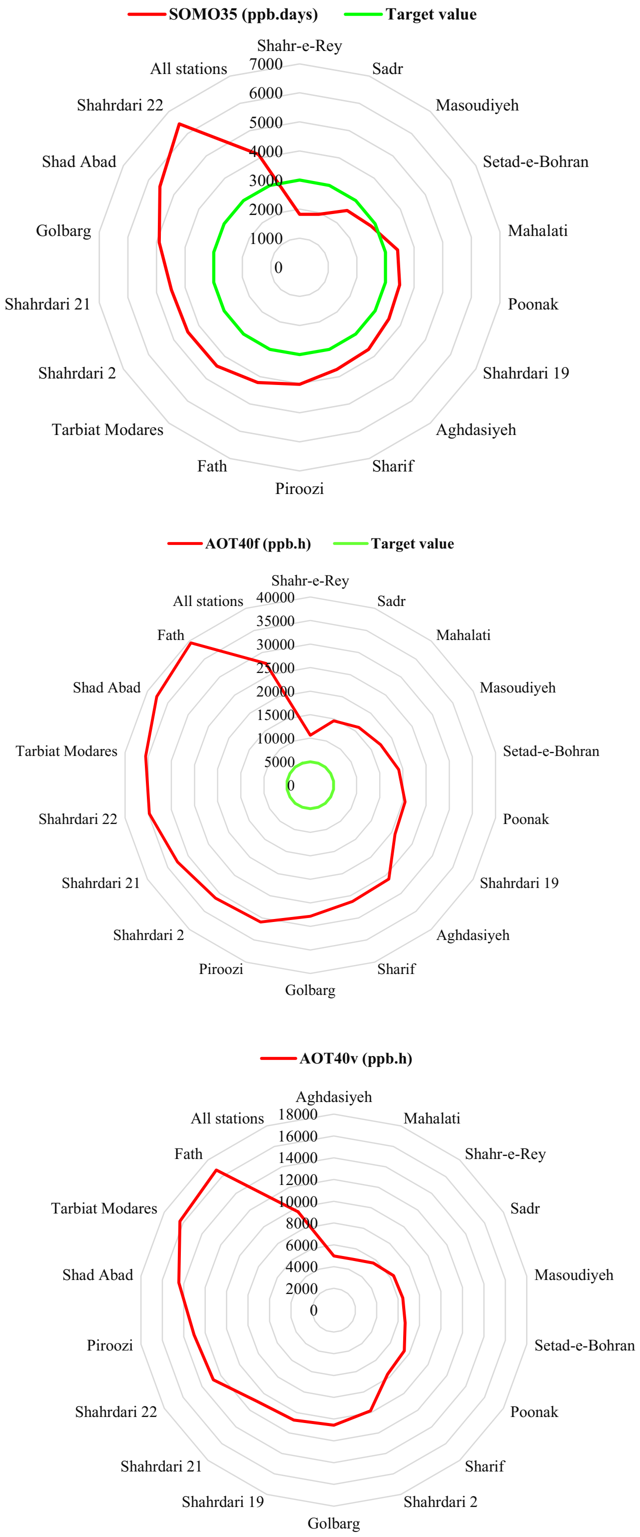


Fig. 6 Spatial distribution of O_3 metrics (SOMO35, AOT40f and AOT40v) in Tehran

6597 ppb. days between 2014 and 2017 [24]. To the best of our knowledge, the current study is the first investigation that reported all O_3 indices across Tehran.

Conclusion

We investigated ambient O_3 concentrations across Tehran megacity and calculated the potential risk of O_3 on human, forest plants and crops by using SOMO35, AOT40f and AOT40v. As the non–attainment days, the number of exceedances of daily maximum 8–hour values more than 51 ppb as recommended by WHO AQG throughout AQMSs of Tehran city was in the range of 45–151 days during the study period. Compared to the objectives of legislative air quality directives, we found a considerable overrun of exposure metrics (SOMO35, AOT40f and AOT40v) across different districts of Tehran. Therefore, it is proposed that the future studies investigate the forest productivity and crop yield in Tehran.

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Authors' contributions SF and AA deigned the study. SF and HF conducted the study and gathered all data. SF and HA analyzed the data. SF drafted the manuscript. AA, HF, SK and HA revised the manuscript.

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Data availability All data generated or analysed during this study are included in this published article.

Compliance with ethical standards

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

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