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Spatiotemporal Variations and Contributing Factors of Air Pollutants in Almaty, Kazakhstan

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ABSTRACT

In this study, spatial and temporal patterns of PM_{10}, $PM_{2.5}$, NO_2, SO_2, and CO in Almaty, the largest city of Kazakhstan, in the period between 2013 and 2018 are explored. Severe degradation of air quality was observed from the data that were used in this study. Annual averages of $PM_{2.5}$, PM_{10}, and NO_2 concentrations exceeded the WHO annual limits by 5.3, 3.9, and 3.2 times, respectively. The maximum levels were observed in the winter, while the minimum levels in the summer. Winter-to-summer difference was more noticeable for $PM_{2.5}$ than for other pollutants. The winter pollution peaks demonstrate the high contribution of large- and small-scale coal combustion for heating, which could be exacerbated with lower winds and possible more frequent thermal inversions. There was a negative correlation between elevation and levels of SO_2, $PM_{2.5}$, and PM_{10}, while no correlation was observed for NO_2 and CO, indicating that the former group could be mainly contributed by point sources located predominantly at lower elevations (e.g., power plants) and the latter group mainly originated from nonpoint sources distributed evenly across the city (e.g., transport). Urgent measures are needed to reduce emissions from the coal-fired power plant and from the domestic heating stoves.

Keywords: Aerosol; Air quality; Atmospheric air pollution; Particulate matter; Kazakhstan; Almaty.

INTRODUCTION

Rapid economic development, exploitation of natural resources, lax environmental regulations, and weak enforcement have led to environmental degradation in many locations in Kazakhstan (Russel *et al.*, 2018). Almaty, the former capital and the largest urban center in Kazakhstan, is one of the most polluted cities in Kazakhstan (Russel *et al.*, 2018; Kerimray *et al.*, 2019), and one of the air pollution "hotspots" in the country, particularly with NO_2 (Darynova *et al.*, 2018). Almaty experienced a constant population and economic growth, which has inevitably resulted (and may continue to result in the future) in an increased number of transportation activities, urbanization, and increased energy demand (World Bank, 2017). Almaty was initially designed for less than a million dwellers (in 1990) (Nazhmetdinova *et al.*, 2018); however, its population has reached 1.85 million due to massive migration waves (Committee of Statistics of the Ministry of the National Economy of the Republic of Kazakhstan, 2019a).

Currently, the city is heavily dependent on the use of coal: 2.6 million tons of coal in total were used in 2015 (World Bank, 2017). For the city of Almaty with its surrounding region, 64% of the electric energy supply originates from local power plants, and the remaining 36% are purchased from Pavlodar region (ALES, 2019). The coal-fired combined heat and power plant named "CHP-2", the largest power plant, located in the north-west of the city is equipped with an emulsifier for cleaning flue gases from ash and dust (ALES, 2019). The effectiveness of SO_2, NO_2, PM_{10}, and $PM_{2.5}$ removal at the CHP-2 are not reported. In Kazakhstan, emissions from coal-fired power plants are substantially higher than the limit values for power plants in Europe: 10 times for PM, by 20% for NO_x and 2.5 times for SO_x

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(Concept on the Transition of the Republic of Kazakhstan to the "Green Economy", 2013).

Given that the maximum concentrations of PM_{10}, NO_2, and SO_2 occur during wintertime, large- and small-scale heat production is a significant source of pollution (World Bank, 2013; Darynova *et al.*, 2018). Residential and commercial buildings without access to district heating rely on coal or gas, which are often burned in inefficient stoves (Kerimray *et al.*, 2018). Due to the cold climate and poor dispersion conditions, small-scale combustion can also contribute to episodic air pollution events in the wintertime (World Bank, 2013).

Elevated concentrations of NO_2 and CO in Almaty can also indicate the contribution of the urban transport sector (World Bank, 2013). Most passenger cars (63%) do not satisfy the requirements of the Euro 4 emission standard (UNDP, 2017), and 75% of the cars are older than 7 years (Municipality of Almaty City, 2018). Quality of oil products is also an issue with frequent cases of noncompliance with fuel quality standards and the late introduction of fuel quality standards (Euro 3 and Euro 4) in 2018 (Kazenergy, 2017). The number of registered light-duty vehicles has increased by 6% annually over 2003–2018 reaching 471 thousand vehicles (Committee of Statistics of the Ministry of the National Economy of the Republic of Kazakhstan, 2019b), without accounting for unregistered vehicles entering and leaving the city on a daily basis from suburban areas.

Natural sources such as windblown dust are likely to have low contributions to the deterioration of the air quality in Almaty as dust and sand storms are more frequent in other locations, particularly in the southern desert zone of Kazakhstan (Issanova and Abuduwaili, 2017).

Exposure to ambient air pollution increases the mortality and morbidity as a result of increased risk of ischemic heart disease, cerebrovascular disease, lung cancer, chronic obstructive pulmonary disease and lower respiratory infections (Cohen *et al.*, 2017). The epidemiological studies suggest that the prevalence of bronchial asthma and chronic obstructive pulmonary disease (COPD) in Almaty is high. The prevalence of "wheezing symptoms" was 74.4, 254.8, and 123.4 per 1000 people in Kyiv (Ukraine), Almaty (Kazakhstan), and Baku (Azerbaijan), respectively (Nugmanova *et al.*, 2018a). Thus, in Almaty, it was 3.4 and 2.1 times higher than in Kyiv and Baku, respectively. The prevalence of chronic obstructive pulmonary disease (COPD) was 66.7 per 1000 people, which is 1.8–2.1 times higher compared to other cities of post-soviet countries (e.g., Ukraine and Azerbaijan) and the higher levels in Almaty were likely due to the poor environmental conditions (Nugmanova *et al.*, 2018b). World Bank (2013) estimated that air pollution by PM_{10} and $PM_{2.5}$ in Almaty resulted in an annual economic loss of 486 million US Dollars due to additional health care costs (0.33% of the national Gross Domestic Product in 2011). These values have been estimated using exposure-response functions to the total suspended solids data from the National Air Quality Monitoring Network in 2011 for four regions of Kazakhstan (including Almaty).

There were few scientific studies on air quality in the cities of Kazakhstan, and Almaty is not an exception. Previous studies in Almaty focused on transportation-related emissions (Carlsen *et al.*, 2013); benzene, toluene, ethylbenzene, and xylenes (BTEX) concentrations and ratios (Baimatova *et al.*, 2016); CO, TSP and lead concentrations and compliance with sanitary standards (Nazhmetdinova *et al.*, 2018); and aerosol variations and sources using Aqua-MODIS Collection 6.1 data (Rupakheti *et al.*, 2019). World Health Organisation (WHO) Global Ambient Air Quality Database (WHO, 2018) does not contain data on PM_{10} and $PM_{2.5}$ concentrations in Kazakhstan cities, and the recent report of United Nations Environment Program (UNEP) on air quality in Asia did also not include Kazakhstan (United Nations Environment Program, 2019). Thus, there is a clear gap in the knowledge of air quality levels in Kazakhstan in international databases and studies.

National Hydrometeorological Service of Kazakhstan "Kazhydromet" owns and operates the National Air Quality Monitoring Network (NAQMN) for many pollutants (total suspended particles - TSP, NO_2, SO_2, CO, etc.) in the cities of Kazakhstan (and some villages). The number of measurement locations of $PM_{2.5}$ and PM_{10} has gradually increased since 2016. In 2017, an independent $PM_{2.5}$ measurement network (Airkaz) was established with a higher number of measurement stations than the NAQMN in the three largest cities of Kazakhstan. The real-time $PM_{2.5}$ measurements are displayed at the Airkaz.org website.

Despite the deteriorating situation, there is a lack of studies exploring spatial-temporal variations of air pollutants and the impact of meteorology on air quality in the city. Studies on air quality are urgently needed because of the high public exposure to dangerous pollution levels, complex and unique topographic, and meteorological conditions. Similar studies have been conducted in other places where significant spatial and temporal variations of particulate matter and gaseous pollutants were detected using data from air quality measurements, and possible reasons for such variations were discussed (Alizadeh-Choobari *et al.*, 2016).

In this work, spatial and temporal patterns of air quality in Almaty were studied based on the data from the NAQMN (TSP, NO_2, SO_2, CO) and Airkaz ($PM_{2.5}$) during the years of 2013–2018. The effects of meteorological parameters on the pollutants were investigated. The spatiotemporal variation of air pollution and its relationships with distance to coal-fired power plants and elevation above sea level have been discussed in detail by addressing possible sources of emissions. The proposed study will be the first comprehensive analysis of the urban air quality not only in Kazakhstan but also in Central Asia, where the degree and impacts of atmospheric pollution have yet to be adequately studied.

METHODOLOGY

Study Area

Almaty is located in the foothills of the northern slope of the Trans-Ili Alatau ridge of the Tien Shan mountain system (Fig. 1). The topographical and geographical conditions provide suitable conditions for the formation of inversion layers, restricting the vertical dispersion of pollutants, which may contribute to severe pollution in daily cycles. In general,

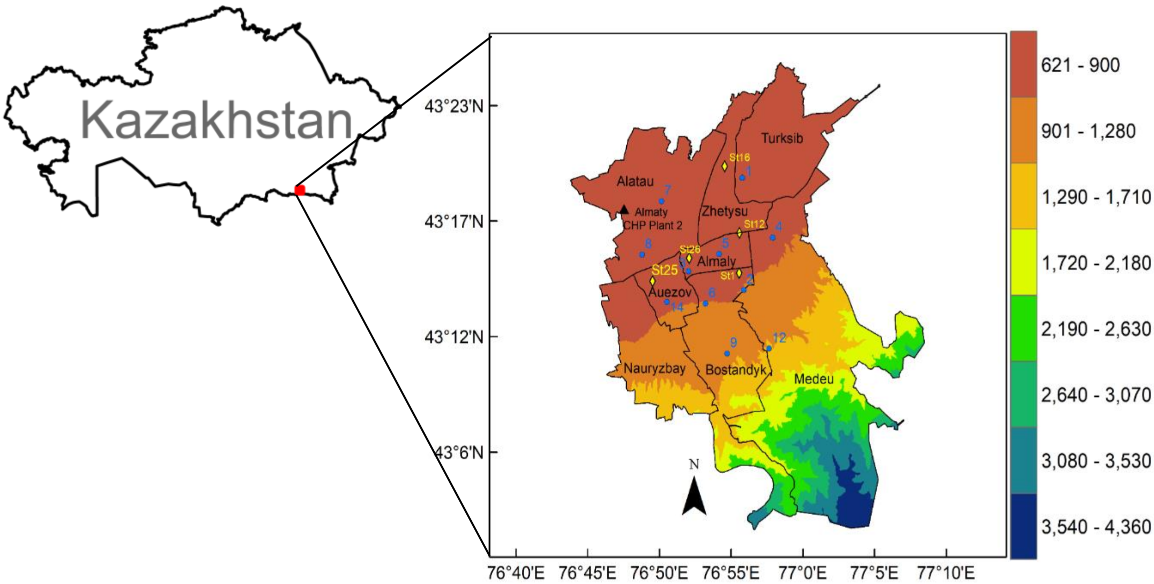

Fig. 1. Location of Almaty in Kazakhstan, and the map of Almaty with the elevation and location of air quality monitoring stations with station code (NAQMN stations marked with yellow; Airkaz stations marked with blue) and location of coal-fired combined heat and power plant (black).

wind speed is very low or absent, influenced by the Siberian anticyclone in winter and the thermal depression on the territory of Kazakhstan in summer (Ecoservice, 2017). Poorly planned construction of the city and its infrastructure prevents horizontal dispersion of air pollutants (Ecoservice, 2017). The areas in the foothills surrounding the mountains were densely built-up in the mid-2000s, leading to a blocking effect on the clean air mass flows from the mountains (Ecoservice, 2017). Fig. 1 presents the location of Almaty in Kazakhstan and location monitoring network stations in Almaty.

Data Obtained from the National Air Quality Monitoring Network (NAQNM)

TSP, NO_2, SO_2 and CO data for 2013-2017 were obtained from Kazhydromet, which owns and operates the National Air Quality Monitoring Network (NAQMN). For TSP, NO_2, SO_2 and CO measurements, the gas sampler (aspirator) OP-824TTs, gas analyzer K-100 and filters AFA-PV-20-1 for the aspirator OP-280 (all made in Russia) are employed. The data are published in information bulletins on a monthly and annual basis. Manual measurements of air quality are carried out three times a day at 07:00, 13:00 and 19:00 at these stations. Locations of five stations are provided in Fig. 1. Descriptive statistics of the pollutant concentrations over 2013–2017 are presented in Table 1.

The NAQMN data included total suspended particles (TSP) measurements while size-specific particulate matter (PM) measurements were not available (e.g., $PM_{2.5}$ and PM_{10}). The size of atmospheric PM can vary significantly in time and space. Ratios of PM_{10}/TSP and $PM_{2.5}$/PM_{10} have not been determined for Almaty and other cities of Kazakhstan, and there are no peer-reviewed publications on such ratios that can be applied for their conversion. In previous studies for Kazakhstan, World Bank (2013) used PM_{10}/TSP = 0.45, and Kenessariyev *et al.* (2013) used the ratio of PM_{10}/TSP = 0.5, so it was decided to use the ratio 0.45 in the current study. Future studies are needed with systematic measurements of TSP, PM_{10}, $PM_{2.5}$ to evaluate those ratios. PM_{10} values (estimated from TSP) from NAQMN may not be directly compared with the $PM_{2.5}$ from Airkaz due to the significant spatiotemporal variations of PM in the study area.

Data Obtained from the Airkaz

Airkaz $PM_{2.5}$ sensors (Pms5003 Plantower, China) were used to measure the concentrations of $PM_{2.5}$ every minute. The concentrations were reported at the airkaz.org portal in real time with 24 stations: 16 sensors were put into operation consequently during 2017, and additional 8 sensors in 2018. Average daily $PM_{2.5}$ values were determined from 22nd March 2017 to 25th March 2019 measurements, and the data for 2018 were used in the further analysis as it covers an entire year period. Descriptive statistics of the $PM_{2.5}$ concentrations are presented in Table 2.

In addition to the above-mentioned monitoring networks, official measurements (NAQMN) of $PM_{2.5}$ and PM_{10} concentration levels in Almaty started in 2016 at two full automatic stations located far from the city center: in the skirts of the mountains (Gornaya street 548) and airport area (Akhmetov street 50). Since 2017, three new stations were added to measure $PM_{2.5}$ levels (also not in the city center): in the northern (Zorge street 14), the north-eastern (Zhankozha Batyr street 202), and the south-eastern ("Orbita" microdistrict) parts of the city. In this study, $PM_{2.5}$ measurements by Airkaz were not compared with the NAQMN data since the provided NAQMN data do not include PM_{10} and $PM_{2.5}$.

Spatial Distribution of $PM_{2.5}$ Using Co-kriging

The co-kriging method utilized in ArcGIS® Geostatistical Analyst tool (https://desktop.arcgis.com/ru/arcmap/) was used to map $PM_{2.5}$ distribution that exceeds the WHO limit

Table 1. Descriptive statistics of the pollutant concentrations (measured three times per day) over 2013–2017.

	PM_{10} (µg m^{-3})					SO_2 (µg m^{-3})				
Station Code	S1	S12	S16	S25	S26	S1	S12	S16	S25	S26
N	5648	4167	4167	4167	4167	5644	4167	4167	4167	4167
Mean	43	131	96	41	58	12	13	15	12	13
Median	45	90	90	45	45	11	11	12	10	11
STD	29	87	69	28	38	9	10	14	11	10
Minimum	0	0	0	0	0	0	0	0	0	0
Maximum	360	540	540	450	450	110	86	110	178	89
Percentiles										
10	0	45	45	0	45	2	3	3	2	3
25	45	45	45	45	45	6	6	6	5	6
50	45	90	90	45	45	11	11	12	10	11
75	45	180	135	45	90	16	17	19	17	17
90	90	270	180	85	90	22	24	31	25	25
	CO (mg m^{-3})					NO_2 (µg m^{-3})				
N	1826	1826	1826	1826	1826	5644	4167	4167	4167	4167
Mean	1.59	1.74	1.38	1.67	1.32	130	180	130	150	130
Median	1.25	1.67	1.00	1.67	1.33	120	160	120	120	120
STD	1.62	1.45	1.36	1.50	1.29	73	90	71	98	71
Minimum	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Maximum	12.25	13.33	10.67	10.67	15.00	800	880	500	500	460
Percentiles										
10	0.00	0.00	0.00	0.00	0.00	80	50	50	60	50
25	0.25	0.68	0.33	0.67	0.67	110	80	80	80	80
50	1.25	1.67	1.00	1.67	1.33	160	120	120	120	120
75	2.25	2.33	2.00	2.33	1.67	230	160	200	160	160
90	3.50	3.33	3.00	3.33	2.67	310	220	290	230	220

Table 2. Descriptive statistics of the average daily $PM_{2.5}$ concentrations (µg m^{-3}) observed in 2018.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S12	S14
N	301	320	355	282	350	351	269	279	305	358	352
Mean	71	55	54	45	61	49	81	49	38	27	57
Median	46	31	29	23	32	27	62	24	25	22	31
STD	62	64	57	50	67	50	66	55	32	19	60
Minimum	10	13	6	6	6	4	11	7	5	6	6
Maximum	340	851	304	283	387	292	369	331	171	193	345
Percentiles											
10	23.5	17.9	11.5	10.9	13.3	11.0	22.5	13.1	11.0	11.4	11.8
25	30.2	22.4	16.4	14.4	19.0	15.5	32.8	17.5	15.2	15.0	16.9
50	45.6	31.2	28.6	22.6	31.5	27.1	62.1	24.4	25.1	21.5	30.8
75	89.0	73.2	71.2	52.7	75.4	61.9	108.2	62.4	50.2	31.0	74.7
90	152.4	122.6	127.2	128.3	143.0	117.2	158.4	113.4	85.3	49.1	140.0

across Almaty in 2018. The digital elevation model (DEM) was used from the Shuttle Radar Topography Mission (SRTM) data (USGS, 2019) as a secondary dataset. In order to build the map, we selected ordinary co-kriging with logarithmic transformation of primary data with a constant order of trend removal with local polynomial interpolation as the data were not normally distributed. The semivariogram contains 12 lags with a size of 0.058 and no shift. The selected model type was stable, without anisotropy.

Meteorological Parameters

NAQMN data did not contain a full dataset on meteorology. Therefore, the meteorological parameters such as wind speed, wind direction, temperature, relative humidity, precipitation were obtained from http://rp5.kz website (Weather Schedule, 2020), which collects and archives the data from the international exchange data server of National Oceanic and Atmospheric Administration (USA) in SYNOP and METAR formats from the station located at 43.15°N, 76.57°E and elevation of 848 m above sea level.

RESULTS AND DISCUSSION

Analysis of NAQMN Data

Long-term Variability of PM_{10}, NO_2, SO_2, and CO

At all NAQMN stations, the annual average concentrations of NO_2 and PM_{10} exceeded WHO annual limit values. The annual average concentration of PM_{10} has increased from 52.7 µg m^{-3} to 86.7 µg m^{-3} over 2013–2016, followed by a decline to 78.5 µg m^{-3} in 2017, exceeding the WHO annual limit value (20 µg m^{-3}) by 3.9 times in 2017 (Fig. 2). This value is slightly higher than the world's average urban PM_{10} level of 71 µg m^{-3}, which ranges by region from 21 to 142 µg m^{-3} (WHO, 2018). The annual average NO_2 concentration had a fluctuating trend, exceeding the WHO annual limit value (40 µg m^{-3}) by 3.2 times in 2017. Darynova *et al.* (2018) also reported a similar fluctuating trend of NO_2 in 2013–2016 based on the observations of the NASA Aura Satellite. NO_2 and PM_{10} concentration levels declined in 2017 compared to 2016, and there is not a piece of evidence that this downward trend would persist in the following years.

Of PM_{10} levels, the urban air quality in Almaty was considerably worse compared to the European countries. The WHO annual air quality limit for PM_{10} was exceeded at 51% stations (1492 out of 2 927) in Europe, and the European Union (EU) annual limit value (40 µg m^{-3}) was also exceeded in 7% of all the reporting stations (European Environment Agency, 2019). As for Kazakhstan, the EU annual limit value (40 µg m^{-3}) was not exceeded in one (out of five) station only in 2013 and 2014. The WHO annual air quality limit for NO_2 was exceeded at 10% of all stations measuring NO_2 in Europe (European Environment Agency), while in Kazakhstan it was exceeded at all five stations.

CO concentrations declined from 2.6 mg m^{-3} in 2013 to 1.5 mg m^{-3} (by 43%) in 2017. The annual concentration of SO_2 in 2017 remained at the level of 2013 (12 µg m^{-3}). Rapidly declining CO concentration levels with simultaneously increasing trends of PM_{10} over 2013–2017 may indicate changes in the shares of contribution sources: declining share of transport emissions (CO, NO_2) and increasing level of coal combustion (PM_{10}). Such declining/stable trends of CO and NO_2 could be as a result of policies and measures in the transport system of the city such as an introduction of Euro 4 fuel quality standard, construction of the subway (only one route), optimization of transport flows with one-way streets, improvement of public transport by renewing the stock of buses, online payment system for bus and mobile application with bus routes. However, due to continuous urbanization and increased number of vehicles, these measures could be surpassed leading to increasing emissions trends in future.

Monthly Variations of PM_{10}, NO_2, SO_2, CO and Meteorological Parameters

Monthly average concentrations of PM_{10}, NO_2, SO_2, and CO show a distinct seasonal variability. Fig. 3 depicts the annual cycle of the PM_{10}, NO_2, SO_2, and CO based on their monthly average concentrations. All of the measured pollutants reached their peak values in the winter months at all stations (with the exception of Station 12) and minimum values were during non-heating months. Half of the monthly maximum concentration values were observed in January. Winter peaks demonstrate the high contribution of fuel combustion for heat generation (from CHPs, heat-only plants, and small-scale household solid fuels burning) because traffic congestion is throughout the year. High pollution levels in the winter time could also be impacted by lower level of atmospheric boundary layer and wind speeds, preventing horizontal and vertical dispersion.

Station 12, which is located in the center of the city with a high traffic load, depict different monthly trends compared to other stations (with peaks for PM_{10} and NO_2 in July and September). This may be explained by the traffic emissions that contribute to air pollution at this location. The highest ratio of maximum to minimum monthly concentration (across all stations) was observed for PM_{10} (5.7), followed by CO (3.4), NO_2 (2.4) and SO_2 (2.4). This is because PM_{10} variation across stations was higher compared to other pollutants. Within one station, the ratio of maximum to minimum monthly concentration was ranging 1.5–1.9 for PM_{10}, 1.2–2.4 for SO_2, 1.9–2.6 for CO and 1.4–2 for NO_2.

January, which is characterized by high levels of pollution, is a month with the lowest wind speed. The lowest wind speed values were observed in the cold season with the

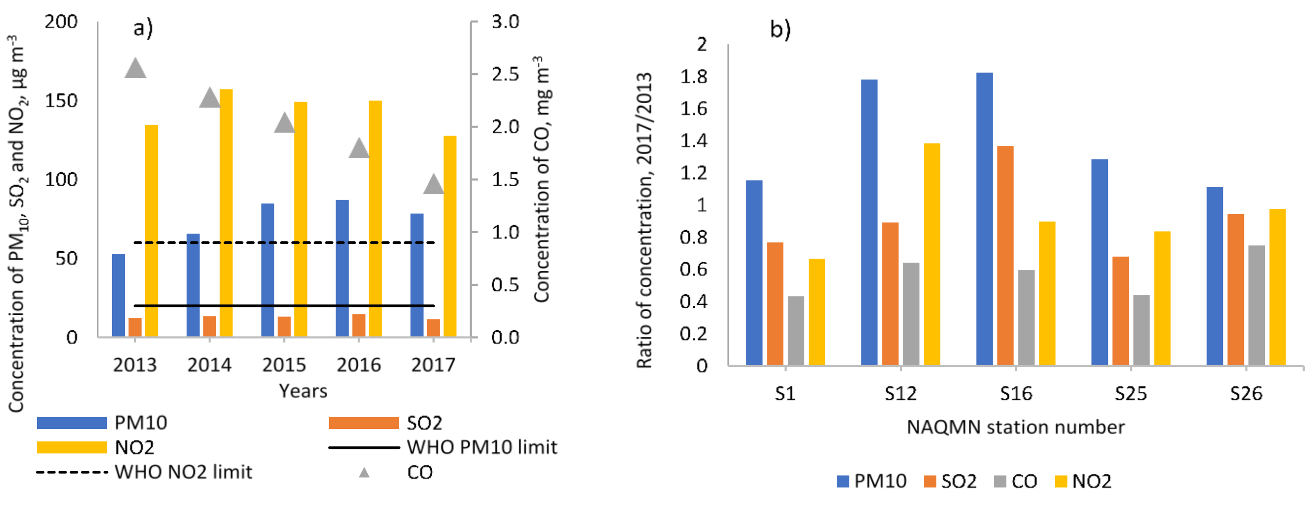

Fig. 2. Annual average concentrations of (a) PM_{10}, NO_2, SO_2 and CO in 2013–2017 years in Almaty and (b) ratios of 2017/2013 concentration levels by stations.

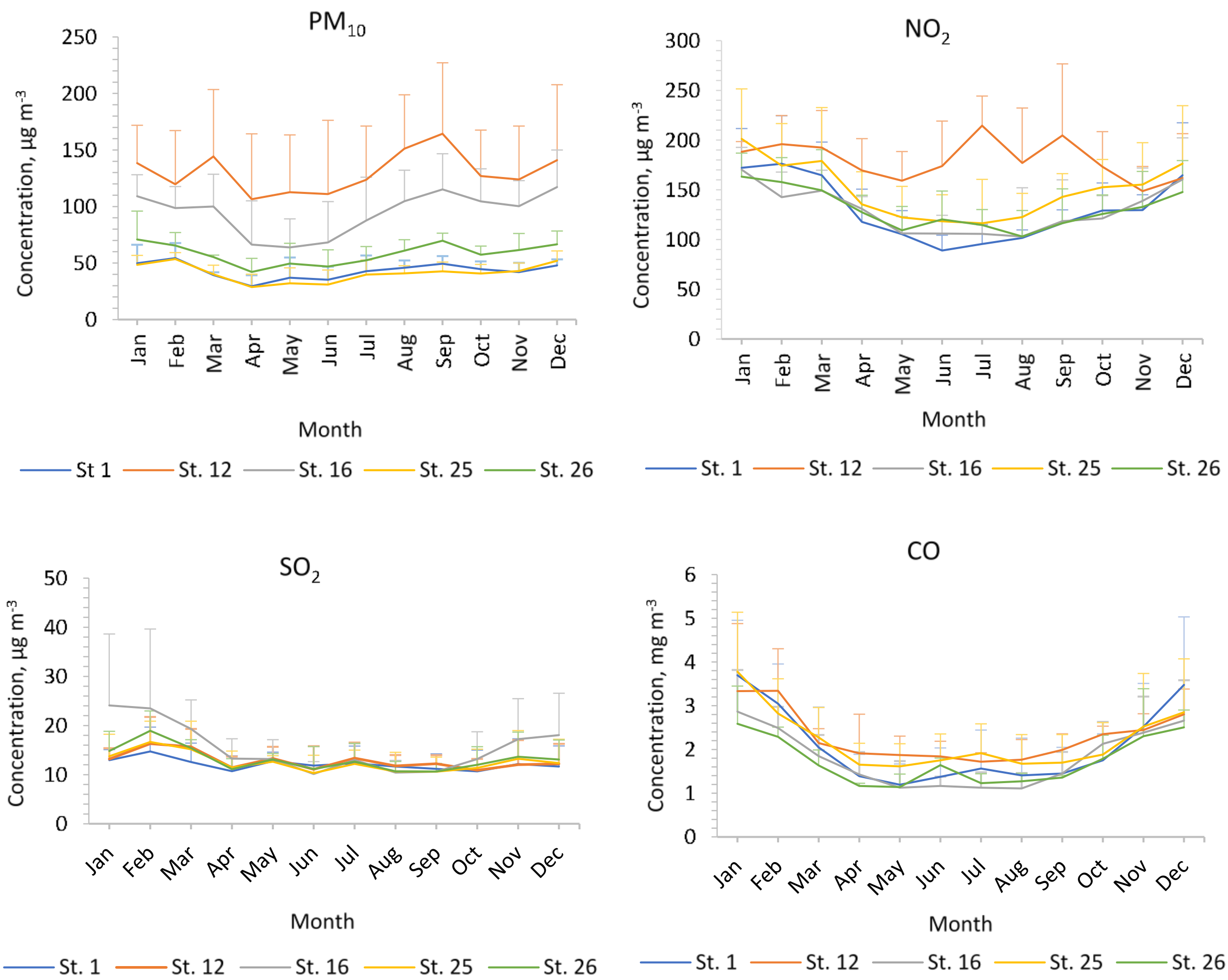

Fig. 3. Annual cycle of the PM_{10}, NO_2, SO_2, and CO based on their monthly average concentrations for the period 2013–2017.

minimum monthly average of 0.3 m s^{-1} in January, whereas the highest value was observed in the warm season with the maximum monthly average of 0.5 m s^{-1} in August (Fig. 4). The relative humidity had the opposite behavior: the lowest values were observed in the warm season with the minimum monthly average in July (41.4%) whereas the highest values were found in the cold season with the maximum monthly average 82.2% in December. Precipitation had a seasonal fluctuation with several peaks in December (9.4 mm), April (7.7 mm), and August (6 mm). From the seasonal variations, it can be concluded that pollutant concentrations have trends similar to the relative humidity, while they follow different seasonal variations with precipitation and wind speed.

Spatial Differences: Districts

The obtained results suggest that all the pollutants exceeded 24-hour mean WHO Air Quality Guideline at least once a year at all stations, and the magnitude of exceedances were different by pollutants. Spatial variations were substantial for the daily concentrations of PM_{10}. In 2013–2017, the share of the number of days exceeding PM_{10} WHO daily limit value (50 µg m^{-3}) was lowest in Bostandyk district (19%), followed by Auezov (27%) and Zhetysu (57%) districts, and highest at Almaly district (65%) (Fig. 5). In Almaly and Zhetysu districts, the concentrations of PM_{10} were higher than 100 µg m^{-3} (exceeding the daily limit by two times) in 48% and 33% of days of the year, respectively. The WHO daily limit was exceeded more than 3 times (150 µg m^{-3}) in those districts in 25% and 10% days of the year (higher than 150 µg m^{-3}), respectively.

For SO_2, daily WHO limit exceedances were 8–17% days of the year (Fig. 6). At the Zhetysu district, in 14 days, the values exceeded three times the daily SO_2 limit (over 2013–2017). CO daily concentration levels were not exceeding the EU daily limit value of 10 mg m^{-3} in most of the days during the year, with only 1–5 days exceedance.

Impact of the Elevation and Distance to the Coal-fired Power Plant

The elevation of the city varies between 600 m and 1300 m due to the proximity to the mountains. There is an inverse correlation for PM_{10} (R^2 = 0.44) and SO_2 (R^2 = 0.81) with the elevation of the monitoring station. At the same time, there is a very low correlation of elevation with NO_2 (R^2 = 0.005) and CO (R^2 = 0.14) (Fig. 6). This may indicate that the PM_{10} and SO_2 emissions were generated by coal power plants and

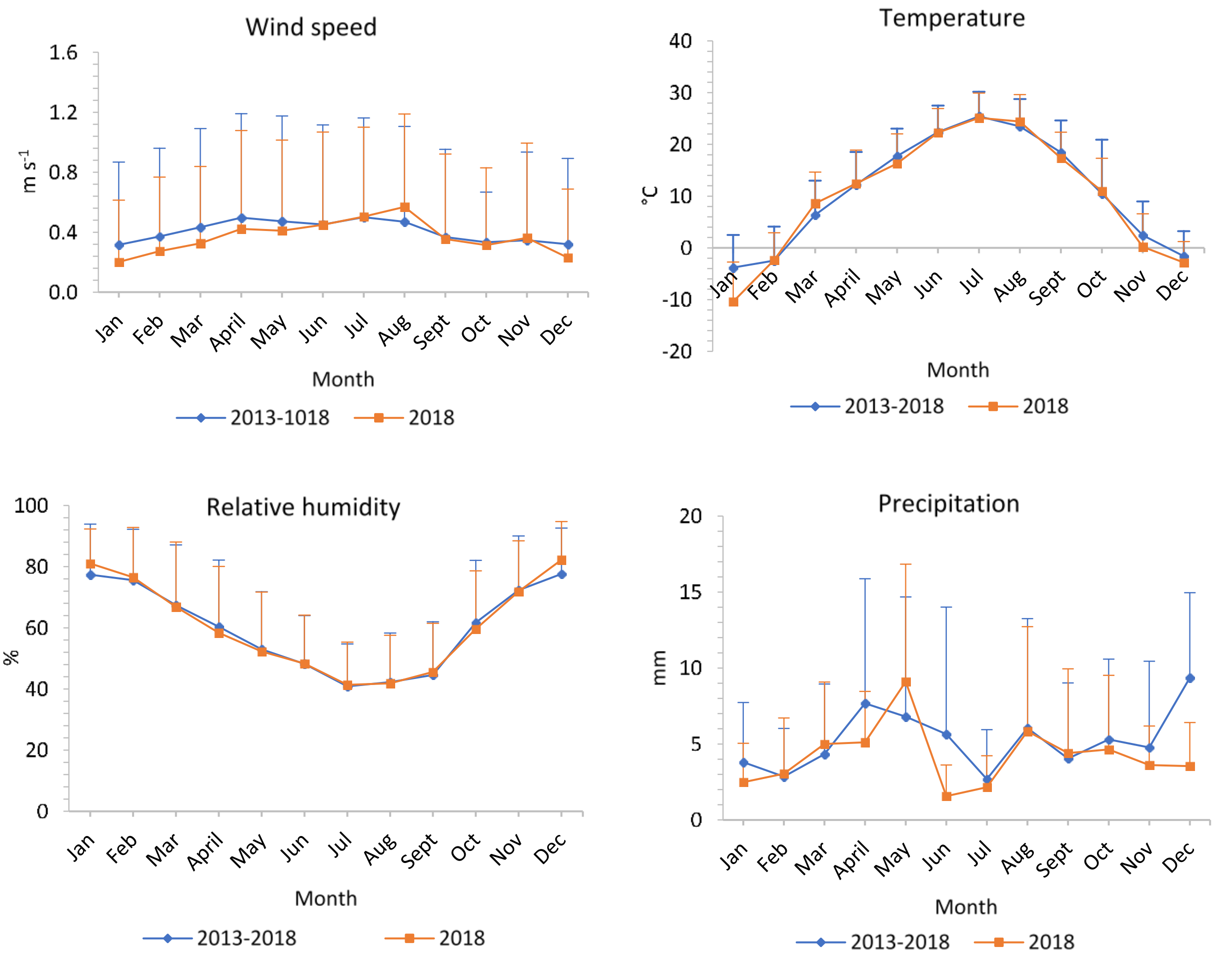

Fig. 4. Monthly average values of wind speed, temperature, relative humidity and precipitation (rp5.kz) for the period 2013–2018.

small-scale coal-fired heating systems located mainly in the northern areas at the low elevations, while NO_2 and CO emissions were caused by transport vehicles which are almost evenly spread across the city. World Bank (2013) also suggested that highly elevated NO_2 and CO concentrations in Almaty were caused by the emissions from transport.

Higher levels of air pollution with PM_{10} and SO_2 at the lower elevations could also be impacted by the topography and meteorological conditions, e.g., mountain-valley circulations, although greatest part of the year is characterized by stable atmospheric conditions (no wind or low wind speed). Future studies should concentrate on the impact of mountain-valley wind circulation on air pollution using high spatiotemporal disaggregated data on meteorology and concentrations of pollutants.

Largest coal-fired combined heat and power plant in the city is CHP-2 (located at the north-west), with an installed electrical capacity of 510 MW and thermal capacity of 1176 Gcal h^{-1} (ALES, 2019). CHP-2 has increased its power generation from 2.63 billion kWh to 2.68 billion kWh and heat generation from 3.2 million Gcal to 3.4 million Gcal over 2016-2018 (ALES, 2019). These increasing levels of electricity and heat generation may also imply increasing levels of coal combustion at this power plant. Values of coal combustion by years/months are not available for CHP-2. It is reported that CHP-2 has fly-ash separator (ALES, 2019), but efficiency of cleaning for each pollutant ($PM_{2.5}$, PM_{10}, NO_2, SO_2) is not reported publicly. Different opinions exist on the impact of the CHP-2 on the air quality degradation of the city. Officials (municipality of Almaty City) claim that "the main source of air pollution is motor vehicles" as total emissions of the transport sector accounted for 79,486 tons in 2016, which represent "sum of all pollutant emissions", without accounting for health risk of each pollutant (Municipality of Almaty City, 2018). Municipality of Almaty City (2018) reported estimated total emissions from stationary sources at 38,800 tons, the majority (81%) of which (31587 tons) is generated from coal-fired power plant CHP-2 (Municipality of Almaty City, 2018). On the other hand, Airkaz claims as "transport is not the main source of emissions" based on the peak values of $PM_{2.5}$ were detected during the winter periods (Informburo, 2019). From another official report prepared by Ecoservice (2017), where inventory of emissions for Almaty is presented, it can be concluded that 91% of the estimated transport emissions is contributed by CO, which is much less toxic (for the same mass) than other pollutants ($PM_{2.5}$, NO_2, SO_2) and its inclusion in total emissions results in the distorted estimation of the input of different sources.

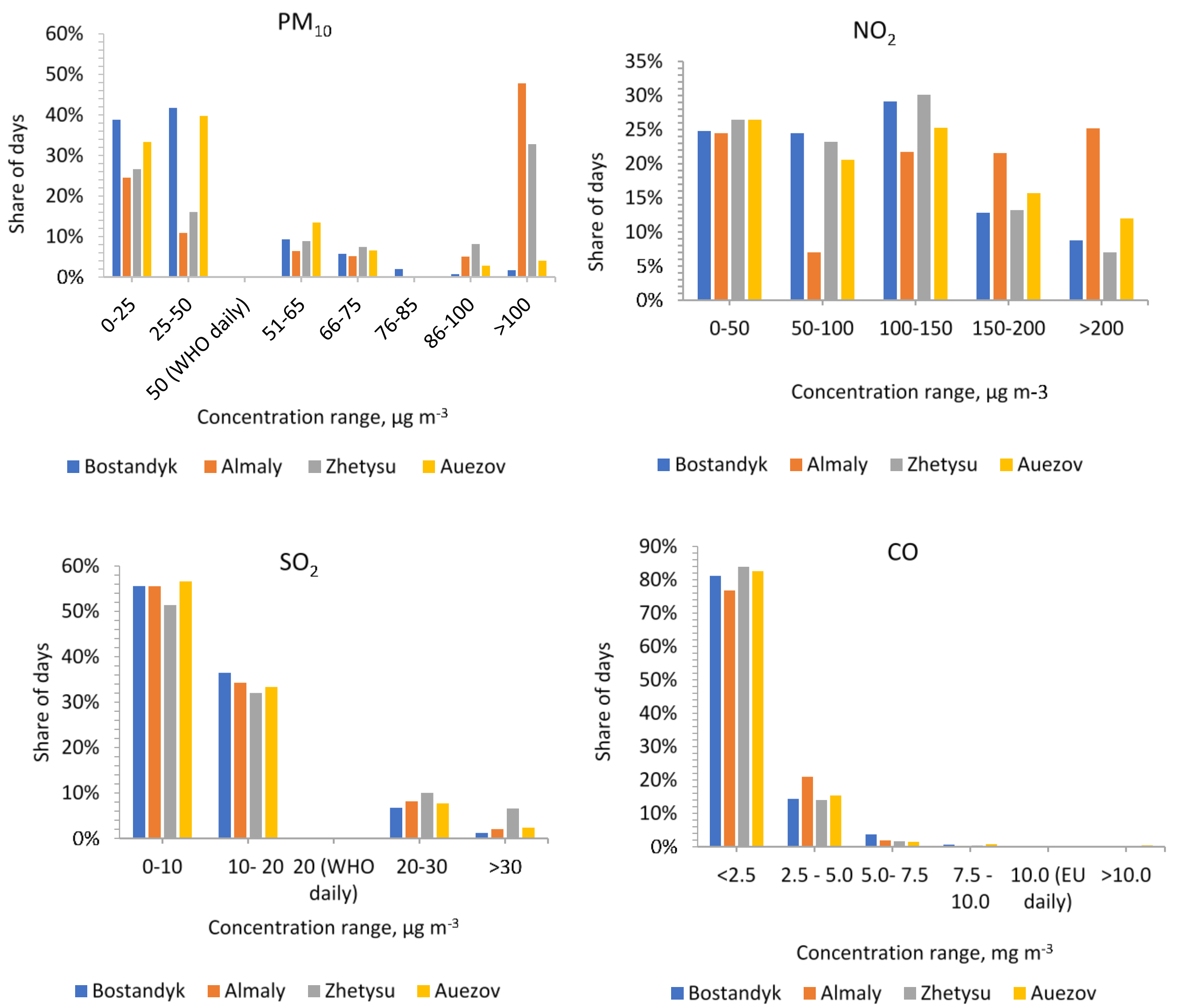

Fig. 5. Share of days in different ranges of daily average concentrations of PM_{10}, SO_2, NO_2, and CO by districts of Almaty in 2013–2017 years.

If CO is excluded from the total sum, share of sources from the total emissions (PM, NO_2, SO_2) becomes 17% transport, 75% stationary combustion and 8% domestic heating. For more accurate estimation of the input of different sources into a concentration of each pollutant, a more accurate source apportionment study with receptor modeling or inventory of emissions is required. Estimating the sources contribution from the sum of emissions of different pollutants is not methodologically correct due to different levels of risks of pollutants for the given mass.

Monitoring stations of NAQMN are located at a varying distance to CHP-2, from 7 to 13 km. Annual average concentrations of NO_2, SO_2, CO and PM_{10} had low correlation coefficients ($R^2 = 0.01$–0.14) with the distance to CHP-2. None of the stations are located close to CHP-2, and this could explain the low correlation values.

Impact of Wind Direction and Speed

In the majority of the studied periods, the "no wind conditions" were 62% in July and 71% (the highest) in December. Thus, wind speed conditions are generally unfavorable for pollution dispersion. Prevailing wind direction is North and North-East, which reaches its maximum share of 6.6–11% in cold months and of 5.4–7.9% in the summer months. Remaining wind directions (blowing from the east, south-east, south, southwest, west, and north-west) had an opposite trend of increasing share in the warmer periods and decreasing in colder months. The least prevailing wind direction was north-west direction with 0.3–2.5%.

Results demonstrate that there is no dominant prevailing wind direction at which the average pollutant concentration was highest or lowest for all seasons and all pollutants. Maximum average concentrations of PM_{10} and SO_2 in winter months were observed when the wind was blowing from the north-west direction. This may address the contribution of the coal-fired CHP-2 located in the north-west zone of the city. The average concentration of NO_2 in the winter period was the highest when there was no wind. This may indicate that the other sources (e.g., transport) can have a higher contribution to NO_2 levels in the city in the

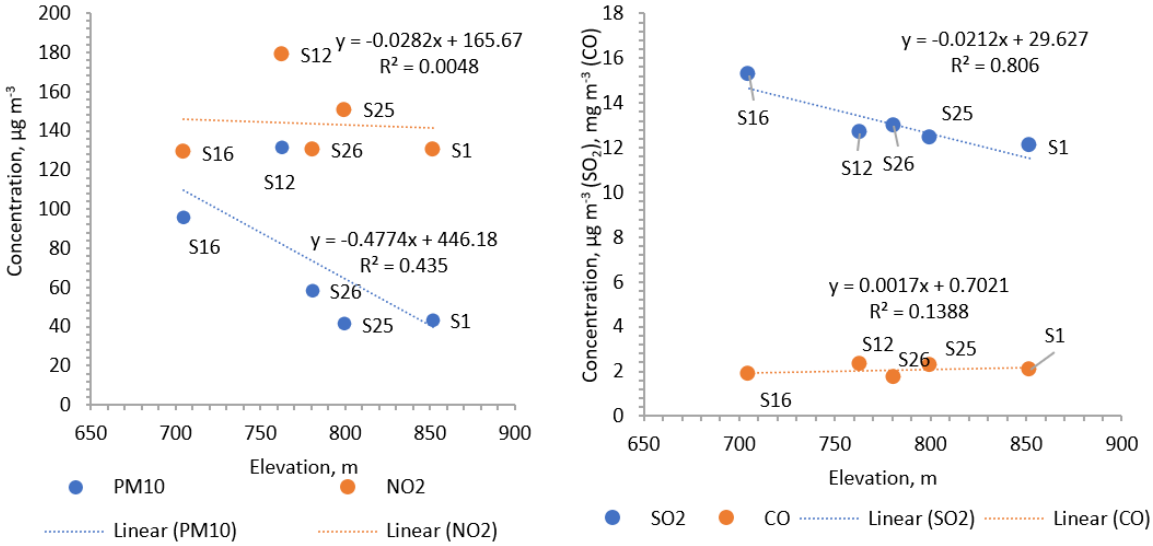

Fig. 6. Effect of the elevation of the monitoring station (x-axis) on the annual average concentrations of PM_{10}, NO_2, SO_2, and CO over 2013–2017 years in µg m^{-3} (except for CO, which is reported in mg m^{-3}) (y-axis).

wintertime. During the summertime, maximum average concentrations of PM_{10}, SO_2, and NO_2 were observed with north-eastern, north-western and northern winds, respectively. This can indicate that SO_2 concentration was affected by the coal-fired CHP plants (located in the northwest), while PM_{10} and NO_2 concentrations were affected by other sources (transport) during the summertime.

Analysis of the Airkaz Data

Annual average $PM_{2.5}$ concentration was 53 µg m^{-3} in 2018, exceeding the WHO annual $PM_{2.5}$ limit 5.3 times, with substantial spatial differences from 27 to 81 µg m^{-3}. This is substantially higher than the population-weighted average in 2015 in Canada and USA (7.9 µg m^{-3}), Western Europe (13.4 µg m^{-3}), global average (43.7 µg m^{-3}), while it is lower than weighted average in China (57.5 µg m^{-3}) and India (74 µg m^{-3}) (Burnett *et al.*, 2018).

The second data set (Airkaz) indicates severe air pollution levels with $PM_{2.5}$. Annual average and daily average $PM_{2.5}$ concentrations exceeded WHO limit values at all stations. Annual average concentrations by stations exceeded the WHO annual limit by 2.7–8.1 times, while daily average concentrations exceeded the daily WHO limit values in the 42–87% of the days of the year. These levels are higher than the exceedances of PM_{10} provided by NAQMN. This indicated that the magnitude of the exceedance of daily and annual limits was higher with the Airkaz network $PM_{2.5}$ data compared to NAQMN PM_{10} data, although the levels of $PM_{2.5}$ from Airkaz cannot be directly compared with NAQMN PM_{10} data (estimated from TSP) because the stations are located at different locations and the periods of measurements are different (2018 for Airkaz and 2013–2017 for NAQM).

Spatial Differences: Districts

Fig. 7 illustrates the estimated share of time in the year in which $PM_{2.5}$ exceeds WHO daily limit value in Almaty.

Majority of the year, the WHO daily limit value was exceeded: 87% in Turksib district, 67% in Alatau district, 61% in Almaly district, 59% in Auezov district and 56% in Bostandyk district, with the exception of Medeu district with slightly lower than a half year (43%). Thus, the Airkaz depicts considerably higher $PM_{2.5}$ exceedance levels in southern areas of the city (43–59%) compared to NAQMN PM_{10} exceedance levels (19–27%). Share of the days with the daily concentrations higher than 75 µg m^{-3} was highest at Turksib district (35%) followed by Alatau (31%), Almaly (25%), Auezov (25%), Bostandyk (21%), and Medeu (9%) districts.

At 21 days of 2018, average daily $PM_{2.5}$ concentration exceeded 250 µg m^{-3} at least in one station. Concentrations above 250 µg m^{-3} correspond to "Hazardous" level of US EPA AQI level indicating severe health impacts on all groups of population with an "emergency" situation (EPA, 2016). In Almaty, such an "emergency" situation due to air pollution has never been announced, probably because the methodology for estimation and the procedure for the announcement by officials is not straightforward, but complicated and bureaucratic.

Analysis of the Elevation and Distance to the Coal-fired Power Plant

Similar to NAQMN PM_{10} data, there was a significant inverse correlation of $PM_{2.5}$ concentration (R^2 = 0.64) with elevation (Fig. 8). Thus, the air quality improved with the increase of elevation and the air quality limit values were also exceeded even at the highest locations, although to the lower extent (2.7 times). $PM_{2.5}$ stations were located at varying distances to the CHP-2 from the closest 4 km to the farthest 18 km. The average annual concentration negatively correlated with the distance to the CHP-2 (R^2 = 0.51) indicating that $PM_{2.5}$ concentration increases with the declining distance to the CHP-2. There was a better correlation with the Airkaz data compared to the NAQMN data, possibly because Airkaz stations located closer (4 km) than NAQMN

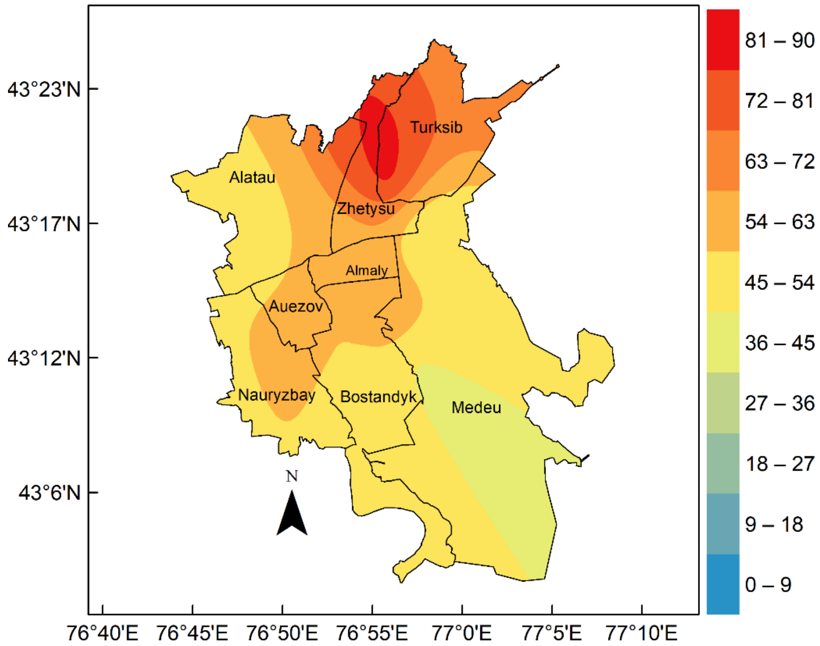

Fig. 7. Estimated share of days in the year, in which $PM_{2.5}$ exceeded WHO daily limit value.

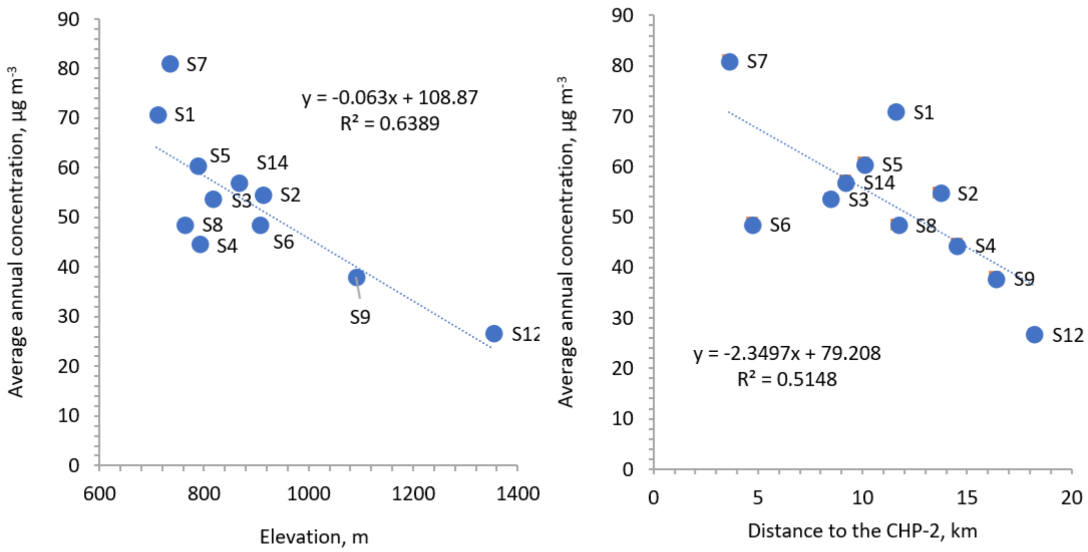

Fig. 8. Average annual concentration of $PM_{2.5}$ in 2018 and elevation (left); average annual concentration and the distance to the CHP-2 (right).

station (7 km). Another reason could be that CHP-2 has a higher removal efficiency for coarse particles (PM_{10}) than for fine particles ($PM_{2.5}$). The results indicate the urgent need for measures to reduce emissions from CHP-2: a fuel switching to gas, installing advanced emissions control technologies, and/or constructing new clean power and heat facilities (gas, renewable sources).

Monthly Variations

Wintertime peak was also pronounced with Airkaz data as maximum to minimum monthly share was 13.7 (Fig. 9). Maximum monthly concentrations were observed in January at ten stations and in December at one station. January and December were characterized by the lowest average monthly temperatures of –10°C and –3°C, respectively, lowest average monthly wind speed (0.2 m s^{-1}) and the highest humidity (81–82%). In Almaty, minimum monthly concentrations at all stations were observed in the warm months: May (3 stations), June (3 stations), July (3 stations), August (2 stations). These results are similar to the monthly variations of NAQMN data for other pollutants.

In Tehran, the stability of the atmosphere was examined using the data from the atmospheric radiosondes data at a synoptic station (Alizadeh-Choobari *et al.*, 2016). Tehran is surrounded by high mountains on two sides; frequent temperature inversions in winter limit horizontal dispersion

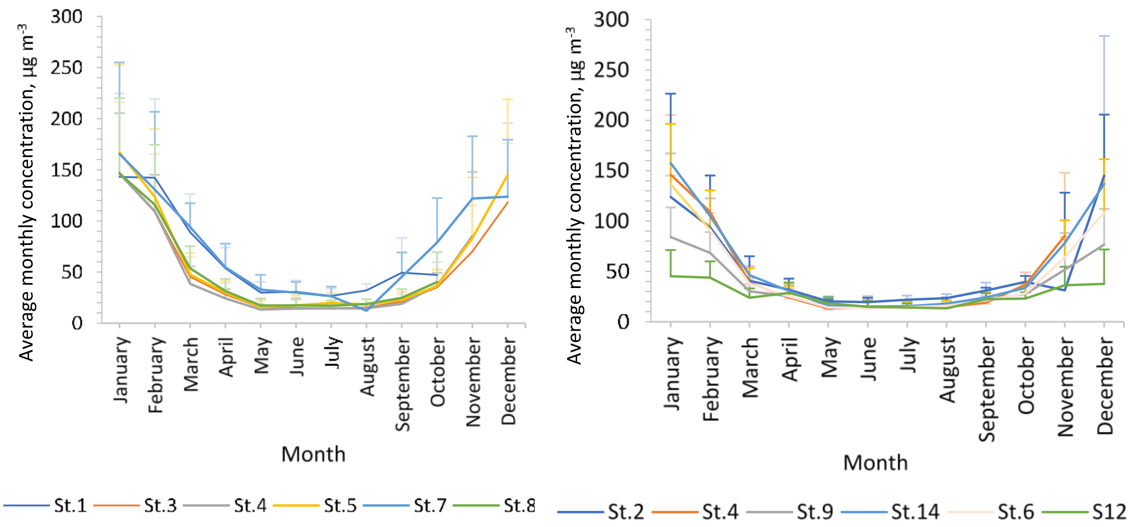

Fig. 9. Monthly average concentrations of $PM_{2.5}$ and standard deviations by stations.

of the pollutants and thus contribute to the high levels of pollution (Alizadeh-Choobari *et al.*, 2016). Ulaanbaatar (capital of Mongolia) is also located in a basin surrounded by mountains and is characterized by long and cold winters. Using lidar and ground-level meteorological observations, Wang *et al.* (2017) studied the variation of the atmospheric boundary layer (ABL) during the 2010 heating season in the episodic days with high air pollution. Wang *et al.* (2017) demonstrated that the atmospheric boundary layer decreased in winter and dropped below 800 m after the second cold wave, which contributed to a high concentration of $PM_{2.5}$ in Ulaanbaatar. In Almaty, there is a lack of meteorological observations on the atmospheric boundary layer. Contribution of surface inversion layer on winter episodes could also be significant for Almaty, and future studies are needed to confirm this statement quantitatively.

Correlation with Meteorological Factors

Daily average concentrations of $PM_{2.5}$ were generally weakly correlated with the temperature, with R^2 varying from 0.09 to 0.37 (Table 3). The determination coefficient was lower at the most polluted districts (Alatau and Turksib districts) and higher at the cleaner districts (Medeu district, $R^2 = 0.365$). The daily average concentrations of $PM_{2.5}$ did not correlate with the wind speed and precipitation (R^2 close to zero). This may be attributed to the fact that wind speed was lower than 0.5 m s^{-1} in 234 days in 2018, and there was no precipitation in 218 days.

At all the stations, the majority of the episode days (the top 25th percentile) were characterized with no precipitation (58–68% from total episode days); with wind speed less or equal to 0.5 m s^{-1} (excluding 0) with the share of 68–74% from total episode days.

CONCLUSIONS

There is a severe air quality degradation in Almaty, which is confirmed by both national air quality monitoring network (NAQMN) and Airkaz independent monitoring network. There was an overall increasing trend of annual PM_{10} concentration in the city over the period 2013–2017. NO_2 and SO_2 concentration levels had fluctuating trends, and CO had a declining trend. This may indicate changing the structure of sources of emissions, with a declining contribution of transport sources due to the improvement of the public transport system and increasing contribution of coal combustion due to the increased heat and electricity generation.

Winter peaks demonstrate the high contribution of large- and small-scale coal combustion for heating because traffic emissions are likely to be stable throughout the year. Pollution levels in the wintertime could also be exacerbated with the lower level of the atmospheric boundary layer and lower wind speed. The annual average $PM_{2.5}$ concentration negatively correlated with the distance to the CHP-2. Coal-fired combined heat and power plants could be significant contributors to PM and SO_2 pollution in the city, although further research such as dispersion modeling and source-apportionment studies are needed to quantify its impact. There is an inverse correlation with the elevation for SO_2, $PM_{2.5}$, PM_{10}, while no correlation was observed for NO_2 and CO. SO_2, $PM_{2.5}$, PM_{10}, which could be mainly generated by point sources typically located at lower elevations (e.g. power plants, residential heating), while NO_2 and CO could originate from nonpoint sources distributed evenly across the city (e.g., transport). Topographic and meteorological conditions may contribute to the higher levels of pollutants at the lower elevation.

The majority of the days during the year in the city is characterized by stable atmospheric conditions, and, therefore, the correlation of pollutant concentrations with meteorological parameters was low. In this study, the height of the atmospheric boundary layer was not analyzed. Future studies are needed to investigate the relationship between the height of the atmospheric boundary layer and the concentrations of pollutants to explore the spatial differences in the meteorological parameters which can be caused by the differences in elevation and urban structures. The monitoring of other pollutants such as ozone and polycyclic aromatic hydrocarbons has to be conducted in Almaty.

Table 3. Determination coefficients (R^2) between daily average concentrations of $PM_{2.5}$ and meteorological factors (temperature, precipitation, wind speed)

	Temperature	Wind speed	Precipitation
Turksib district			
S1	0.147	0.041	0.005
Alatau district			
S7	0.090	0.017	0.006
S8	0.197	0.034	0.002
Bostandyk district			
S2	0.149	0.028	0.001
S3	0.187	0.031	0.004
S6	0.207	0.030	0.003
S9	0.291	0.025	0.023
Medeu district			
S4	0.365	0.057	0.024
Auezov district			
S14	0.209	0.028	0.003
Almaly district			
S5	0.179	0.029	0.008

Urgent measures are needed to reduce emissions from CHP-2: switching it to gas, installing advanced emissions control technologies, or constructing new clean power and heat plant (e.g., gas, renewable energy sources). Household coal combustion should be discouraged, with incentives provided to switch to cleaner options. Measures in the transport sector could include stringent standards for vehicle emissions and further improvement of the public transport system (e.g., expansion of the subway routes). In households, a gradual coal ban can be introduced.

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