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Impact of Covid-19 lockdown on air quality in the Poland, Eastern Europe

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ABSTRACT

The first case of COVID-19 in Poland was registered on 4 March 2020. Governmental measures significantly restricted social and economic activities. This study investigates the impact on air quality resulting from the preventive measures taken by the government to manage Covid-19. The study was carried out with use of aerosol optical depth (AOD) retrieved from Moderate Resolution Imaging Spectrometer (MODIS) satellite and tropospheric column NO_2 observed by Ozone Monitoring Instrument (OMI). Concentrations of atmospheric pollutants ($PM_{2.5}$, PM_{10}, NO_2 and SO_2) retrieved from ground-based air quality stations, located in five large cities of the country, were also used for quantitative assessment of air quality change. Ground-based and satellite data demonstrated the reduction of pollutants in the period of lockdown as compared to the same periods in 2018 and 2019. In particular, AOD data shows reductions of aerosol concentrations in the air column in April and May of approximately by −23% and −18% as compared to 2018–2019. The greatest contraction was for $PM_{2.5}$ in April and May with reductions of −11.1% to −26.4% and from −8.7 to −21.1% respectively. For $PM_{10,}$ the reductions were from −8.6% to −33.9% and from −8.5% to −31.5% as compared to the same months in 2019. The results showed that restrictions imposed to prevent the spread of COVID-19 significantly improved Poland's air quality.

1. Introduction

COVID-19 was first identified in December 2019 in Wuhan, Hubei province, China. As early as the end of February the number of new COVID-19 cases outside China exceeded the number of infections within the country. Having spread first in China, and later in the neighboring countries, and then in the countries of North and Latin America and Europe, COVID-19 became a severe global pandemic.

China government adopted drastic measures to prevent the virus' spread, including restrictions on movement around the country, reduction of public transport, closure of schools, shops and many businesses (Filonchyk et al., 2020). These measures led to a decrease in the spread of the virus in the country. By March, there was a large increase in the number of confirmed cases in many European countries including Italy, Spain, Germany and Great Britain. Lockdowns were imposed leading to a drastic reduction in the use of fossil fuels.

Recent studies, carried out in various regions of the world, showed that national lockdowns led to local reductions of pollutants in the atmosphere. In Quito, the capital of Ecuador, there was a reduction in concentrations of $PM_{2.5}$ (−29%), SO_2 (−48%), NO_2 (−68%) and CO (−38%) in the first month of quarantine (17 March-12 April 2020) (Zalakeviciute et al., 2020). In the Eastern Europe, in the lockdown period, there was a significant reduction in CO (−20%) and NO_2 (−30%), associated with the decrease of anthropogenic and transport activity (Filonchyk et al., 2020). In the urban areas of Malaysia, in the period of lockdown, the concentrations of PM_{10}, $PM_{2.5}$, NO_2, SO_2 and CO were reduced by 26–31%, 23–32%, 63–64%, 9–20% and 25–31%, respectively, as compared to the corresponding periods in 2018 and 2019 (Kanniah et al., 2020). In the two largest cities of Spain, Madrid and Barcelona, there was a reduction of car traffic by 75% in the lockdown period, which led to the decrease of NO_2 concentration by −62% and −50%, respectively (Baldasano, 2020). In the 22 largest Indian cities, located in different regions of the country, there was a reduction of PM_{10} (−31%), $PM_{2.5}$ (−43%), NO_2 (−18%) and CO (−10%) concentrations in the lockdown period as compared to the preceding years (Sharma et al., 2020). Nevertheless, in spite of the significant improvement of the air quality in many regions, it had a short-term effect, since during the gradual increase of human activity after lockdown, there was an increase of emissions up to the lockdown period (Bherwani et al., 2020; Chen et al., 2020; Filonchyk et al., 2020; Filonchyk and Peterson, 2020; Wang and Su, 2020). The majority of studies covered different regions of Asia and Latin America (Broomandi et al., 2020;

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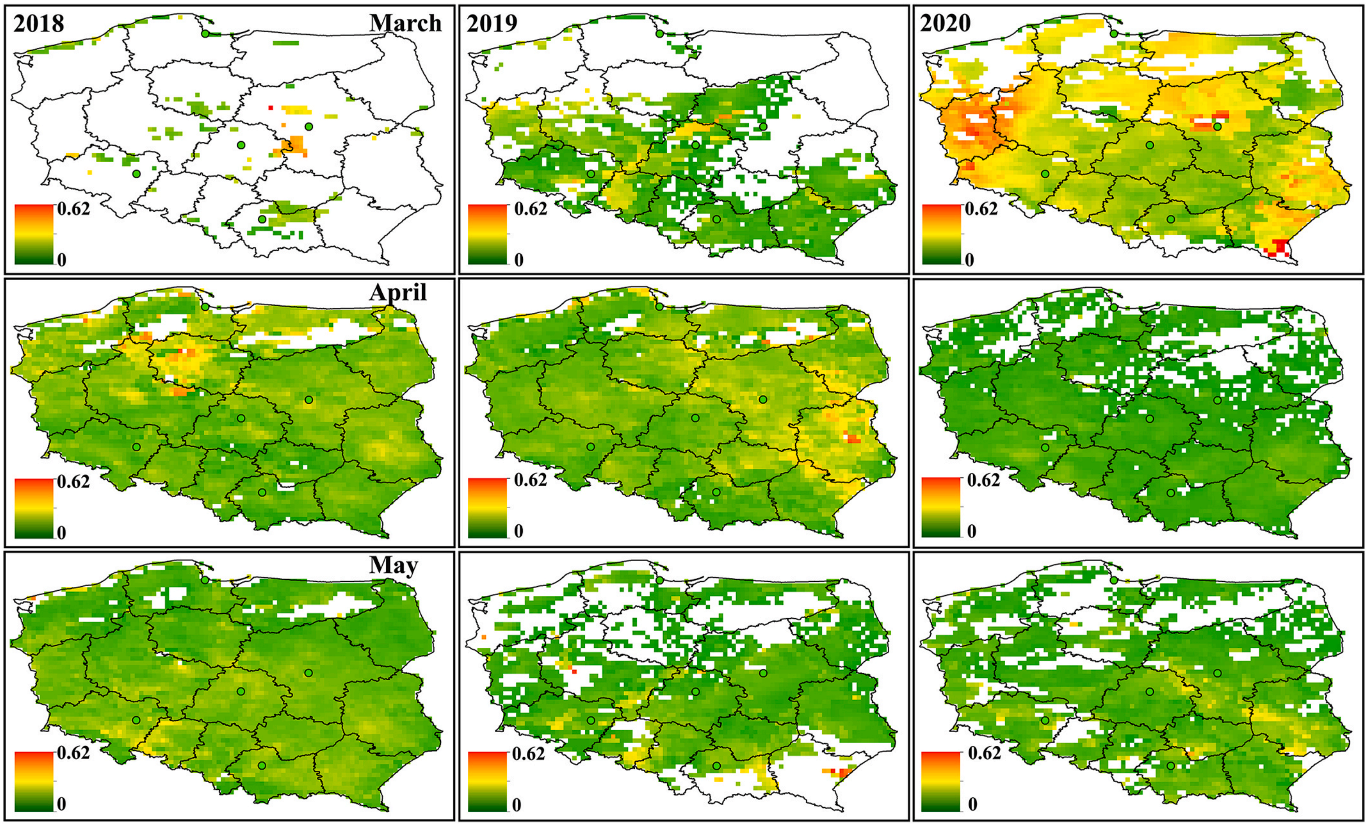

Fig. 1. Spatial distribution of MODIS AOD at 550 nm during March, April and May from 2018 to 2020.

Dantas et al., 2020; Mahato et al., 2020; Siciliano et al., 2020; Velásquez and Lara, 2020; Zambrano-Monserrate and Ruano, 2020). Only a small number of studies examined regions in Europe, including various areas in Italy (Bontempi, 2020; Zoran et al., 2020) and Spain (Baldasano, 2020). No similar studies have examined Eastern Europe. Therefore, this study intends to investigate the impact of lockdown on air quality in Poland, the largest country in Eastern Europe.

2. COVID-19 outbreak in Poland

Poland suffered from COVID-19 like many other countries. The first case of COVID-19 was registered on 4 March 2020. As of 12 July 2020, there have been 37,216 cases and 1562 deaths. The government of the country declared an epidemic threat from 14 March 2020. A partial limitation of passage across the state border was implemented the following day including air and railway transport passage. Citizens were told not to leave their houses unless absolutely necessary. The government closed of all educational facilities, including child care institutions, for two weeks (from 12 to 25 March 2020). Passport control was introduced on all land frontiers of the country, and only Polish citizens could enter the country. After arrival, all citizens needed to quarantine for 14 days. A prohibition on all public events came into effect. Entertainment facilities and foodservice outlets were closed. The majority of firms closed their offices and implemented work from home.

The main objective of this work is to study the effect of the COVID-19 lockdown on air quality in Poland. Data on $PM_{2.5}$, PM_{10}, NO_2 and SO_2, obtained from automatic air quality monitoring stations located in the largest cities of the country, were analyzed and compared to the values of 2018 and 2019. An evaluation of columnar aerosol optical depth (AOD) and tropospheric NO_2 concentrations obtained with Moderate Resolution Imaging Spectrometer (MODIS) and Ozone Monitoring Instrument (OMI) was also carried out. The findings obtained may help to implement future environmental protection measures after the pandemic to maintain the best air quality within the entire region.

3. Methods

3.1. Ground-based observations of air pollutants

Data on surface concentrations of atmospheric pollutants were obtained based on hourly concentrations of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 received from Chief Inspectorate for Environmental Protection (http://powietrze.gios.gov.pl/pjp/archives). Hourly data on mass concentrations of the four pollutants were retrieved from automatic stations of air quality monitoring, located in the five largest cities of the country, namely Warsaw, Wroclaw, Lodz, Krakow and Gdansk. Daily mean concentrations of each pollutant were obtained using hourly data averaging. Data were retrieved from 28 automatic air quality monitoring stations located in various areas, including urban, suburban, rural and industrial zones.

3.2. Satellite data observations

Moderate Resolution Imaging Spectrometer (MODIS) is a part of NASA EOA (Earth Observing System); on board the Terra and Aqua satellites and provides for continuous monitoring of aerosols with high spatial-temporal resolution. Since Aqua satellite crosses the Equator at 1:30 p.m. like the Aura satellite at 1:45 p.m., this study will use data retrieved from Aqua satellite. MODIS Level 2 Collection 6.1 aerosol products with spatial resolution 10 km were downloaded from the Level 1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (LAADS DAAC). This study uses MODIS combined Dark Target and Deep Blue AOD retrievals algorithm that uses high-quality AOD retrievals and combines both Dark Target (over dark surfaces) and Deep Blue (over lighter surfaces) retrievals (Hsu et al., 2013; Levy et al., 2013). The expected error over land and ocean is $\pm 0.05 \pm 0.15 \times$

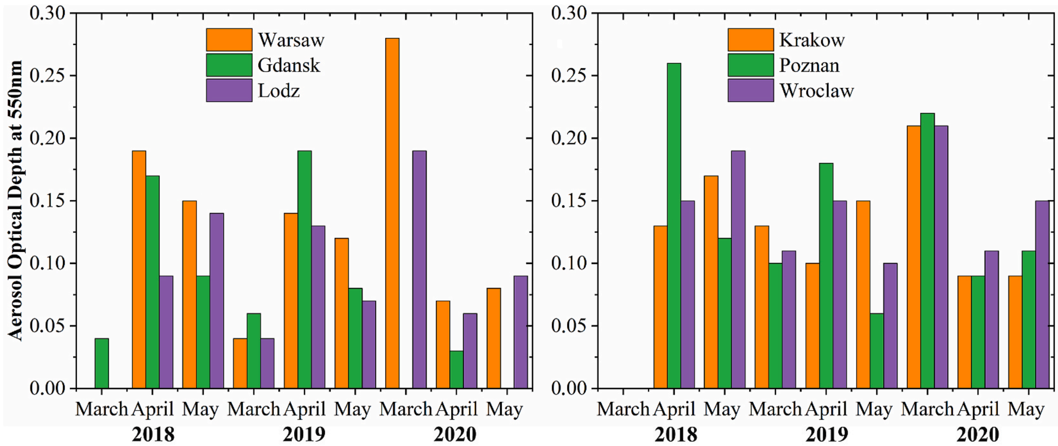

Fig. 2. The monthly mean AOD at 550 nm over six large cities in Poland during March–May 2018–2020.

AOD and ±0.03 ± 0.05 × AOD, respectively (Remer et al., 2005).

A regional study of tropospheric NO_2 content may be done more efficiently using OMI (Ozone Monitoring Instrument) measurements aboard the NASA Aura satellite (Levelt et al., 2006) since this device combines relatively high spatial and temporal data resolution. OMI device measures the solar radiation scattered by the Earth's atmosphere in ultraviolet and visible parts of spectrum with spectral resolution of ~0.5 nm and spatial resolution of 13 × 24 km^2 in nadir, and the full (horizontal) scanning is done within 24 h (in high latitudes, due to overlapping of neighboring satellite orbits, OMI may do several measurements over the same area during daylight hours). NO_2 content is determined using spectral range of 405–465 nm (Boersma et al., 2007). NO_2 content in the slant column of atmosphere is determined directly from the measurements. This study uses level-3 daily OMI tropospheric NO_2 product with a spatial resolution of 0.25° available in NASA GES DISC archive.

4. Results and discussion

4.1. Satellite observations of AOD

Data on aerosol ratios were obtained with Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS proved itself to be good in AOD observations, showing slight uncertainties in many regions of the world (Wang et al., 2019; Filonchyk and Hurynovich, 2020). Fig. 1 shows monthly mean AOD at 550 nm retrieved from MODIS that were compared between the periods, including March, April and May 2018, 2019 and 2020. The comparison was carried out to identify potential changes in the atmospheric column during COVID-19 period.

It is worthwhile noting that quantitative characteristics of AOD changes are in a wide range (from 0 to 0.62) over the whole territory of the country, while the major part of the country is in the range from 0 to 0.3 indicating a low aerosol loading and thus the lower turbidity of atmosphere as compared to other regions of the world in the period before and during the pandemic (Filonchyk and Peterson, 2020; Kanniah et al., 2020; Nichol et al., 2020). When comparing images for March 2018, 2019 and 2020, it can be noted the increase of AOD values up to 0.3–0.62 over the major area of the country in 2020 as compared to the previous years. Nevertheless, in April and May, a remarkable AOD decrease is noted by approximately −23% and −18% as compared to 2018 and 2019. This may be related to implementation of quarantine measures, associated with reduction of economic activity, suspension of high power-consuming plants, suspension of air and railway traffic, decrease of power production, which leads to reduction of anthropogenic emissions into atmosphere, thus reducing aerosol loading (Alshayef et al., 2019). AOD reduction in the period of partial lockdown may also be associated with restrictive measures, taken in other EU countries (Menut et al., 2020; Zoran et al., 2020), resulting in reduction of pollutants transportation to other neighboring regions. Nevertheless, the foci with higher AOD, observed in April and May 2020, may be related to some kinds of agricultural activity, associated with emissions from biomass and peat burning and dust (Ahmed et al., 2020) due to people staying-at-home.

Table 1
Relative percentage change in AOD at 550 nm during March–May 2018–2020. (where: 2020/2019 is ratio of 2020 vs 2019, 2020/2018 is ratio of 2020 vs 2018).

	2018/2020			2019/2020		
	March	April	May	March	April	May
Warsaw	–	−63.2	−46.7	60	−50	−33.3
Gdansk	–	−82.4	–	–	−84.2	–
Lodz	–	−33.3	−35.7	37.5	−53.8	28.6
Krakow	–	−30.8	−47.1	61.5	−10	−40
Poznan	–	−65.4	−8.3	120	−50	–
Wroclaw	–	−26.7	−21.1	90.9	−26.7	50

Apart from high spatial-temporal variability in AOD variations in the regional scale, a study of aerosol ratios variation in the largest cities of the country was carried out (Fig. 2). The results suggest AOD reduction in April and May over Warsaw (0.19, 0.14, 0.07 and 0.15, 0.12, 0.08), Gdansk (0.17, 0.19, 0.03 and 0.09, 0.08), Lodz (0.09, 0.13, 0.03 and 0.14, 0.07, 0.09) Krakow (0.13, 0.1, 0.09 and 0.17, 0.15, 0.09), Poznan (0.26, 0.18, 0.09 and 0.12, 0.06, 0.11) and Wroclaw (0.15, 0.15, 0.11 and 0.19, 0.1, 0.15) for 2018, 2019 and 2020, respectively. No AOD data were obtained in March over almost all cities and in May over Gdansk and Poznan. These cities are characterized by a high anthropogenic activity with various types of industry. Data shown in Table 1 suggest AOD reduction in the range from −10% (Krakow) to −84.2% (Gdansk) in April and from −8.3% (Poznan) to −47.1% (Krakow) in May as compared to previous years. Significant AOD decrease in all the areas is attributed to the total cessation of anthropogenic activity aimed at preventing the spread of COVID-19 (Jarynowski et al., 2020). Similar results were obtained in other regions of the world, where AOD decrease occurred in the period of partial lockdown.

4.2. Satellite observations of NO_2

Nitrogen oxides are some of the most hazardous ingredients in smog. Their toxicity is many times higher as compared to carbon monoxide or sulfur dioxide. Nitrogen dioxide (NO_2), which is most commonly formed as a result of nitrogen oxide (NO) oxidation in the atmosphere, is particularly dangerous for human health (Kamarehie et al., 2017). This

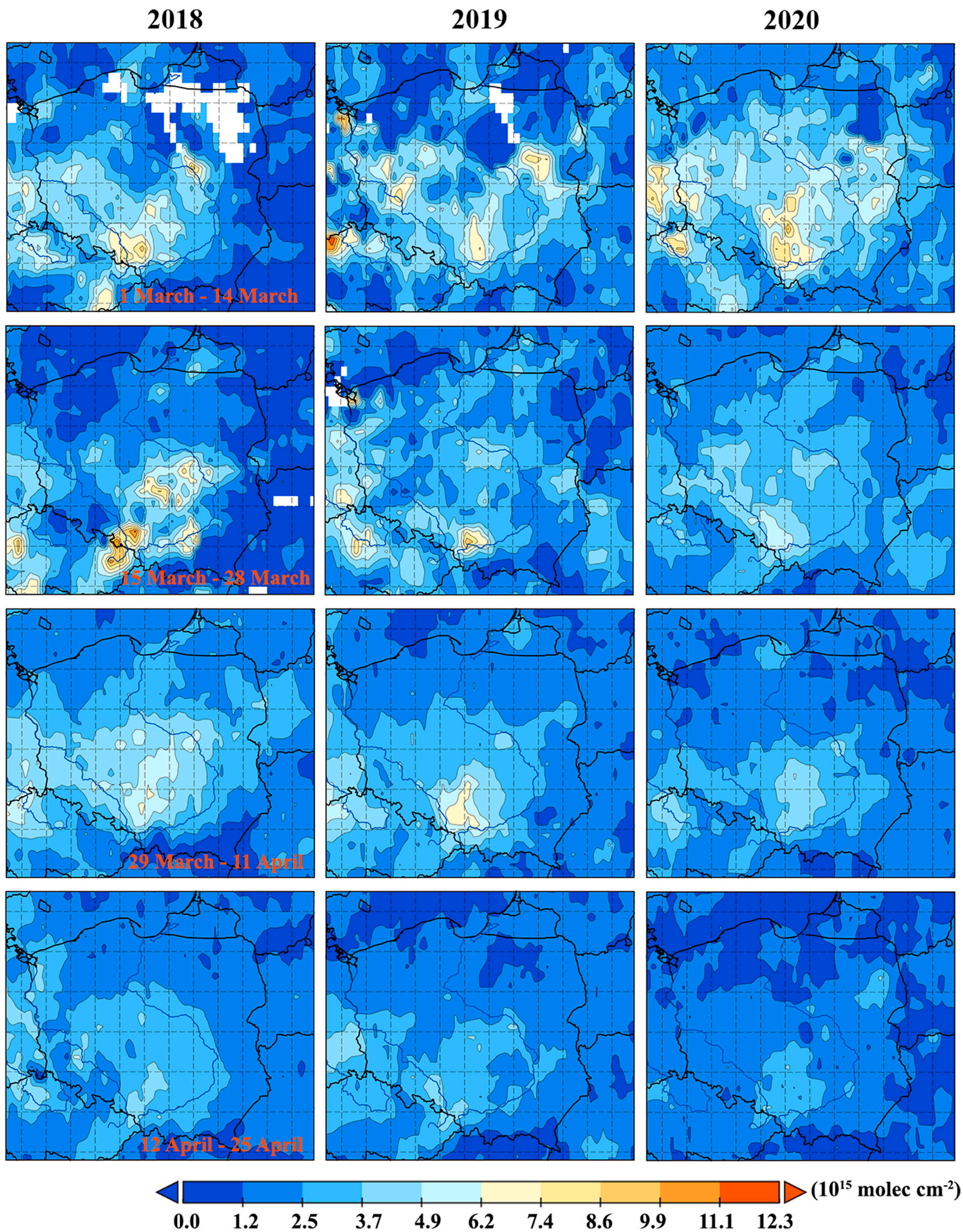

Fig. 3. Spatial distribution of tropospheric OMI NO_2 during four periods from 2018 to 2020.

gas is the main reason of photochemical smog formation in the cities with the greatest motor-vehicle traffic. Nitrogen dioxide easily undergo chemical reactions. The main anthropogenic source of NO_2 formation is burning of any fossil types of fuel (motor-vehicles, power generation, manufacturing facilities) (Li et al., 2018). The higher air concentrations of NO_2 are observed in large Polish cities (Krakow, Warsaw, Wroclaw) as compared to other cities of the country; it is associated with high motor-vehicle traffic.

Fig. 3 shows the tropospheric NO_2 column obtained with OMI satellite sensor. The data were averaged for a fortnight period before (Period 1: 1–14 March) and during (Period 2: 15–25 March, Period 3: 26 March - 11 April, and Period 4: 12 April - 25 April) lockdown measures taken in 2020, and for the same fortnight period in 2018 and 2019. NO_2 is used as an indicator of total activity connected with emissions in

Table 2
Relative percentage change in OMI NO_2 during 2018–2020. (where: 2020/2019 is ratio of 2020 vs 2019, 2020/2018 is ratio of 2020 vs 2018).

	2020 vs 2019				2020 vs 2018			
	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4
Warsaw	5.8	−5.1	9.2	−110.5	−30.8	−62.2	2.1	−78.9
Gdansk	−76.5	−18	−25.8	−18.8	−82.4	−13	−35.5	−18.8
Lodz	50.6	−16.2	−4.8	−25	19	−161.3	−45.2	−7.1
Krakow	−8.3	−45.8	−35.6	−13.2	6.7	−10.4	−37.8	−7.4
Poznan	26.4	39.5	−100	−60	26.4	11.6	−186.7	−153.3
Wroclaw	−2.8	−3.5	−30	−13	3.9	12.3	−70	−4.3

different regions of the country. The observed tropospheric NO_2 showed the reduction of values over the entire area of Poland from the mid-March (Period 2) and in April (Period 3 and Period 4) 2020 as compared to the same period in 2018 and 2019.

Considerable reduction of NO_2 concentration was detected in many large Polish cities, such as Warsaw, Krakow, Lodz, Gdansk, Poznan and Wroclaw. It is predominantly associated with reduction of traffic and the quantity of motor-vehicles on the roads of the country. In late March, the General Directorate for National Roads and Motorways reported the reduction of motor-vehicles on the roads by 25–54% as compared to the same period of 2019. Statistical data, obtained by Apple, about the number of movements during COVID-19 pandemic, based on the number of routing queries in Apple Maps, showed the reduction of transport activity in the cities of the country by more than 60%, and walks by more than 65% (Apple Inc, 2020). This data is generated based on the count of a number of routing queries in Apple Maps in certain countries/regions, subregions and cities. In other regions of the country with smaller population densities, changes in NO_2 concentration were not as significant.

Generally, NO_2 concentrations in Poland in Period 1 were higher by 15% and 13% than in 2019 and 2018. After the implementation of lockdown measures, there was a reduction in NO_2 in Period 2 by −25% and −19%, respectively, as compared to the same period of 2018 and 2019. For Period 3 and Period 4, there was also a noted reduction generally in the country by −16%, −18% and −13%, −10%, respectively, as compared to the previous years. Similar results were also obtained by Menut et al. (2020), which reported a reduction of NO_2 concentration by −27% in March 2020 as compared to the same period of 2019. When considering the largest cities of the country, almost in all the cities, the concentrations of tropospheric NO_2 in Period 1 were higher, than in the same period of 2019 and 2018. In Period 2 in Krakow, Gdansk and Lodz, there was a reduction approximately by −45.8%, −18% and −16.2%, respectively, in Warsaw and Wroclaw, there were insignificant reductions by −5.1% and −3.5%, respectively.

In Periods 3 and 4 there was a significant reduction revealed in Poznan, Krakow, Wroclaw, Gdansk by −100% and −60%, −35.6% and −13.2%, −30% and −13%, −25.8% and −18.8% as compared to the same period of 2019 (see Table 2). This is attributed to the traffic limitations due to the partial lockdown. As has been mentioned before, such significant reductions are predominantly related to the decrease of motor-vehicle traffic. Anthropogenic activity in all the periods was at the same level as in the previous years. In proof of this assertion, data on active fire and thermal hotspot retrieved from Visible Infrared Imaging Radiometer Suite (VIIRS) were used. VIIRS detects hotspots, and spatial resolution of 375 m gives information about fires on relatively small areas of territory (Schroeder et al., 2014). The results showed that the number of fire spots in the country for March–April was practically the same for the last three years. In 2018 there were 1546 fire spots, in 2019 - 1486 fire spots and in 2020 - 1788 fire spots. This proves that anthropogenic activity did not change in the period of lockdown, and moreover, people staying at home could engage in agricultural activity, likely the reason for the increase of fire spots.

4.3. Ground-based concentrations of air pollutants

A total of 28 automatic air quality monitoring stations were used to study surface concentrations of pollutants, such as $PM_{2.5}$, PM_{10}, NO_2 and SO_2. However, it is worthwhile noting that many stations only monitor some of these pollutants. Thus, $PM_{2.5}$ concentrations is monitored in 11 stations, PM_{10} in 23 stations, NO_2 in 19 stations and SO_2 in 12 stations in

Table 3
Average daily concentration of $PM_{2.5}$, PM_{10}, NO_2 and SO_2 ($\mu g/m^3$) in Wroclaw, Lodz, Krakow, Warsaw and Gdansk during March–May 2018–2020.

Cities		2018			2019			2020			Relative % Change					
											2020 vs 2018			2020 vs 2019		
		March	April	May	March	April	May	March	April	May	March	April	May	March	April	May
Wroclaw	$PM_{2.5}$	37.9	19.7	15.3	18.8	21.3	13.3	20.9	16	10.5	−45	−18.9	−31.2	11.1	−24.7	−21.1
	PM_{10}	43.1	31	23.3	28	33.5	19.2	26.7	26.8	14.1	−37.9	−13.5	−39.6	−4.3	−20.1	−26.9
	NO_2	32.6	26.9	24.6	24.1	26	23.3	24.1	23.4	22	−25.9	−12.8	−10.6	0.3	−9.9	−5.3
	SO_2	4.9	2.6	2.4	3.9	5.2	2.7	5.1	5.8	3.2	4.3	127.3	33.7	29.8	11.1	18.5
Lodz	$PM_{2.5}$	32.9	16.6	12.2	18.5	19.2	12.9	20.8	14.2	10.2	−36.9	−14.7	−16.3	12.5	−26.4	−20.7
	PM_{10}	47.5	33.1	26.9	29.6	40.5	22.7	35.9	34.6	20.8	−24.5	4.6	−22.7	21	−14.5	−8.5
	NO_2	32.6	26.9	24.6	20.7	31.9	22.3	25.4	24.2	20.4	−22	−10.1	−17	22.6	−24.2	−8.5
	SO_2	9.6	3.8	2.3	5.2	3.8	2.6	4.6	3.9	2.7	−52.4	2.1	17.6	−13	3.7	1.2
Krakow	$PM_{2.5}$	52.7	24.4	19.1	26.7	24.4	15.7	27.3	21.7	14.4	−48.2	−11.2	−24.8	2.3	−11.1	−8.7
	PM_{10}	69.8	41	29.9	38.6	36.3	23.3	36.7	33.2	21	−47.3	−19	−29.8	−4.8	−8.6	−9.9
	NO_2	47.4	44.4	38	40.6	40.2	35.1	34.8	31.9	28	−26.6	−28.2	−26.3	−14.2	−20.7	−20.2
	SO_2	11.3	4.8	5.1	7.2	5.6	3.7	5.3	5	3.6	−53.5	3.4	−28.8	−26.7	−11.2	−1.4
Warsaw	$PM_{2.5}$	35.7	20	13.3	19.8	21	14	24.5	16.7	12.3	−31.5	−16.4	−7.8	23.4	−20.4	−12.4
	PM_{10}	47.5	35.6	29.3	28.4	36.2	21.9	33.3	31.9	19.7	−29.9	−10.4	−32.9	17.2	−11.8	−9.9
	NO_2	37.7	37.7	30.2	33.3	29.6	30.6	28.3	27.1	24.6	−25.1	−28.2	−18.7	−15.2	−8.6	−19.6
	SO_2	–	–	–	3.7	2.4	0.9	4.3	3	2.7	–	–	–	16	27.7	190.8
Gdansk	$PM_{2.5}$	21.9	16.9	13.7	–	–	–	24.4	12.5	9.4	11.4	−25.6	−31.4	–	–	–
	PM_{10}	25.5	22	18.8	14.2	28.2	18.7	23.4	18.6	12.8	−8.4	−15.2	−31.5	64.2	−33.9	−31.5
	NO_2	19.9	17.1	13.8	12.8	17.1	12.2	16.3	11.7	8.4	−18.4	−31.7	−38.7	27.3	−31.7	−30.8
	SO_2	3.9	4.5	2.7	2.3	2.5	1.9	4.4	3.7	2.6	12.8	−18.3	−4.5	86.4	49.6	37.6

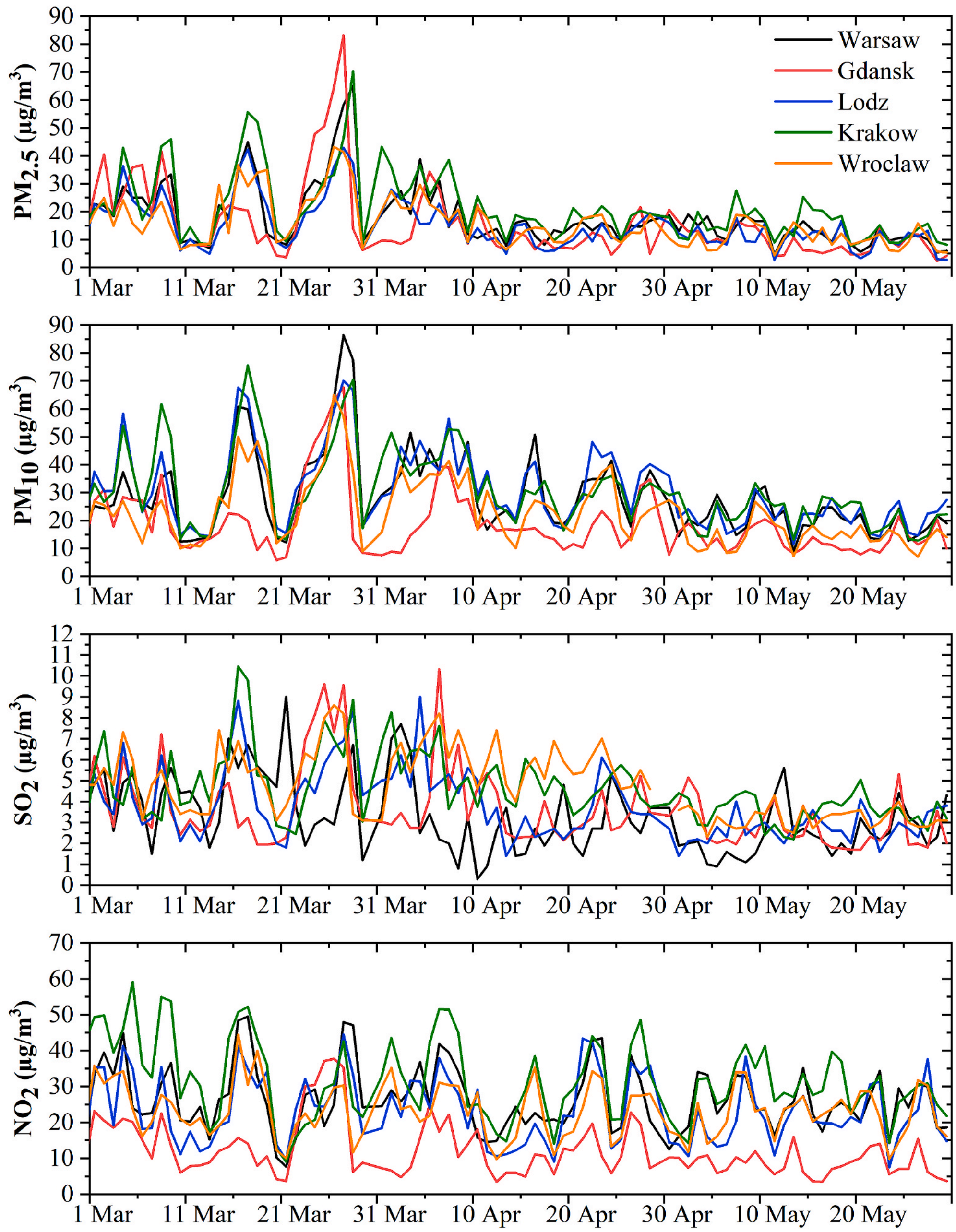

Fig. 4. Daily variability of the $PM_{2.5}$, PM_{10}, SO_2 and NO_2 concentrations in five cities of Poland during March–April 2020.

five cities. The analysis performed may help to evaluate the contribution of different sources on the total decrease or increase of pollutants during the COVID-19 lockdown period. Table 3 shows daily mean concentrations of $PM_{2.5}$, PM_{10}, NO_2 and SO_2 in Wroclaw, Lodz, Krakow, Warsaw and Gdansk, and there was also a comparison carried out between the period from March to May 2020 with the same period in 2019 and 2018.

Generally, pollutant concentrations in 2020 were lower compared to 2018, however, as against 2019, some cities experienced the increase of pollutants in 2020, especially in March (Table 3), when lockdown measures were not yet fully implemented. In April and May, there was a significant reduction of all pollutants, except for SO_2, as compared to the previous years. The greatest reductions of $PM_{2.5}$ were registered in Wroclaw in April (−18.9% and −24.7%) and May (−31.2% and −21.1%), Lodz in April (−14.7% and −26.4%) and May (−16.3% and −20.7%) as compared to 2018 and 2019. Nevertheless, other cities also showed significant reductions in $PM_{2.5}$ concentrations in April by −20.4% (Warsaw) and −11.1% (Krakow) as compared to the same period of 2019.

Although, there was a significant $PM_{2.5}$ reduction in many cities, the $PM_{2.5}$ concentrations still exceeded concentrations recommended by WHO (10 μg/m^3). For PM_{10}, the levels also exceeded that recommended by WHO (20 μg/m^3). There was, however, a significant reduction in April and May in all the cities as compared to the previous years. In particular, in April and March, PM_{10} concentrations in Gdansk were reduced by −33.9% and −31.5% and in Wroclaw by −20.1% and −26.9% as compared to 2019. An even greater reduction was observed in relation to NO_2 levels, which in April and May were reduced the greatest in Gdansk by −31.7% and −30.8% and Krakow by −20.7% and −20.2% as compared to 2019. Data on surface NO_2 concentrations is to a great extent similar to the results of tropospheric NO_2 concentrations, obtained by OMI satellite (Fig. 3).

As has been mentioned before, the main reason for $PM_{2.5}$, PM_{10} and NO_2 reduction was a significant decrease of international and local transportation, reducing the consumption of crude oil and coal, greatly influencing air quality. Coronavirus closed schools, museums, cinemas, shop malls and slowed down the development of global industry and transport (Jarynowski et al., 2020). While the power demand for households increased as people stayed home, the suspension of production in many sectors of industry caused an overall reduction in power consumption, reaching 20% as compared to 2019. It is worth noting that in 2018 the main raw material for power production in Poland was coal and crude oil. The country consumed 50.5 million tons of oil equivalent of coal and 32.8 million tonnes of oil (BP, 2019). According to PSE-Operator, the coal share in power production in the pandemic period was reduced by 24%. Nevertheless, it is worthwhile to suggest that the reduction in pollution will be short-term. With the end of the pandemic, the chimneys of electric power plants will start emit smoke again.

The main source of SO_2 emissions is an active burning of fuel (predominantly coal) in stationary sources, constituting almost 100% of national emissions of sulfur dioxide (KOBiZE, 2018). SO_2 emission in the course of production is related to the processing of crude oil, coke and sulfuric acid production and constitutes only about 2.6% of the national emissions. Generally, motor-vehicles are responsible for only about 0.0005% of national emissions of sulfur dioxide due to low sulfur content in the liquid fuel consumed (KOBiZE, 2018). As compared to other pollutants, SO_2 concentration in air increased, related to the fact that some manufacturing facilities continued working during the quarantine period. The greatest increase was detected in Gdansk by 86.4%, 49.6% and 37.6%; and Warsaw by 16%, 27.7% and 190.8%, respectively, as compared to March, April and May 2019. Nevertheless, in Krakow, SO_2 concentrations were reduced, which is associated with reduction of industrial activity. It is worth noting that it is freely soluble in water and carried by air and its duration of stay in atmosphere is about two weeks. Therefore, SO_2 pollution is of regional significance in view of the fact that a cloud with gas may be transported regionally, indicating that sources and regions of pollution may be different.

Fig. 4 shows daily change of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 concentrations before and during a partial lockdown. Starting from the late March, sharp reduction of $PM_{2.5}$, PM_{10} and SO_2 concentrations was registered in all the cities under study.

It is worth noting that although NO_2 concentrations decreased as compared to the previous years, the pollutant concentrations before and after lockdown albeit reduced, it was not so significant as other pollutants. Nevertheless, as is seen from the figure, all the pollutants are characterized by a well-defined weekly variation with peaks corresponding to the weekends. This may be related to the increase of motor-vehicle traffic due to active leaving the cities by the population to rest in the country. These results emphasize that significant reduction in pollutants emission may be associated with restrictive measures aimed to prevent COVID-19 distribution.

5. Conclusions

This study showed the extent to which the lockdown to prevent the spread of COVID-19 in Poland affected the spatial and temporal aspects of air pollution. Data retrieved from ground-based air quality monitoring stations, located in five large cities of the country (Wroclaw, Lodz, Krakow, Warsaw and Gdansk), showed a reduction of pollutant concentrations as compared to the same periods of the previous years. The greatest reduction was registered in April and May for $PM_{2.5}$ with range from −11.1% to −26.4% and from −8.7 to −21.1%, for PM_{10} the reductions were from −8.6% to −33.9% and from −8.5% to −31.5% as compared to the same period of 2019.

AOD data retrieved from the MODIS satellite also showed reductions of aerosol concentration in the air column in April and May approximately by −23% and −18% as compared to 2018 and 2019. In addition, Tropospheric NO_2 retrieved from the OMI satellite instrument showed a clear reduction starting from 15 March to 25 April approximately by −10 to −19%. Less economic activity, closure of high power-consuming plants, suspension of air and railway traffic, reduction of car traffic, decrease of power production all led to a reduction of emissions into the atmosphere resulting in a marked improvement in air quality. The findings represent a unique opportunity to implement future environmental protection measures after the COVID-19 pandemic to maintain the best air quality within the entire region. The results show that even short-term changes in anthropogenic activity can significantly affect air quality. These results can serve as a reference for many countries in assessing the impact of the COVID-19 on the global environment.

CRediT authorship contribution statement

Mikalai Filonchyk: Writing - original draft, Methodology, Conceptualization, Software, Data curation. **Volha Hurynovich:** Writing - review & editing, Visualization, Methodology. **Haowen Yan:** Project administration, Writing – review & editing.

Declaration of competing 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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References

Ahmed, A., Nawaz, R., Woulds, C., Drake, F., 2020. Influence of hydro-climatic factors on future coastal land susceptibility to erosion in Bangladesh: a geospatial modelling approach. J. Geovisual. Spatial Anal. 4, 1–24.

Alshayef, M.S., Javed, A., Mohammed, A.M.B., 2019. Appraisal of potential hydrocarbon zones in Masila oil field, Yemen. J. Geovisual. Spatial Anal. 3 (2), 17.

Apple Inc, 2020. COVID-19 - Mobility Trends Reports. https://www.apple.com/covid19/mobility. (Accessed 22 July 2020).

Baldasano, J.M., 2020. COVID-19 lockdown effects on air quality by NO2 in the cities of Barcelona and Madrid (Spain). Sci. Total Environ., 140353

Bherwani, H., Nair, M., Musugu, K., Gautam, S., Gupta, A., Kapley, A., Kumar, R., 2020. Valuation of air pollution externalities: comparative assessment of economic damage and emission reduction under COVID-19 lockdown. Air Qual. Atmos. Health 13, 683–694.

Boersma, K.F., Eskes, H.J., Veefkind, J.P., Brinksma, E.J., Van Der A, R.J., Sneep, M., Bucsela, E.J., 2007. Near-real time retrieval of tropospheric NO 2 from OMI. Atmos. Chem. Phys. 2013–2128.

Bontempi, E., 2020. First data analysis about possible COVID-19 virus airborne diffusion due to air particulate matter (PM): the case of Lombardy (Italy). Environ. Res., 109639

BP, 2019. BP Statistical Review of World Energy 2019, 68th edition https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

Broomandi, P., Karaca, F., Nikfal, A., Jahanbakhshi, A., Tamjidi, M., Kim, J.R., 2020. Impact of COVID-19 event on the air quality in Iran. Aerosol Air Qual. Res. https://doi.org/10.4209/aaqr.2020.05.0205.

Chen, Q.X., Huang, C.L., Yuan, Y., Tan, H.P., 2020. Influence of COVID-19 event on air quality and their association in Mainland China. Aerosol Air Qual. Res. 20, 1541–1551. https://doi.org/10.4209/aaqr.2020.05.0224.

Dantas, G., Siciliano, B., França, B.B., da Silva, C.M., Arbilla, G., 2020. The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro. Brazil. Sci. Total Environ. 729, 139085.

Filonchyk, M., Hurynovich, V., 2020. Validation of MODIS aerosol products with AERONET measurements of different land cover types in areas over Eastern Europe and China. J. Geovisual. Spatial Anal. 4, 10.

Filonchyk, M., Hurynovich, V., Yan, H., Gusev, A., Shpilevskaya, N., 2020. Impact assessment of COVID-19 on variations of SO2. NO2. CO and AOD over East China. Aerosol Air Qual. Res. 20, 1530–1540.

Filonchyk, M., Peterson, M., 2020. Air quality changes in Shanghai, China, and the surrounding urban agglomeration during the COVID-19 lockdown. J. Geovisual. Spatial Anal. 4 (2), 1–7.

Hsu, N.C., Jeong, M.J., Bettenhausen, C., Sayer, A.M., Hansell, R., Seftor, C.S., Tsay, S.C., 2013. Enhanced Deep Blue aerosol retrieval algorithm: the second generation. J. Geophys. Res. Atmos. 118 (16), 9296–9315.

Jarynowski, A., Wójta-Kempa, M., Płatek, D., Czopek, K., 2020. Attempt to understand public health relevant social dimensions of COVID-19 outbreak in Poland. Soc. Reg. 4, 7–44.
Kamarehie, B., Ghaderpoori, M., Jafari, A., Karami, M., Mohammadi, A., Azarshab, K., Noorizadeh, N., 2017. Quantification of health effects related to SO2 and NO2 pollutants by using air quality model. J. Adv. Environ. Health Res. 5 (1), 44–50.
Kanniah, K.D., Zaman, N.A.F.K., Kaskaoutis, D.G., Latif, M.T., 2020. COVID-19's impact on the atmospheric environment in the Southeast Asia region. Sci. Total Environ., 139658
KOBiZE (Krajowy Ośrodek Bilansowania i Zarządzania Emisjami, National Center for Emissions Management and Balancing), 2018. National Balance of Emissions of SO2, NOx, CO, NH3, NMLZO, Dust, Heavy Metals and TZO for the Years 2015-2016. IOŚ-PIB, KOBZE, Warsaw (in Polish).
Levelt, P.F., van den Oord, G.H., Dobber, M.R., Malkki, A., Visser, H., de Vries, J., Saari, H., 2006. The ozone monitoring instrument. IEEE Trans. Geosci. Rem. Sens. 44, 1093–1101.
Levy, R.C., Mattoo, S., Munchak, L.A., Remer, L.A., Sayer, A.M., Patadia, F., Hsu, N.C., 2013. The Collection 6 MODIS aerosol products over land and ocean. Atmos. Meas. Tech. 6 (11), 2989.
Li, M., Klimont, Z., Zhang, Q., Martin, R.V., Zheng, B., Heyes, C., He, K., 2018. Comparison and evaluation of anthropogenic emissions of SO2 and NO2 over China. Atmos. Chem. Phys. 18, 3343–3456.
Mahato, S., Pal, S., Ghosh, K.G., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi. India. Sci. Total Environ., 139086
Menut, L., Bessagnet, B., Siour, G., Mailler, S., Pennel, R., Cholakian, A., 2020. Impact of lockdown measures to combat Covid-19 on air quality over western Europe. Sci. Total Environ., 140426
Nichol, J.E., Bilal, M., Ali, M., Qiu, Z., 2020. Air pollution scenario over China during COVID-19. Rem. Sens. 12 (13), 2100.
Remer, L.A., Kaufman, Y.J., Tanré, D., Mattoo, S., Chu, D.A., Martins, J.V., Eck, T.F., 2005. The MODIS aerosol algorithm, products, and validation. J. Atmos. Sci. 62 (4), 947–973.
Schroeder, W., Oliva, P., Giglio, L., Csiszar, I.A., 2014. The New VIIRS 375 m active fire detection data product: algorithm description and initial assessment. Remote Sens. Environ. 143, 85–96.
Sharma, S., Zhang, M., Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions during COVID-19 on air quality in India. Sci. Total Environ. 728, 138878.
Siciliano, B., Carvalho, G., da Silva, C.M., Arbilla, G., 2020. The impact of COVID-19 partial lockdown on primary pollutant concentrations in the atmosphere of Rio de Janeiro and São Paulo megacities (Brazil). Bull. Environ. Contam. Toxicol. 1–7 https://doi.org/10.1007/s00128-020-02907-9.
Velásquez, R.M.A., Lara, J.V.M., 2020. Gaussian approach for probability and correlation between the number of COVID-19 cases and the air pollution in Lima. Urban Clim., 100664
Wang, Q., Su, M., 2020. A preliminary assessment of the impact of COVID-19 on environment–A case study of China. Sci. Total Environ., 138915
Wang, Y., Yuan, Q., Li, T., Shen, H., Zheng, L., Zhang, L., 2019. Evaluation and comparison of MODIS Collection 6.1 aerosol optical depth against AERONET over regions in China with multifarious underlying surfaces. Atmos. Environ. 200, 280–301.
Zalakeviciute, R., Vasquez, R., Bayas, D., Buenano, A., Mejia, D., Zegarra, R., Lamb, B., 2020. Drastic improvements in air quality in Ecuador during the COVID-19 outbreak. Aerosol Air Qual. Res. https://doi.org/10.4209/aaqr.2020.05.0254.
Zambrano-Monserrate, M.A., Ruano, M.A., 2020. Has air quality improved in Ecuador during the COVID-19 pandemic? A parametric analysis. Air Qual. Atmos. Health 1–10. https://doi.org/10.1007/s11869-020-00866-y.
Zoran, M.A., Savastru, R.S., Savastru, D.M., Tautan, M.N., 2020. Assessing the relationship between surface levels of PM2.5 and PM10 particulate matter impact on COVID-19 in Milan. Italy. Sci. Total Environ., 139825