Impact of COVID-19 Pandemic on Air Pollution in Poland Based on Surface Measurements and Satellite Data

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ABSTRACT

Since its first detection in December 2019 in the Chinese city of Wuhan, the virus has become a global pandemic within just three months. The Polish government declared a state of emergency on March 14, 2020, which was connected with the adoption of a number of measures aimed to prevent the spread of the virus. These restrictive measures have led to improvements in air quality throughout the country. Therefore, evaluation of the reduction in anthropogenic emissions due to COVID-19 and related government measures to constrain its spread is crucial to define its impact on air pollution. During this study, aerosol optical depth (AOD) observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) were used along with tropospheric NO₂ and SO₂ vertical column densities from TROPospheric Monitoring Instrument (TROPOMI). The data on ground-based concentrations of pollutants (PM_{2.5}, PM₁₀, NO₂ and SO₂) obtained from air quality monitoring stations were also considered to assess changes in aerosols and air pollutants connected with the cessation of various kinds of anthropogenic and industrial activities due to preventive measures for COVID-19. In large cities of the country, the concentrations of PM_{2.5}, PM₁₀ and NO₂ were reduced in the range from –5.1% to –35.5%, from –8.3% to –33.1% and from –0.4% to –18.8%. In addition, satellite data for NO₂ and SO₂ also indicate a decrease in concentration across the country by –10.8% and –25.6% during the COVID-19 restrictions period. The lockdown events may play a vital role as a potential solution to reduce air pollution in future as it may not be uncommon for governments to introduce deliberately selective hotspot lockdowns to control pollution levels.

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1 INTRODUCTION

The coronavirus disease (COVID-19), first detected at the end of December 2019 in Wuhan, Hubei province, has quickly spread first in China, and then within a month, to neighboring countries as well as South and North America and Europe. The World Health Organization (WHO) announced on March 11, 2020 that the spread of the new coronavirus has reached the stage of a pandemic, as most countries and all the continents have been infected, and cases have already been reported in 114 countries.

To prevent the spread of the virus, many countries have taken emergency public health measures to suppress this pandemic, with strict local and regional actions. This has led to a sharp decline in industrial and commercial activity, traffic on the roads and the movement of people. Despite negatively affecting economic growth, the decline in anthropogenic activity had a positive effect on the environment (Chakraborty and Maity, 2020; Somani *et al.*, 2020; Yunus *et al.*, 2020; Ye *et al.*, 2021).

The favorable effects of the COVID-19 lockdown have led to significant reductions in atmospheric

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pollution in various countries across the world, such as China (Filonchyk *et al.*, 2020b; Liu *et al.*, 2020; Wang *et al.*, 2020), India (Mahato *et al.*, 2020; Siddiqui *et al.*, 2020; Singh *et al.*, 2020), Ecuador (Pacheco *et al.*, 2020), Saudi Arabia (Anil *et al.*, 2020), Spain (Baldasano, 2020), Iran (Broomandi *et al.*, 2020), Russia (Ginzburg *et al.*, 2020), France (Sbai *et al.*, 2021), Bangladesh (Islam *et al.*, 2021), United Kingdom (Jephcote *et al.*, 2020). The improvements in air quality have been caused by significant reductions in the number of anthropogenic pollutants such as restrictions on road traffic and industrial activities during the COVID-19 pandemic. Therefore, an evaluation of the change in air quality in Poland is necessary for a global comparison, since the data for the countries of Eastern Europe are quite narrow or completely absent. New data can provide important recommendations for introducing measures or modifying existing strategies to improve air quality not only at the level of one country, but at the level of the whole region.

Poland, located in Eastern Europe, like many other countries, suffered from COVID-19. As of 7 February 2021, in Poland, 1,550,255 cases of COVID-19 including 39,087 deaths have been officially confirmed. The first case of COVID-19 was reported in Poland on March 4, 2020 in the small town of Cybinka, near the border with Germany. On March 14, 2020, a state of emergency was declared in Poland due to the epidemic, which, in particular, manifested in limitations of movement. In March, most service and commerce organizations were closed. Universities and schools were locked down and mass events were prohibited. On March 20, a pandemic was officially declared in Poland. Additional restrictions have been introduced to prevent the spread of COVID-19. The restrictions for movement have been tightened and since March 31, based on a government decree: people walking the streets must keep a distance of two meters, parks, boulevards, beaches, hairdressers and beauty salons are closed, and unaccompanied underaged are prohibited from leaving their homes. Despite the growing numbers of confirmed cases and many victims of COVID-19, the government decided in mid-April to adopt a policy of gradually easing the pandemic restrictions.

This study is aimed to determine whether the lockdown measures taken by the Polish government have had a positive impact on air quality. The dynamics of the ground-based concentrations of PM_{2.5}, PM₁₀, NO₂ and SO₂ in March and April 2020 were compared with the same periods in 2019. In addition, the TROPOspheric Monitoring Instrument (TROPOMI) and Moderate Resolution Imaging Spectroradiometer (MODIS) were used to assess the concentration levels of NO₂, SO₂ and aerosol optical depth (AOD). These results will help to find out if the air quality in the country has improved due to the lockdown introduced after the COVID-19 pandemic.

2 MATERIALS AND METHODS

2.1 Study Area

Poland is one of the largest states in Europe, with an area of 312.7 thousand km² and a population of 37.7 million. It's located between Germany in the west and four Eastern European countries—Russia, Lithuania, Belarus and Ukraine in the east (Fig. 1). From the north it is washed by the Baltic Sea, in the south—along with the mid-altitude Sudetes and the Carpathians it borders on the inland Czech Republic and Slovakia. The length of the territory from north to south is 649 km, and from east to west—689 km. The administrative division of Poland includes 16 voivodeships.

Daily satellite (AOD, NO₂ and SO₂) and surface (PM_{2.5}, PM₁₀, NO₂ and SO₂) data were acquired and processed for each period of national isolation introduced in Poland as measures to constrain the spread of COVID-19. For a more in-depth understanding of changes in pollutant concentrations, the data were classified in two-week periods: Period 1 (1–14 March; before lockdown), Period 2 (15–28 March; during lockdown), Period 3 (29 March–11 April; during lockdown), and Period 4 (12–25 April; after lockdown) and analyzed using simple mathematics and statistics. The average data of each pollutant for 2019 was also used to reveal the absolute differences with the lockdown periods in 2020.

2.2 MODIS Data

The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor is used to obtain daily AOD over Poland. AOD data were obtained from the MCD19A2 V6 data product is a MODIS Terra and Aqua combined Multi-angle Implementation of Atmospheric Correction (MAIAC)

Fig. 1. Location of the study site.

Land Aerosol Optical Depth (AOD) gridded Level 2 product at a wavelength of 0.55 μm produced daily at 1 km resolution (Lyapustin *et al.*, 2018). The MAIAC AOD product (MCD19A2) was downloaded from NASA's *Level-1 and Atmosphere Archive and Distribution System* (LAADS) Distributed Active Archive Center (DAAC) (<https://ladsweb.nascom.nasa.gov>).

2.3 TROPOMI/Sentinel-5p Data

The TROPospheric Monitoring Instrument (TROPOMI) on board the European Space Agency's Sentinel-5P satellite gathers the data needed to assess air quality. TROPOMI is a multispectral sensor that records the reflectance of wavelengths important for measuring atmospheric concentrations of SO_2 , NO_2 , CH_4 , CO , O_3 , CH_2O and aerosols (Veefkind *et al.*, 2012). Until August 6, 2019, the spatial resolution of TROPOMI was 7×3.5 km for NO_2 and SO_2 . After that, the spatial resolution was updated to 5.5×3.5 km with a wide swath of about 2600 km, with daily global coverage. TROPOMI Level 2 NO_2 and SO_2 data were downloaded from the Copernicus Open Access Hub platform.

2.4 Ground-based Data

Ground-based measurements of $\text{PM}_{2.5}$, PM_{10} , NO_2 and SO_2 were obtained from air quality monitoring stations located in major cities in Poland operated by the Chief Inspectorate of Environmental Protection in March and April 2020. In total, data from 32 air quality monitoring stations which provide systematic measurements of air pollution in residential, industrial and rural areas, were used.

2.5 Meteorology

The chemical composition of the atmosphere, weather and climate are closely related. Climate variability and change have consequence for the chemical composition of the atmosphere by modifying factors that influence the life cycle (sources, transport, chemical/physical transformation and removal) of a pollutant in the atmosphere, such as temperature, cloud cover, precipitation, etc. mixing properties of the boundary layer (Liu *et al.*, 2020). The meteorology data consisted of total precipitation rate ($\text{kg m}^{-2} \text{s}^{-1}$), near surface wind speed (m s^{-1}) and near surface air temperature ($^{\circ}\text{C}$), which were from the NASA Global Land Data Assimilation System Version 2 (GLDAS-2) with spatial resolution 0.25° (Rodell *et al.*, 2004). The modeling period is from 1 March to 30 April 2019 and 2020. Data on meteorological parameters are provided in Supplementary Materials (Figs. S1–S3).

3 RESULTS AND DISCUSSION

3.1 Aerosol Optical Depth (AOD) Observation by MODIS

Average AODs during the lockdown period were lower than the average AODs for the same period in 2019 (Fig. 2). The analysis shows that in all regions of the country there was a decrease in AOD. This may be due to the restrictions imposed in many sectors of the economy in the battle against COVID-19, which led to changes in the sources of aerosols (emissions from various kinds of anthropogenic activities, electricity production, biomass combustion and vehicles) (Filonchik *et al.*, 2020b). Manufacturing and mining were the only sectors of the economy not subjected to restrictions (Krzysztofik *et al.*, 2020). When considering the spatial-temporal variation of AOD in certain regions of the country (Fig. 3), it can be seen that the greatest decrease was observed during Period 3 in Opole (−67.5%) and Masovian (−66.7%), followed by Podlaskie (−60.0%), Łódź (−55.6%) and Lublin Voivodeships (−52.8%). During Period 4, the largest declines were in Świętokrzyskie (−36.4%), West Pomeranian (−33.3%) and Subcarpathian Voivodeships (−32.0%). There was a general decrease in AOD across the country by −47.9% (Period 3) and −20.3% (Period 4). At the same time, during the lockdown, the AOD values varied from 0.1 to 0.25 (Table S1). It is worth to state that the overall decrease in AOD confirms the positive impact of lockdown on air quality. The observed decline in AOD across the country during lockdown could be connected not only to reduced vehicle emissions, but also to reduced international and local bus traffic and large flight cancellations. The temporary suspension of international (from March 15) and domestic (from March 16) air travelling by the Polish government has led to a significant reduction of traffic in Polish aerospace. In 2020, air traffic decreased by 56.4% compared to 2019 (Sas, 2021).

A similar situation was registered in the largest cities of the country, where a downward trend in AOD was observed (Table 1). This indicates that the nationwide lockdown covers all regions of the country. It is worth mentioning that during Period 1 and Period 2 of 2020, both in cities and in the country as a whole, AOD levels were higher compared to 2019. This is probably due to unfavorable meteorological factors that can affect the accumulation of pollutants in the atmosphere (Suhaimi *et al.*, 2020; Hoang and Tran, 2021). Less precipitation and a lower temperature was recorded in March 2020, compared to the same period in 2019. This, as well as low wind speeds (Figs. S1–S3), combined with persistent anthropogenic emissions (space heating during colder seasons) can result in higher AOD values.

Fig. 2. Changes in aerosol optical depth (AOD) over Poland during 4 periods 2019 and 2020.

Fig. 3. Percentage change of aerosol optical depth during COVID-19 pandemic compared with same periods in 2019 and 2020.

Table 1. The AOD levels and relative change (%) of AOD at major cities in Poland before, during and after lockdown.

	2019				2020				Relative change (%)			
	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4
Krakow	0.13	0.15	0.33	0.21	0.1	0.22	0.16	0.16	-23.1	46.7	-51.5	-23.8
Lodz	0.08	0.1	0.37	0.19	0.12	0.16	0.15	0.17	50.0	60.0	-59.5	-10.5
Poznan	–	0.09	0.32	0.2	0.14	0.12	0.19	0.13	–	33.3	-40.6	-35.0
Wroclaw	0.12	0.16	0.39	0.17	0.17	0.15	0.22	0.17	41.7	-6.3	-43.6	0.0
Warsaw	0.09	0.06	0.37	0.18	0.19	0.15	0.15	0.16	111.1	150.0	-59.5	-11.1
Gdansk	0.1	0.19	0.33	0.22	0.28	0.28	0.22	0.14	180.0	47.4	-33.3	-36.4
Szczecin	–	–	–	–	–	–	–	–	–	–	–	–

3.2 Nitrogen Dioxide (NO₂) Observation by Sentinel-5P/TROPOMI

Nitrogen dioxide (NO₂) play a key role in atmospheric chemistry and are a precursors to a number of harmful secondary air pollutants. NO₂, along with other nitrogen oxides and non-methane hydrocarbons (NMHC), can contribute to the formation of photochemical smog (Sher, 1998). The absolute mixing ratios and their relation NO_x/NMHC (and the composition of NMHCs) control the production of oxidants (especially O₃).

The main anthropogenic activities that cause NO₂ emissions include power generation, oil and gas extraction as well as smelting (McGonigle *et al.*, 2004; Paraschiv and Paraschiv 2019; Biswas *et al.*, 2020). NO₂ is produced during power generation if burned coal contains sulfur impurities that are not removed out of plant's flue gas dusts. Also, NO₂ is mainly emitted from the combustion of fossil fuels (diesel, gasoline, coal) emitted from car exhaust pipes and chimneys during power generation (Sher, 1998; Anttila *et al.*, 2011; Melkonyan and Kuttel, 2012). Therefore, changes in the level of NO₂ in the atmosphere can be used as an indicator of changes in human activity. NO₂ changes can be estimated by comparing NO₂ satellite data during the isolation period with similar periods last year. However, it should be noted that the interpretation of satellite NO₂ data is not the same as the concentration observed at the ground level. NO₂ levels are influenced by dynamic and chemical processes in the atmosphere. The concentration of NO₂ in the atmosphere can vary due to changes in the weather, which affects both the lifespan of NO₂ molecules and their spread by the wind (Schindler *et al.*, 2020). It is also important to mention that satellites observing NO₂ cannot monitor through clouds. Therefore, all the data shown is applicable only for days with low clouds level.

Data from the Sentinel-5P satellite show a decrease in NO₂ concentration level over the entire territory of Poland (Fig. 4). This decline is particularly noticeable in the southern and western regions of the country, which coincides with a nationwide lockdown to prevent the spread of the coronavirus.

Fig. 4. Changes in tropospheric NO₂ concentrations over Poland from 4 periods in 2019 and 2020.

Such changes were expected, since these areas and cities are the most industrialized in Poland. The overall decrease in NO₂ concentration in 2020 was –10.8% compared to the same period in 2019. At the same time, the largest reductions were during Period 1 (–17.6%) and Period 4 (–13.8%).

Tight restrictions are an important factor in the significant reduction in NO₂ concentrations in the country. Fig. 5 shows that in many regions of the country there was a decrease in NO₂ compared to the previous year. The largest decrease was recorded in Kuyavian-Pomeranian, Opole, Warmian-Masurian and West Pomeranian Voivodeships, with tropospheric NO₂ concentrations ranging from 65 to 96 $\mu\text{mol m}^{-2}$ (Table S2) depending on the region of the country during the lockdown (Period 3). In large cities of the country, a noticeable decrease in NO₂ concentration was also observed (Table 2). These results correlate with recent studies from different regions of the world such as India, China, Ecuador, Spain, Malaysia, Germany, which indicate a decrease in NO₂ concentration during the COVID-19 lockdown compared to the days before it (Baldasano, 2020; Filonchik *et al.*, 2020b; Pacheco *et al.*, 2020; Siddiqui *et al.*, 2020; Suhaimi *et al.*, 2020; Burns *et al.*, 2021).

3.3 Sulfur Dioxide (SO₂) Observation by Sentinel-5P/TROPOMI

While some of the SO₂ in the atmosphere is generated by natural processes, a significant amount is formed by anthropogenic activity, mainly in power plants that burn fossil fuels (Li *et al.*, 2018; Kaczmarczyk *et al.*, 2020). Fig. 5 shows that in almost all regions of the country there was a decrease in SO₂ concentration level during the isolation period. The most significant declines were in Greater Poland (–42.8%), Łódź (–48.2%) and Świętokrzyskie (–48.6%) Voivodeships. At the same time, across the whole country, there was a decrease in SO₂ by –25.6%. Although the outbreak of COVID-19 and the subsequent lockdown led to significant reductions in SO₂ emissions due to the suspension of some production processes and a decrease in the number of cars on the roads, nonetheless, coal-fired power plants and some types of industries could make a significant contribution to air pollution. It is worth mentioning that the installed overall capacity of the Polish electricity system in 2019 was 46,799 MW. The share of installed capacity for coal and lignite was 67% (31,541 MW) and only 5.7% (2,788 MW) for natural gas. This indicates the dominance of coal-fired power plants in the country's energy sector. Moreover, Poland, along with Germany, burns more coal than other Western European countries (Osička *et al.*, 2020). Also due to recommendations to stay at home, there was an increase in electricity consumption

Fig. 5. Percentage change of NO₂ and SO₂ observed from the Sentinel-5P during COVID-19 pandemic compared with same periods in 2019 and 2020.

Table 2. Tropospheric NO₂ concentrations (μmol m⁻²) and relative change (%) over major cities in Poland before, during and after lockdown.

	2019				2020				Relative change (%)			
	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4
Krakow	122	141	122	97	114	99	114	89	-6.6	-29.8	-6.6	-8.2
Lodz	113	96	98	98	103	94	86	84	-8.8	-2.1	-12.2	-14.3
Poznan	96	85	89	98	93	93	77	80	-3.1	9.4	-13.5	-18.4
Wroclaw	122	92	108	104	90	95	87	93	-26.2	3.3	-19.4	-10.6
Warsaw	116	104	110	103	105	93	101	89	-9.5	-10.6	-8.2	-13.6
Gdansk	129	85	76	80	76	81	78	74	-41.1	-4.7	2.6	-7.5
Szczecin	113	101	87	90	99	95	74	76	-12.4	-5.9	-14.9	-15.6

on cold days. Increased demand has forced power plants to generate more electricity, leading to increased SO₂ emissions. Located in Opole and Lower Silesian Voivodeships Opole and Turow coal-fired Power Plants with generation capacity of 3,332 MW and 2,106 MW could have influenced the increase in SO₂ by 59.6% and 71% during Period 4.

The study showed that despite having a decrease in SO₂ concentration throughout the country, there was a significant increase in SO₂ concentrations in many individual cities studied, with the exception of Poznan (-2.1%) and Gdansk (-20.3%) (Table 3). The increase in SO₂ concentration

Table 3. The column density of SO₂ concentration ($\times 10^{-6}$ mol m⁻²) and relative change (%) over major cities in Poland before, during and after lockdown.

	2019				2020				Relative change (%)			
	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4
Krakow	530	546	351	492	1053	1152	491	282	98.7	111.0	39.9	-42.7
Lodz	114	1030	275	292	581	985	378	438	409.6	-4.4	37.5	50.0
Poznan	322	932	470	165	709	1012	460	401	120.2	8.6	-2.1	143.0
Wroclaw	495	452	270	299	707	985	461	313	42.8	117.9	70.7	4.7
Warsaw	486	1041	269	410	528	1474	543	220	8.6	41.6	101.9	-46.3
Gdansk	940	621	492	705	289	1020	392	445	-69.3	64.3	-20.3	-36.9
Szczecin	407	403	514	189	654	1432	644	395	60.7	255.3	25.3	109.0

can be related to uncontrolled or partially controlled industrial and automotive activities in large cities, even during the isolation. It is also likely that power plants in other countries were still operating at full capacity due to the heating season, so transboundary transport of air pollutants may have an impact on changing pollutant concentrations (Halkos and Tsilika, 2019; Lai and Brimblecombe, 2021).

3.4 Ground-based Concentrations of Air Pollutants

The seven largest cities in the country were selected to study the ground-based concentration of pollutants (PM_{2.5}, PM₁₀, NO₂ and SO₂). Hourly data for each pollutant was obtained from 32 air quality monitoring stations. Table 4 shows the average concentrations of the main pollutants in the atmosphere and their percentage changes monitored in each city during and after lockdown, compared to the same period in 2019.

As can be seen from Table 4, in all the cities there was an improvement in air quality during and after lockdown (Period 3 and Period 4). The most notable reductions were found for PM_{2.5}, PM₁₀ and NO₂, as concentrations of these pollutants decreased in almost all the cities during and after the lockdown. During the lockdown, the highest level of PM_{2.5}, PM₁₀ and NO₂ emission reductions was observed in Szczecin (-35.5%, -32.3% and -3.2%), followed by Poznan (-25.0%, -26.6% and 10.7%). Wroclaw (-24.9%, -26.6% and -12.0%) and Lodz (-17.4%, -11.5% and -15.5%). After the lockdown, PM_{2.5}, PM₁₀ and NO₂ concentrations also continued to decline. The only exception is the capital of the country, Warsaw, where PM_{2.5} and PM₁₀ concentrations had slightly increased by 2.8% and 2.5% during the lockdown and decreased by -25.2% and -11.5%, respectively. This may be due to the difficulty of isolating a whole large city within the short period of time, however, the gradual isolation has led to a significant reduction in pollutants after the lockdown. The process of SO₂ changes was ambiguous with an increase during the period of isolation in Gdansk (80.4%), Warsaw (33.1%) and Lodz (12.4%), and a decrease from -5.1% (Wroclaw) to -26.6% (Szczecin). This may be due to SO₂ emissions from industrial processes, power plants and heating systems that continued to operate during the isolation period. However, the overall decline in air pollution indicates that significant air quality improvements can be expected if strict air quality control measures such as lockdowns are implemented. It should be noted that the data on the surface concentration of NO₂ and SO₂ are similar to the data obtained by Sentinel-5P.

No doubts that during and after the lockdown, there were trends towards a decrease in the concentration of pollutants, still, in the periods before the lockdown (Period 1 and Period 2), situation was the opposite: an increase in the concentration of pollutants was observed compared to 2019. There was a significant increase in the concentration of pollutants in the atmosphere of cities, this may be due to the high anthropogenic activity in 2020 connected with the high production of electricity, residential heating, industry and agriculture (Kaczmarczyk *et al.*, 2020), which are likely to be affected by lockdown restrictions as well as by unfavorable meteorological conditions the least. According to the change in the meteorological parameters, presented in the Supplementary Materials (Figs. S1–S3), in March 2019, there was recorded a lower air temperature than in 2020 by about 5°C, which may have led to a higher load on heat production for heating. In addition, lower wind speeds and a lower planetary boundary layer led to a decrease in the

Table 4. Mean concentrations and relative change (%) concentrations of ground-level PM_{2.5}, PM₁₀, NO₂ and SO₂ (μg m⁻³) at major cities in Poland before, during and after lockdown.

		2019				2020				Relative change (%)			
		Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4
Krakow	PM _{2.5}	25.4	30.8	33.0	24.8	22.2	30.4	31.4	16.6	-12.4	-1.3	-5.1	-33.0
	PM ₁₀	28.8	42.7	46.8	34.5	31.2	40.9	42.9	28.2	8.3	-4.3	-8.3	-18.1
	NO ₂	37.7	42.1	42.4	39.9	40.8	30.5	34.4	27.1	8.3	-27.6	-18.8	-32.1
	SO ₂	6.2	7.8	7.4	5.1	4.5	5.8	5.8	4.7	-27.4	-25.1	-20.9	-7.4
Lodz	PM _{2.5}	16.6	18.9	23.4	16.3	17.7	23.7	19.3	10.2	6.3	25.4	-17.4	-37.1
	PM ₁₀	26.0	30.0	45.7	37.6	28.7	42.4	40.5	31.2	10.5	41.2	-11.5	-16.9
	NO ₂	19.8	20.8	31.9	31.6	23.5	27.2	27.0	19.9	18.9	30.7	-15.5	-37.0
	SO ₂	4.8	5.5	4.8	3.8	3.9	4.9	5.4	3.2	-19.6	-10.7	12.4	-14.7
Poznan	PM _{2.5}	15	16.9	24	17.9	19.7	26	18	10.1	31.3	53.8	-25.0	-43.6
	PM ₁₀	20.4	22.2	40.3	34.6	25.1	37.9	29.6	21.7	23.0	70.7	-26.6	-37.4
	NO ₂	20.5	24.4	19.6	19.3	19.5	19.7	17.5	14.1	-4.9	-19.3	-10.7	-26.9
	SO ₂	3.7	4.4	4	3.2	3.8	3.7	3.6	2.8	2.7	-15.9	-10.0	-12.5
Wroclaw	PM _{2.5}	16.2	18.5	27.8	19.9	15.1	26.8	20.9	12.9	-6.9	44.7	-24.9	-35.1
	PM ₁₀	23.9	27.7	41.4	31.9	18.7	36.1	30.4	24.1	-21.7	30.2	-26.6	-24.5
	NO ₂	21.1	24.9	28.5	26.5	24.6	25.1	25.0	20.3	16.3	0.9	-12.0	-23.6
	SO ₂	3.6	4.0	6.0	5.0	4.6	6.0	5.7	5.7	27.4	51.7	-5.1	13.5
Warsaw	PM _{2.5}	16.9	19.4	23.9	18.0	19.1	27.8	24.5	13.5	12.9	43.1	2.8	-25.2
	PM ₁₀	26.0	28.0	39.9	32.1	23.1	40.7	40.9	28.4	-11.4	45.1	2.5	-11.5
	NO ₂	35.0	38.2	31.0	30.3	30.0	28.6	30.9	25.0	-14.2	-25.0	-0.4	-17.7
	SO ₂	4.0	3.9	2.6	2.3	4.0	4.8	3.4	2.8	0.2	22.4	33.1	20.4
Gdansk	PM _{2.5}	–	–	–	–	22.2	28.7	16.0	8.9	–	–	–	–
	PM ₁₀	13.9	13.9	28.8	25.2	20.4	29.2	19.3	15.7	47.2	110.2	-33.1	-37.8
	NO ₂	15.2	13.1	18.8	16.7	15.3	20.2	15.3	11.3	0.7	54.0	-18.5	-32.5
	SO ₂	2.8	2.1	2.4	2.3	4.0	4.9	4.4	3.0	43.3	132.3	80.4	25.9
Szczecin	PM _{2.5}	12.6	16	21.7	17.7	15.6	22.1	14	8.8	23.8	38.1	-35.5	-50.3
	PM ₁₀	15.9	19.9	31.6	33.5	19.4	31	21.4	18.1	22.0	55.8	-32.3	-46.0
	NO ₂	14.4	15.4	18.7	17.2	18.6	25.2	18.1	15.2	29.2	63.6	-3.2	-11.6
	SO ₂	4.2	2.4	6.4	5	2.9	4.9	4.7	5.5	-31.0	104.2	-26.6	10.0

mixing height, thereby contributing to an increase in the concentration of pollutants. Although high precipitation results to the deposition of pollutants, it can also contribute to the hygroscopic growth of aerosols (He *et al.*, 2016). According to Filonchyk *et al.* (2020a), westerly winds prevail in spring, which can also contribute to changes in the concentration of pollutants. However, a detailed analysis of changes in pollutants will require an in-depth study of differences in meteorological models over time, which is beyond the scope of this article.

Data from countries in the European Economic Area (EEA) show that the concentration of NO₂ emitted mainly by road transport has decreased in many European cities where containment measures have been taken (EEA, 2020). A significant reduction in the concentration of pollutants has also been found in many regions of the world, indicating that isolation measures have a positive effect on air quality (Broomandi *et al.*, 2020; Ginzburg *et al.*, 2020; Jephcote *et al.*, 2020; Liu *et al.*, 2020; Zangari *et al.*, 2020; Anil and Alagha, 2021; Islam *et al.*, 2021; Sbai *et al.*, 2021). In particular, measurements carried out at 129 monitoring stations located in the United Kingdom revealed average reductions in PM_{2.5} by -16.5% and NO₂ by -38.3% (Jephcote *et al.*, 2020). The reduction in emissions resulted to a PM_{2.5} decrease by 37% to 55% in four major cities in the Yangtze River Delta Region, China (Shanghai, Hangzhou, Nanjing, and Hefei) (Liu *et al.*, 2020). In New York City, USA, PM_{2.5} and NO₂ data obtained from 15 monitoring stations showed decreases in concentration by -36% and -51%, respectively (Zangari *et al.*, 2020).

The COVID-19 pandemic affects not only people's lives, but also has a direct impact on energy consumption and emissions of air pollutants both globally and regionally. During this time, short-term reductions in energy consumption and emissions can lead to short-term improvements in air quality (Filonchyk *et al.*, 2020b; Giani *et al.*, 2020; Wang and Su, 2020; Zangari *et al.*, 2020).

One of the most obvious short-term effects of isolation from COVID-19 has been dramatic improvements in air quality, especially in some of the world's most polluted cities (Mahato *et al.*, 2020; Rodríguez-Urrego and Rodríguez-Urrego, 2020; Singh and Chauhan, 2020; Wang *et al.*, 2020). While air quality levels appear to be returning to pre-lockdown period in many parts of the world as stricter lockdown measures are lifted, this period has highlighted some of the benefits that can be brought by sustained reductions in air pollution.

4 CONCLUSION

The decrease in the level of anthropogenic activity caused by the national lockdown due to the COVID-19 pandemic has had a tangible positive effect on air quality in Poland. The results show a noticeable reduction in concentration of air pollutants during the isolation period, especially in Krakow, Szczecin, Poznan and Wroclaw. Decreases in AOD, NO₂ and SO₂ values obtained from MODIS and TROPOMI were observed in almost all regions of the country. AOD values during the isolation period (Period 3) across the country decreased by –47.9% in 2020 compared to the same period in 2019. In addition, satellite data for NO₂ and SO₂ also indicate a decrease in concentration of –10.8% and –25.6% during the COVID-19 restrictions. This decrease was due to the measures taken by the government to restrict the movement of people within and between countries, as well as to control industrial and business activity. Measures to contain the spread of the virus resulted in significant reductions in PM_{2.5} and PM₁₀ concentrations from –5.1% to 35.5% and from –8.3% to 33.1% in major cities compared to previous years. In all the cities studied, there was a decrease in the ground-based concentration of NO₂ by –0.4 to 18.8%. These results show how the air quality in the country has improved due to the restrictive measures introduced during the COVID-19 pandemic. Moreover, the detailed role of meteorology has not been assessed or quantified in this study, and a more detailed study of the impact of meteorological conditions on air quality in Poland is recommended in future. This study has provided a basic scenario that in the future may help the correspondent authorities to develop pollution control policies, mainly connected to industrial and transport emission limits.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.4209/aaqr.200472>

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