# Air Pollution in Ukraine from space

**Study based on the Copernicus Sentinel 5p satellite imagery and quality-controlled air pollution data from the Copernicus Atmosphere Monitoring Service**

**Prague - Kyiv, 2020**

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ЧИСТЕ ПОВІТРЯ ДЛЯ УКРАЇНИ
TRANSITION Transition Promotion Program
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**Air pollution in Ukraine from space**

WORLD FROM SPACE

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The study contains modified Copernicus Atmosphere Monitoring Service data [2017-2020] and modified Copernicus Sentinel data [2018-2020]. The maps contain data from © OpenStreetMap contributors (openstreetmap.org) and the Humanitarian Data Exchange (data.humdata.org).

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**ABBREVIATIONS AND ACRONYMS**

ADS – Atmosphere Data Store

API – application programming interface

ECMWF – European Centre for Medium-Range Weather Forecasts

CAMS – Copernicus Atmosphere Monitoring Service

$CH_4$ – methane

CO – carbon monoxide

$CO_2$ – carbon dioxide

EEA – European Environment Agency

EU – European Union

GIS – geographic information system

HCHO – formaldehyde

NMVOC – non-methane volatile organic compounds

$NO_2$ – nitrogen dioxide

$O_3$ – ozone

PM – particulate matter

$PM_{2.5}$ – particulate matter 2.5 micrometres or less in diameter

$PM_{10}$ – particulate matter 10 micrometres or less in diameter

SP5 – Sentinel 5P

SH – Sentinel Hub

$SO_2$ – sulphur dioxide

TROPOMI – TROPOspheric Monitoring Instrument

UN – United Nations

UNFCCC – United Nations Framework Convention on Climate Change

WHO – World Health Organization

# Key findings

Air pollution is one of the most serious threats to human health. **Approximately 7 million people worldwide die of polluted air each year.**

The current air quality situation in Ukraine is diverse and it reflects the distribution of the urban and industrial centres. **Overall, the Dnipropetrovsk, Donetsk, Kyiv, Luhansk, and Zaporizhia regions are those most seriously affected by air pollution. From a city perspective, there should be a focus on six key urban areas, including Dnipro, Donetsk, Kryvyi Rih, Kyiv, Mariupol, and Zaporizhia.**

The distribution of $NO_2$ is relatively even, with several regions (Kyiv, Donetsk, the Zaporizhia region, etc.) having much higher concentrations than the rest of the country. Higher concentrations are mostly found in the largest urban areas and industrial and coal mining regions. **There is a significant intake of $NO_2$ from Poland in the north-west of Ukraine during the winter season.**

The human impact on CO concentrations is visible in the lowlands within the major steel production centres, including Mariupol, Zaporizhia, Kryvyi Rih, and Kamianske. The regions that are most affected are Dnipropetrovsk, Kyiv, and Zaporizhia.

There is a generally low concentration of formaldehyde and $SO_2$ over Ukraine. Higher concentrations are located around urban areas and especially in the eastern part of the country, with active coal mines, coke, the chemical industry, and heavy industry.

The concentrations of particulate matter ($PM_{2.5}$ and $PM_{10}$) decrease from the south to the north of the country, with the highest concentrations located in the industrial region of eastern Ukraine. **Average concentrations of $PM_{2,5}$ exceed the WHO limits in 127 districts, with those most affected being the Donetsk and Dnipropetrovsk regions and the city of Kyiv.** Even the countrywide $PM_{2,5}$ average was over the WHO limit in March 2017, November 2018, and February 2019.

**WHO guidelines for $PM_{10}$ have been exceeded in Mariupol and in certain parts of four cities – Kryvyi Rih, Dnipro, Zaporizhia, and Donetsk**, all of which are located in south-western Ukraine. There were two months when the country average reached the WHO $PM_{10}$ limit (September 2018 and March 2020).

Public policies supporting air quality improvements should focus on four main areas: improving air quality monitoring, supporting inventories of emissions and plans, conducting changes in management practices in key sectors, and involving the public into decision-making procedures.

# Introduction

**With** the rapid increase in the world's population and its high consumer demand, the problem of air pollution is rising. Among the most common causes of air pollution are urbanization, energy production, heavy industry (such as iron and steel smelting, cement kilns, coking, waste incineration, or chemical production), transportation, and motorization. Also, population growth and exposure to air pollutants have a negative impact on the quality of the environment and human health. The World Health Organization (WHO) has identified air pollution as the single largest environmental health risk in the world.

Almost 92% of the world population breathes air polluted beyond the acceptable limits. Ukraine had the most deaths attributed to atmospheric air pollution per every 100,000 people according to the ranking of 120 countries in 2017.[1] Another study published in 2019 showed that the death rate caused by air pollution exceeds 200 per 100,000.[2] Overall, according to the WHO, 14,400 people die annually in Ukraine as a result of air pollution.[3]

> ***"About 14,400 people die annually in Ukraine as a result of air pollution."***
> *Source: WHO*

Together with climate change, air pollution is one of the most serious threats to global health. It has been estimated by the WHO that approximately 7 million people die every year from exposure to polluted air,[4] with ambient (i.e. outdoor) pollution alone causing about 4.2 million premature deaths every year, mainly from heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections in children.[5]

The biggest air pollutants encountered in our daily life are particulate matter (PM), ozone ($O_3$), nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$), carbon monoxide (CO), and carbon dioxide ($CO_2$). Out of these, the pollutants with the strongest evidence for public health concern are PM, $O_3$, $NO_2$, and $SO_2$. Moreover, recognition is growing of the combined health effects of multiple pollutants (the synergistic toxic effect).

The aim of this analysis is to assess the current state of air pollution in Ukraine. The concentration of six pollutants in the atmosphere has been observed using both satellite data from the European satellite mission Sentinel-5P and data from major European models provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).

## Nitrogen dioxide ($NO_2$)

Nitrogen dioxide ($NO_2$) is an important trace gas present in both the troposphere and the stratosphere, but it is also a key atmospheric pollutant produced by anthropogenic activities. According to the European Environment Agency 2018 Air Quality report,[6] more than 60% of the $NO_2$ in European cities comes from motor vehicle exhaust

1 https://www.researchgate.net/publication/338784844_Risk_Assessment_for_the_Population_of_Kyiv_Ukraine_as_a_Result_of_Atmospheric_Air_Pollution
2 https://academic.oup.com/eurheartj/article/40/20/1590/5372326
3 https://www.who.int/quantifying_ehimpacts/national/countryprofile/ukraine.pdf?ua=1
4 https://www.who.int/news-room/air-pollution
5 https://www.who.int/airpollution/ambient/health-impacts/en/
6 https://www.eea.europa.eu/publications/air-quality-in-europe-2018
A1 Wagner H-M. Absorption von NO und NO2 in MIK- und MAKKonzentrationen bei der Inhalation [Absorption of NO and NO2 in mikand mak-concentrations during inhalation]. Staub, Reinhaltung der Luft,1970, 30:380–381.
A2 Berglund M. et al. Health risk evaluation of nitrogen oxides. Exposure. Scandinavian Journal of Work, Environment and Health, 1993, 19(Suppl. 2):14–20.

fumes. Other sources of $NO_2$ are oil and metal refining, electricity generation (especially from coal-fired power stations), other manufacturing industries, and food processing. Natural sources of the gas include microbiological processes in soils, wildfires, and lightning. When inhaled, up to 90% of nitrogen dioxide enters the human body and is absorbed into the blood.[A1] This contaminant affects the metabolism in the lungs, causes inflammation and swelling of tissues, and increases the vulnerability of the respiratory system to bacterial and viral infections.[A2] According to the WHO,[7] higher nitrogen dioxide levels can lead to respiratory infections and reduced lung function and growth; it is also linked with increased symptoms of bronchitis and asthma. Asthma sufferers are the most vulnerable group. Exposure to even low concentrations of nitrogen dioxide causes hyper-reaction, the exacerbation of symptoms, and increased airway response in patients with asthma and chronic bronchitis.[A3] The interaction of $NO_2$ with water and other chemicals in the atmosphere leads to the formation of acid rain, causing changes in forest and aquatic ecosystems. A high content of nitrogen dioxide in the air is also related to global climate change and photochemical smog.[A4]

**MAIN HUMAN SOURCES**
- motor vehicle exhaust fumes
- coal-fired power stations
- oil and metal refining
- production of steel and cast iron

## Carbon monoxide (CO)

Carbon monoxide (CO) is a colourless, tasteless, and odourless poisonous gas. CO is generally considered an important indirect greenhouse gas as it enhances the lifetime of greenhouse gases such as methane, halocarbons, and tropospheric ozone. It is a product of incomplete combustion as encountered in the operation of vehicles, heating, coal power generation, the coke and steel industry, and the burning of biomass. Approximately 40% of CO comes from natural sources such as **volcanic eruptions**, **emissions of natural gases, decomposition of vegetation and animals, and forest fires**, and 60% comes from **fossil fuel consumption, waste incineration, tobacco smoke, and charcoal fires.**[8] In equatorial regions the oxidation of isoprene and the burning of biomass play the most important role in CO production, while in higher latitudes fossil fuel combustion is the main source.

There is a clear causal link between human systemic diseases and the effects of elevated concentrations of carbon monoxide in the air.[A5] CO has a toxic effect on the organs of tissues with high oxygen consumption – the brain, heart, and a developing foetus. There are proven toxic effects of carbon monoxide on the health of mothers during pregnancy and the development of congenital heart defects in infants. High concentrations of carbon monoxide enhance the combined action of other pollutants ($O_3$, $SO_2$, PM, $NO_2$) and increase the risk of all respiratory diseases.

**MAIN HUMAN SOURCES**
- fossil fuel consumption
- waste incineration
- fires, e.g. burning biomass

> *“There is considerable evidence on human environmental and occupational exposure to carbon monoxide. The organs and tissues that are mostly affected include the brain, the cardiovascular system, exercising skeletal muscle, and the developing foetus”*[9]
> *Source: WHO*

**7** https://www.euro.who.int/__data/assets/pdf_file/0017/123083/AQG2ndEd_7_1nitrogendioxide.pdf?ua=1

A3 Devalia JL et al. Effect of nitrogen dioxide and sulfur dioxide on airway response of mild asthmatic patients to allergen inhalation. *Lancet*, 1994, 344:1668–1671.

A4 Air quality criteria for oxides of nitrogen. Research Triangle Park, NC, US Environmental Protection Agency, 1993 (EPA Report No. EPA/600/8-91/049aF-cF. 3v)

**8** Handbook of Toxicology of Chemical Warfare Agents. Academic Press, Apr 2, 2009. eBook ISBN: 9780080922737

**9** https://www.euro.who.int/__data/assets/pdf_file/0020/123059/AQG2ndEd_5_5carbonmonoxide.PDF

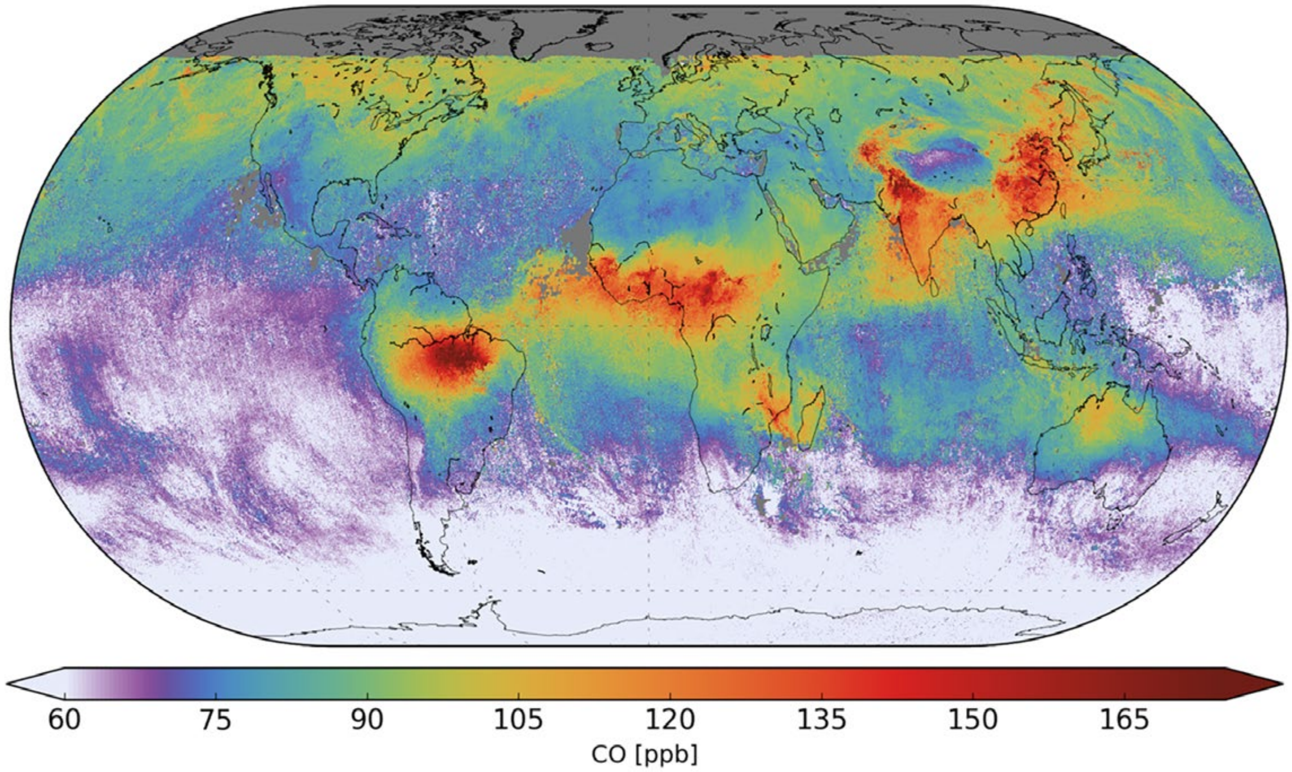


**Fig. 1:** *The global CO total column mixing ratio average concentration created with TROPOMI L2 data (13-19 November 2017), The data clearly shows CO enhancement by wildfires in Brazil, Africa, Madagascar, and Australia, as well as anthropogenic air pollution in India and China; http://www.tropomi.eu/data-products/carbon-monoxide*

While CO accumulates in the atmosphere during the winter, it is rapidly depleted as a result of natural reactions in the spring. Thus, in the northern hemisphere, CO concentrations are generally lowest in June, July, and August. [10]

## Sulphur dioxide ($SO_2$)

Sulphur dioxide ($SO_2$) is located in both the stratosphere, where it has a lifetime of several weeks, and in the troposphere, where its lifetime is in the order of days. About 30% of the $SO_2$ that is emitted comes from natural sources such as volcanoes. Anthropogenic sources include coal-fired power stations, industrial processes, or other fossil fuel-burning activities. According to the WHO,[11] "$SO_2$ can affect the respiratory system and the functions of the lungs, and causes irritation of the eyes. Inflammation of the respiratory tract causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis and makes people more prone to infections of the respiratory tract. Hospital admissions for cardiac disease and mortality increase on days with higher $SO_2$ levels." The interaction of $SO_2$ with water forms sulphurous and sulphuric acids, which are the main components of acid rain. The S5P satellite has limitations in terms of its ability to separate anthropogenic and natural sulphur dioxide emissions. Therefore, the data must be interpreted in a cautious manner.

> **MAIN HUMAN SOURCES**
> - coal-fired power stations
> - industrial processes
> - heating

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## Formaldehyde (HCHO)

Formaldehyde (HCHO) is a colourless, highly flammable gas with a sharp odour. It is a carcinogen and as such represents a significant threat to human health[A6] HCHO is an intermediate gas in almost all oxidation

**10** https://sos.noaa.gov/datasets/carbon-monoxide-2008-2011/
A5 Integrated Science Assessment for Carbon Monoxide. US EPA. January 2010. 2 EPA/600/R-09/019F
**11** https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

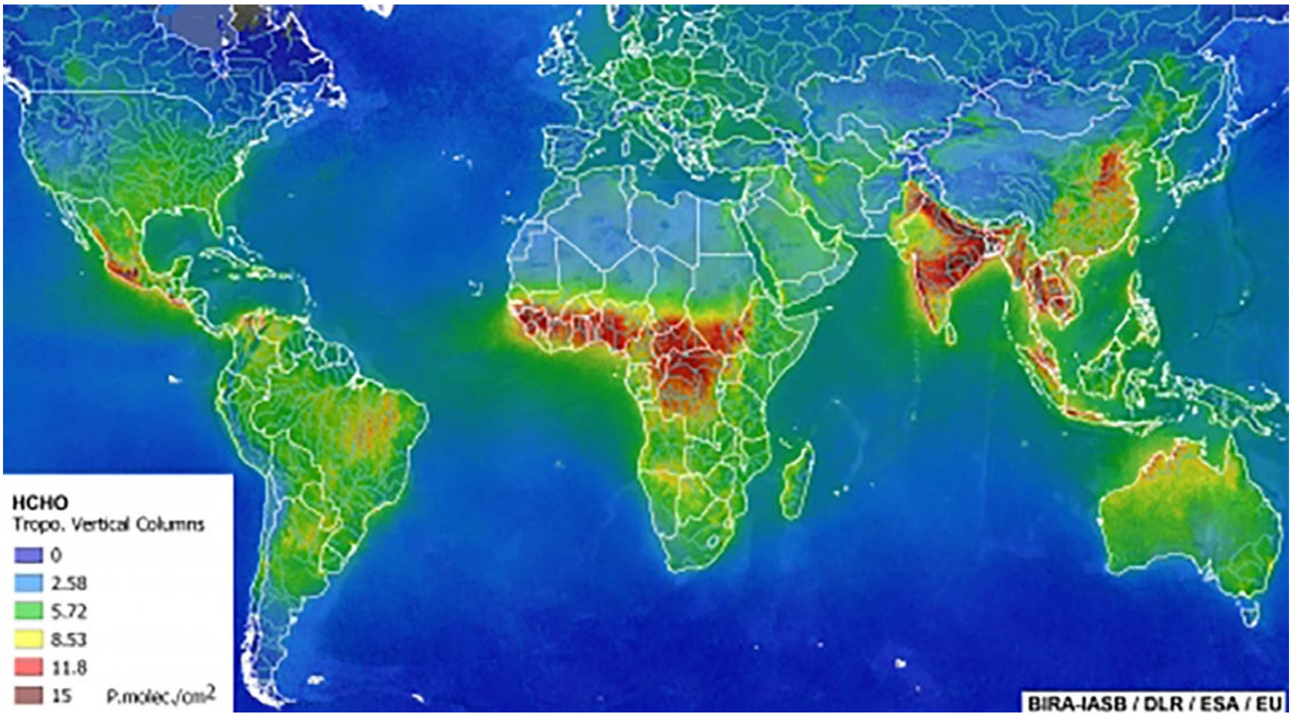


**Fig. 2:** *The global HCHO concentrations created with TROPOMI L2 data (November 2017-June 2018), http://www.tropomi.eu/data-products/formaldehyde, Particulate matter (PM2.5 and PM10)*

chains of non-methane volatile organic compounds (NMVOC); its column is composed of different sorts of volatile organic compounds. As its lifetime in the atmosphere is only a few hours, monitoring its concentrations in the atmosphere allows for a relatively precise localization of its sources.[A7] The major source in the remote atmosphere is $CH_4$ oxidation. Over the continents, the natural sources of HCHO are vegetation (naturally, the highest concentrations are distributed over **tropical rainforests** because of high biogenic emissions) and **wildfires**. *"It depends on the region but 50-80% of the signal* [detected by the SP5 satellite] *is from some biogenic origin."*[12] The anthropogenic sources of HCHO include **traffic, industrial processes,** and **petrochemical industrial sources** (the production of fertilizers, paper, plywood, particle board, and many other consumer products). The seasonal variations in the distribution of formaldehyde are principally related to temperature changes, fire events, and changes in anthropogenic activities.[13]

> *"The highest concentrations (of formaldehyde) measured in the environment occur near anthropogenic sources; these are of prime concern for the exposure of humans and other biota."* Source: WHO[14]

**MAIN HUMAN SOURCES**
- petrochemical industrial sources
- industrial processes
- heating

## Particulate matter

Particulate matter or atmospheric aerosols are solid or liquid particles suspended in the air and capable of free movement in the atmosphere. They are classified by size, rather than their chemical properties. On the basis of size, particulate matter is often

**12** https://www.bbc.com/news/science-environment-44550091
**13** http://www.tropomi.eu/data-products/formaldehyde
A6 Formaldehyde, 2-butoxyethanol and 1-tert-butoxypropan-2-ol. Lyon: International Agency for Research on Cancer; 2006. Formaldehyde; pp. 39–325. (IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans, Vol. 88)
A7 https://www.who.int/ipcs/publications/cicad/en/cicad40.pdf
**14** https://www.who.int/ipcs/publications/cicad/en/cicad40.pdf

divided into two main groups. The coarse fraction contains the larger particles with a size ranging from 2.5 to 10 μm ($PM_{2.5}$-$PM_{10}$). The fine fraction contains the smaller ones with a size up to 2.5 μm ($PM_{2.5}$). The former is primarily produced by mechanical processes such as **construction activities**, **road dust** re-suspension, and wind, whereas the latter originates primarily from combustion sources, including **domestic heating** and **transport**. Other significant sources include **industrial processes** and **power plants**. Naturally, particles are released into the atmosphere during **volcanic activities, fires,** and **erosion** and from **seawater**.

**MAIN HUMAN SOURCES**
- construction activities
- transport
- domestic heating
- industrial processes
- power plants

> *"Long-term exposure to $PM_{2.5}$ is associated with an increase in the long-term risk of cardiopulmonary mortality by 6-13% per 10 μg/m³ of $PM_{2.5}$."*[15] Source: WHO

There is a direct negative effect of the concentrations of particulate matter on human health.[A8 A9] The effect depends on the size, chemical composition, and shape, but generally concerns the respiratory and cardiovascular systems. PM have toxic and genotoxic effects – they increase carcinogenic risks,[A10] affect the structure and integrity of endoepithelial cells, increase the potential for vascular thrombosis,[A11] and increase blood coagulation and the risk of stroke, myocardial infarction,[A12] and atherosclerosis.[A13]

PM can act as a catalyst for chemical reactions on its surface.[A14] Thus, the toxic effect of PM is enhanced by the content of other pollutants in the air. All these features make it impossible to clearly define the "safe" concentration of PM in the air. That is why the WHO experts recommend values that determine the minimum risk to public health.

The WHO offers **guideline annual mean values** for particulate matter concentrations in the air designed to offer guidance in reducing the health impacts of air pollution. In the case of fine particles **$PM_{2.5}$**, the guidance values are **10** μg/**m³** and for coarse particulate matter (**$PM_{10}$**) the value is **20** μg/**m₃**. However, according to the WHO, usage of the $PM_{2.5}$ guideline value for both $PM_{2.5}$ and $PM_{10}$ is recommended.[16] Short-term levels of pollution should not exceed 25 μg/m³ ($PM_{2.5}$) and 50 μg/m³ ($PM_{10}$) on a 24-hour mean.[17] According to the WHO, "*Long-term exposure to $PM_{2.5}$ is associated with an increase in the long-term risk of cardiopulmonary mortality by 6-13% per 10 μg/m3 of $PM_{2.5}$.*"[18]

**15** https://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf

**16** https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1

**17** https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

**18** https://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf

A8 Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulphur dioxide. WHO, 2005.
A9 Integrated Science Assessment for Particulate Matter. December 2009 EPA/600/R-08/139F.
A10 Karlsson HL, Nygren J, Moller L. Genotoxicity of airborne particulate matter: the role of cell-particle interaction and of substances with adduct-forming and oxidizing capacity. Mutation Research, 2004, 565:1–10.
A11 Gilmour PS et al. The procoagulant potential of environmental particles (PM10). Occupational and Environmental Medicine, 2005, 62:164–171.
A12 Peters A et al. Increased particulate air pollution and the triggering of myocardial infarction. Circulation, 2001, 103:2810–2815.
A13 Kunzli N et al. Ambient air pollution and atherosclerosis in Los Angeles. Environmental Health Perspectives, 2005, 113:201–206.
A14 Brown JS, Zeman KL, Bennett WD. Ultrafine particle deposition and clearance in the healthy and obstructed lung. American Journal of Respiratory and Critical Care Medicine, 2002, 166:1240–1247.

# Data and methodology

## Sentinel-5p

The Sentinel-5P mission (S5P) is a satellite devoted to atmospheric monitoring launched in October 2017 as a part of the EU Copernicus Programme. It carries a TROPOMI spectrometer (TROPOspheric Monitoring Instrument) covering wavelength bands between the ultraviolet and the shortwave infrared. SP5 measures gases such as $NO_2$, ozone, formaldehyde, $SO_2$, methane, carbon monoxide, and aerosols daily with a spatial resolution of about 5.5 km x 3.5 km (7 km to 5.5 km until August 2019).

Satellite data from Sentinel-5P is obtained via the Sentinel Hub (SH) operated by Sinergise. The Sentinel Hub supports Sentinel-5P level 2 (L2) data products which are geolocated, primarily preprocessed, and contain a "qa_value". The "qa_value" means "quality assurance value" and indicates the status and quality of each ground pixel. It is a continuous variable ranging from 0 (error) to 1 (no errors). For most Sentinel-5p products, pixels with values under 0.5 are filtered out (for $NO_2$ products it is 0.75). The "qa_value" is an important parameter that reduces the seamless coverage of the areas of interest by S5P data and the proposed methodology takes it into account. $NO_2$, $SO_2$, HCHO, and CO products (since May 2018 to April 2020) are obtained via SH.

> *"The distribution of satellite-measured air pollution does not take into account anthropogenic sources only; it includes the results of naturally occurring processes as well.*

SP5 satellite data products are mostly measured and provided in mol/m$^2$ units. The $NO_2$ product gives the total atmospheric $NO_2$ column between the surface and the top of the troposphere[19] (tropospheric column). The CO clear sky TROPOMI observations provide total CO columns with sensitivity to the tropospheric boundary layer.[20] The HCHO and $SO_2$ observations give the total atmospheric column between the surface and the tropopause.[21] As a result of several identified satellite images that contained errors, median concentrations were used instead of mean values for $SO_2$ observations.

When using SP5 satellite data, it is important to take into account the difference in how the values are measured. Health limit values are usually given in units used for ground-based measuring instruments. Therefore, converting values from satellite imagery (mol/m$^2$) to ground-based units (μg/m$^3$) is not recommended.[22]

## Quality flags and observation frequency

It is important to take into account the fact that the quality of the accessible pixels is highly dependent on weather conditions, sensor errors, and other parameters, including cloud cover. Altogether, it is generally defined by the "qa_value". The S5P revisit time for Europe (including the area of Ukraine) is more than once a day. There are scanning overlaps at higher latitudes as a result of the near-polar, sun-synchronous orbit of the satellite. Thus, the processed data comprises all the available satellite measurements. Using all the available data means combining data from several satellite orbits with varying grid sizes and orientations. To address this, all S5P satellite observations were downscaled to obtain a regular grid with a resolution of **1 km x 1 km**

19 https://sentinels.copernicus.eu/documents/247904/3541451/Sentinel-5P-Nitrogen-Dioxide-Level-2-Product-Readme-File
20 http://www.tropomi.eu/data-products/carbon-monoxide
21 https://sentinels.copernicus.eu/documents/247904/3541451/Sentinel-5P-Formaldehyde-Readme.pdf
22 https://www.researchgate.net/post/How_can_I_convert_the_unit_from_molecules_cm2_to_ppm

via SH. The data was automatically preprocessed and downloaded to a cloud space using our proprietary Python scripts using the SH service. The final processing steps were performed on desktop GIS to get **monthly and selected seasonal averages** per pixel over the whole area. A season was defined as a three-month period in winter (December-February) and summer (June-August) to obtain simplification of the air quality caused by weather conditions. For every single pollutant, a **total average per pixel for the whole referenced period is processed as well**.

## Copernicus Atmosphere Monitoring Service (CAMS)

As Sentinel-5P does not provide monitoring of particulate matter ($PM_{2.5}$ and $PM_{10}$) concentrations, these were obtained through the Copernicus Atmosphere Monitoring Service (CAMS). CAMS, part of the Copernicus Programme implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF),[23] provides global, quality-controlled information related to air pollution, solar energy, greenhouse gases, and climate forcing.

Over Europe, CAMS produces specific daily air quality analyses and forecasts at a spatial resolution of 0.10.1 degrees (approx. 1010 km). Nine European air quality forecasting systems are utilized in the production, using a median ensemble from individual outputs.[24] Furthermore, the analysis combines model data with real ground observations provided by the European Environment Agency (EEA) into a complete and consistent dataset using various data assimilation techniques. In parallel, air quality forecasts are produced once a day for the next four days. Both the analysis and the forecast are available at hourly time steps at eight height levels: surface, 50 m, 250 m, 500 m, 1000 m, 2000 m, 3000 m, and 5000 m.

For the purpose of the analysis presented here, the surface level concentrations of $PM_{2.5}$ and $PM_{10}$ were obtained through the **Atmosphere Data Store (ADS)** – a distributed data and information system which provides access to all CAMS datasets through unified web and API interfaces. In order to keep the observation time in line with the values monitored by the S5P satellite, daily concentrations modelled for 13:00 UTC have been used. As the database of CAMS data offered through the ADS consists of three years of the most recent data (termed a rolling archive), our analysis of $PM_{2.5}$ and $PM_{10}$ concentrations covers the period from 15 July 2017 to 14 July 2020.

Moreover, in order to compare the results from two independent sources, we use the modelled surface values of the concentrations of $SO_2$ provided by the CAMS service in conjunction with the values measured by the Sentinel-5P satellite. For these pollutants, the same period of observation has been used as in the case of the Sentinel-5P monitoring, i.e. 1 January 2018 to 30 April 2020.

> *“CAMS, part of the Copernicus Programme, provides global, quality-controlled information related to air pollution.*

**23** https://www.ecmwf.int/

**24** https://atmosphere.copernicus.eu/sites/default/files/2020-01/ENSEMBLE_Fact_Sheet_2020.pdf

# Results

**This** chapter provides an overview of the main statistical indicators of individual pollutants obtained from the Sentinel-5P satellite and CAMS models. In all cases, the average concentration of a certain pollutant for the whole country is given, supplemented by a map of average concentrations throughout the country and a chart displaying the development of average concentrations in the country over the observed period.

## Nitrogen dioxide

As can be seen from Figure 3, the distribution of $NO_2$ over Ukraine is relatively even, with several regions having significantly higher $NO_2$ concentrations than the rest of the country. These regions mainly include the vicinity of the capital city, Kyiv, and regions (in Ukrainian "oblast") in the eastern and south-eastern parts of the country, including the Donetsk, Zaporizhia, Kharkiv, and Dnipropetrovsk regions. Higher concentrations correlate well with the distribution of the country's largest urban areas and the localization of specific industries (the metallurgical, coke, and petro-chemical industries, heavy engineering and metal processing, etc.). A higher population density, associated with higher mobility, leads to higher emission levels from motor vehicles but also from electricity production in coal-burning power plants.

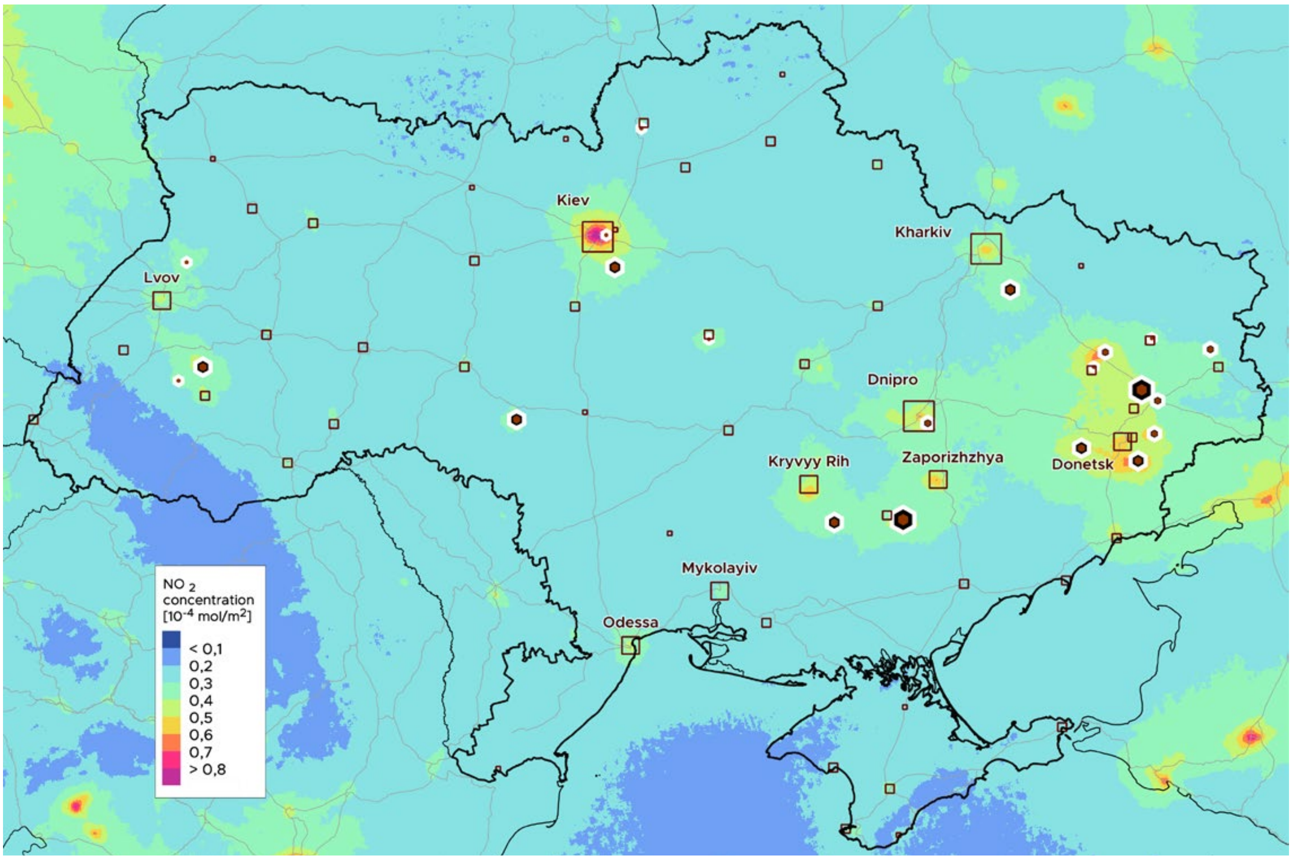


**Fig. 3:** *Average concentrations of $NO_2$ in Ukraine between May 2018 and April 2020. Major cities are displayed as dark red squares, classified by their population. Coal-burning power plants[25] are displayed as dark red hexagons, classified by their capacity.*

25 Based on the Global Power Plant Database. Source: https://datasets.wri.org/dataset/globalpowerplantdatabase

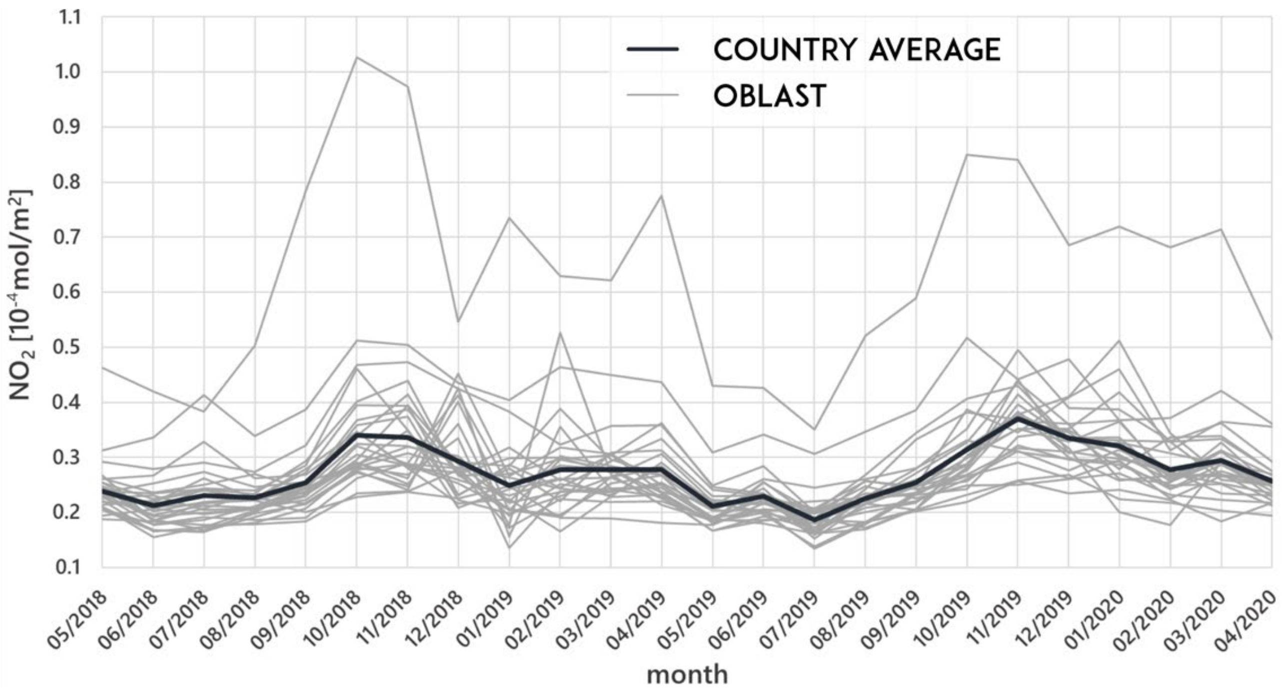


**Fig. 4:** *Average monthly concentrations of $NO_2$ in Ukraine and its regions between May 2018 and April 2020.*

## THE MOST AFFECTED REGIONS

- Kyiv region
- Donetsk region
- Dnipropetrovsk region

While the average $NO_2$ concentration in Ukraine between May 2018 and April 2020 reached a value of **0.28 * $10^{-4}$ mol/m²**, in the Kyiv city region, the average value was more than double: 0.63 * $10^{-4}$ mol/m². Moreover, all ten of Kyiv's city districts (in Ukrainian "raion") are among the 15 most polluted districts in the country. The districts with the highest concentrations of $NO_2$ within the city and the whole country are the Shevchenkivskyi district (0.83 * $10^{-4}$ mol/m²), Pecherskyi district (0.81 * $10^{-4}$ mol/m²), and Solomianskyi district (0.79 * $10^{-4}$ mol/m²) of the city of Kyiv. Outside Kyiv, the highest concentrations have been observed in the Lyman and Sloviansk districts, both within the Donetsk region, with the local concentrations reaching 0.62 * $10^{-4}$ mol/m² and 0.61 * $10^{-4}$ mol/m² respectively. Nitrogen dioxide concentrations were also high in the Zaporizhia (0.48 * $10^{-4}$ mol/m²), Dnipro (0.47 * $10^{-4}$ mol/m²), Kharkiv (0.66 * $10^{-4}$ mol/m²), and Kryvyi Rih (0.45 * $10^{-4}$ mol/m²) districts.

The development of the average monthly concentrations of $NO_2$ in Ukraine is displayed in Figure 4. As can be seen from the chart, the highest concentrations of $NO_2$ in 2018 and 2019 were reached in late autumn (October, November), while the lowest concentrations were observed in the late spring and summer months. However, the observed seasonal differences in concentrations are relatively small, generally in the region of up to 0.15 * $10^{-4}$ mol/m².

Figure 5 shows a comparison of the winter and summer season concentrations of $NO_2$ in Ukraine. The direct effect of coal power plants (represented as black-and-white dots on the map) on the increased $NO_2$ concentrations is visible in the summer months. During the winter, there is a significant intake of $NO_2$ from Poland in the north-west of Ukraine and the higher concentration of $NO_2$ also correlates well with the distribution of the country's largest urban areas and its industrial and coal mining region in the south-east. This is connected both to heavier use of combustion power plants for wintertime home heating and to the fact that $NO_2$ stays in the air longer in the winter, as the atmospheric lifetime of $NO_2$ is driven primarily by reactions initiated by sunlight.[26]

26 https://sos.noaa.gov/datasets/nitrogen-dioxide/

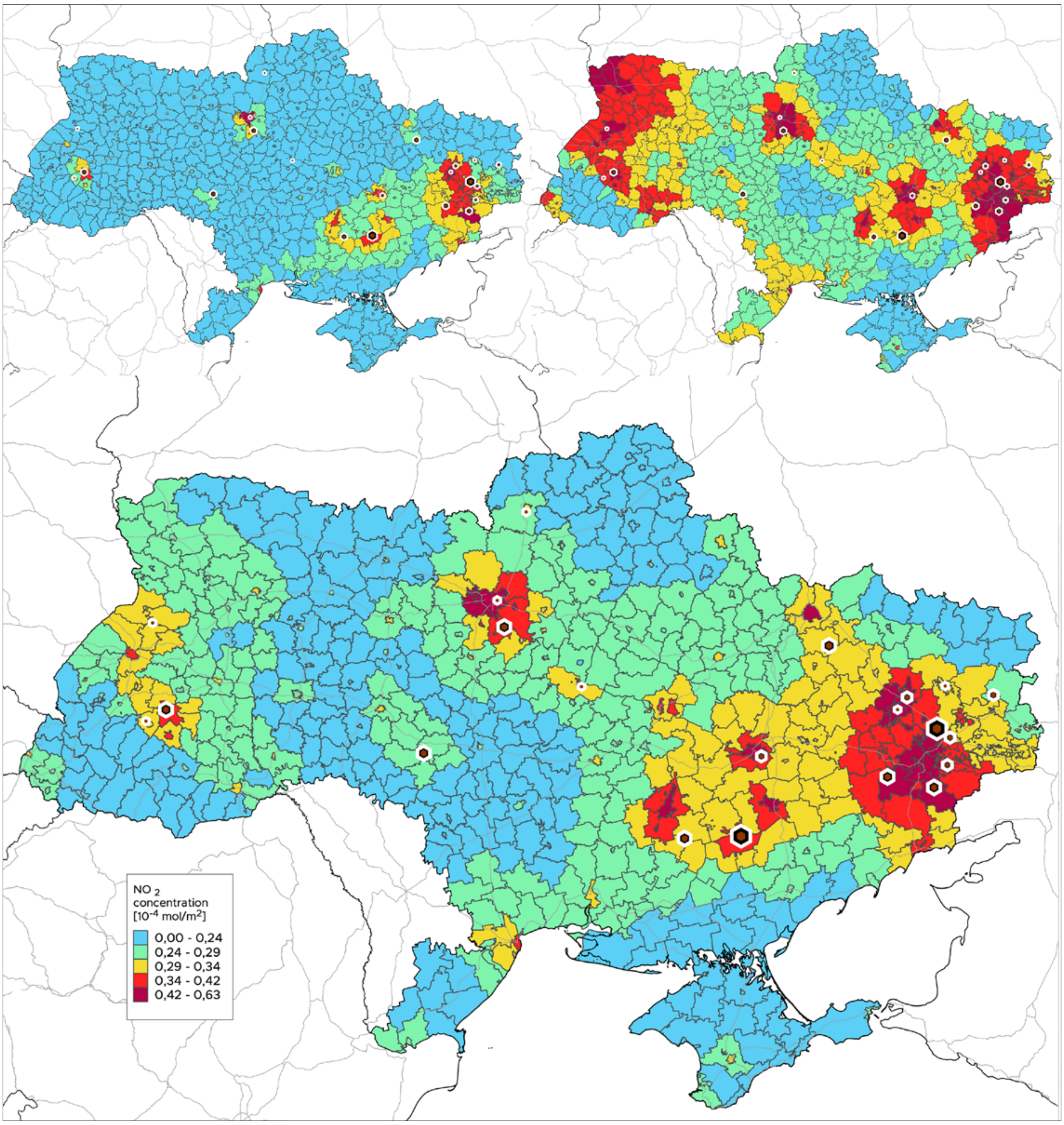


**Fig. 5:** *Average concentrations of $NO_2$ in the districts of Ukraine between May 2018 and April 2020 (bottom), summer season (upper left) and winter season (upper right)*

> *"During the winter season, there is a significant intake of $NO_2$ from Poland in the north-west of Ukraine and the higher concentration of $NO_2$ also correlates well with the distribution of the country's largest urban areas and its industrial and coal-mining region in the south-east.*

The development of $NO_2$ concentrations in the selected regions of Ukraine between May 2018 and April 2020 is shown in Figure 6. The five regions with the highest average concentrations and the five regions with the lowest average concentrations have been selected for the illustration. As can be seen from the graph, the average monthly concentrations of $NO_2$ in the city of Kyiv greatly exceed the concentrations in other regions in almost every month

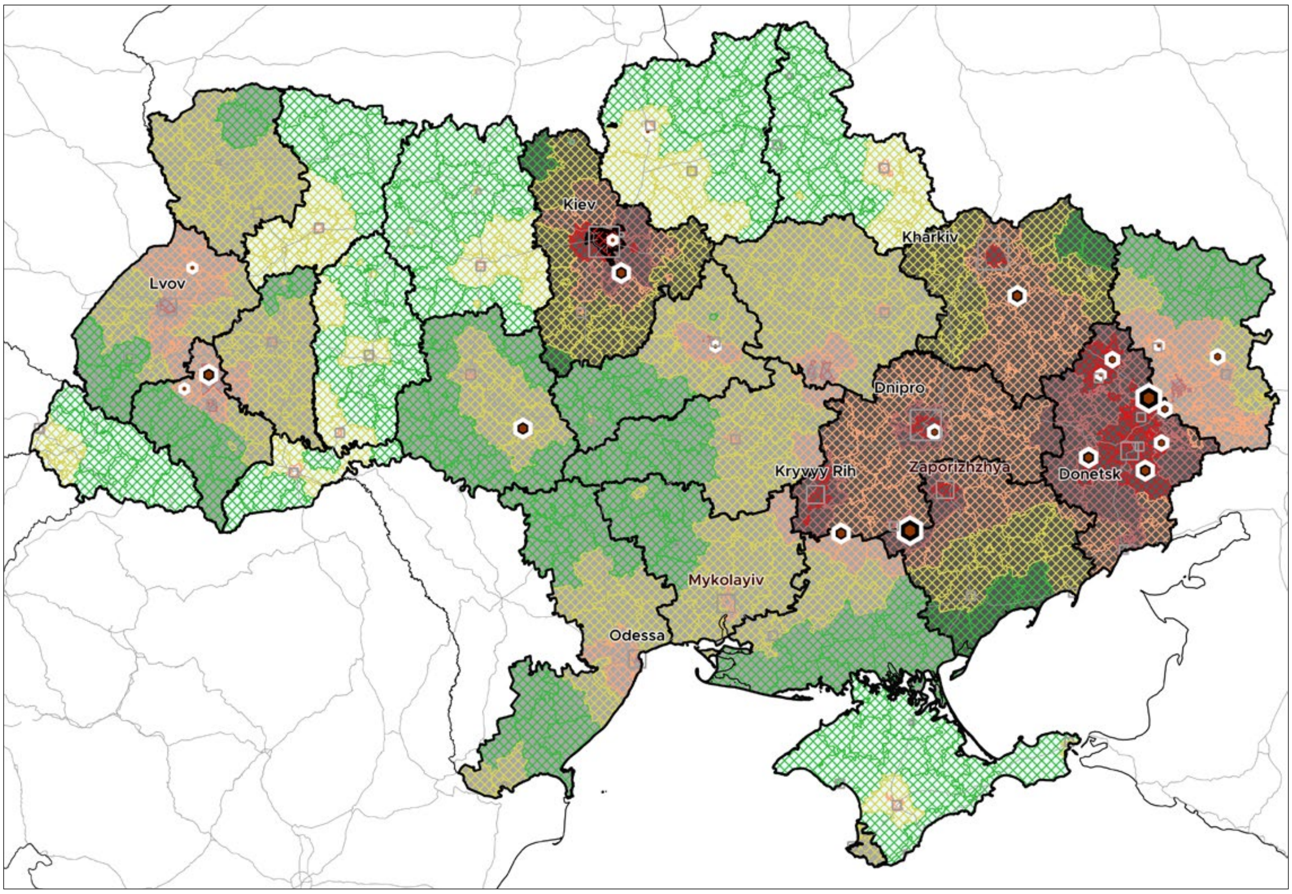


**Fig 6:** *Development of the average concentrations of $NO_2$ in the selected regions of Ukraine between May 2018 and April 2020.*

of the period that was monitored. This can partly be attributed to the urban character of the capital city and partly to the size of the Kyiv city region itself, as it only has an area of about 832 km², while the areas of the Donetsk, Dnipropetrovsk, Kyiv, and Kharkiv regions are in a range from about 27,000 to 32,000 km².

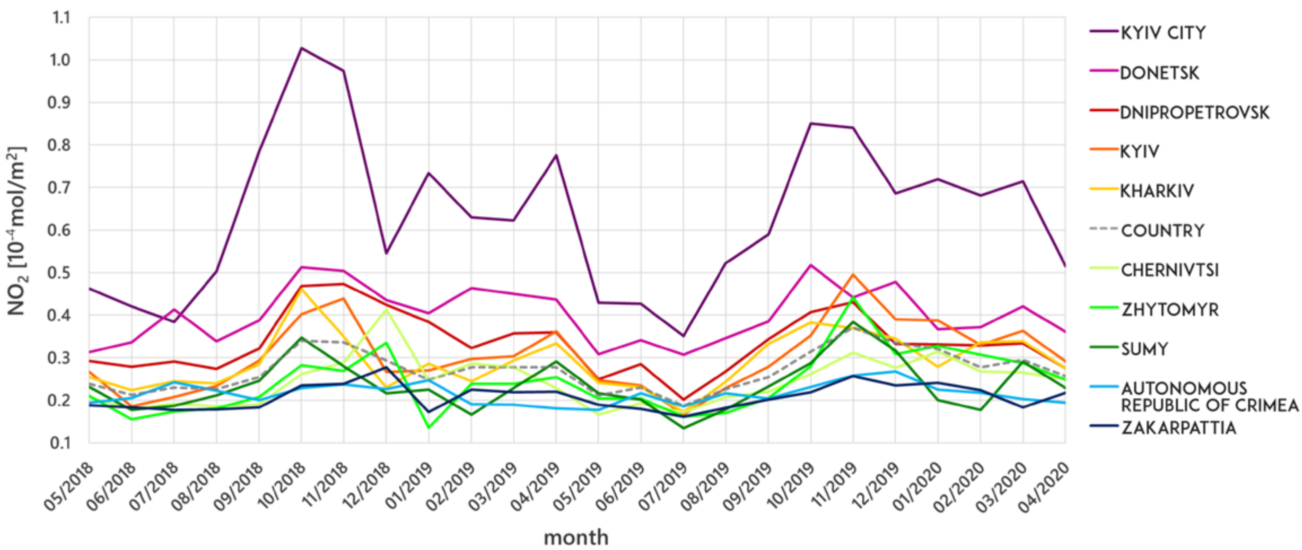


**Fig 7** *$NO_2$ in the regions (oblast) and districts (raion) of Ukraine and the distribution of coal-burning power plants. Coal-burning power plants[27] are displayed as dark red hexagons, classified by their capacity.*

**27** Based on the Global Power Plant Database. Source: https://datasets.wri.org/dataset/globalpowerplantdatabase

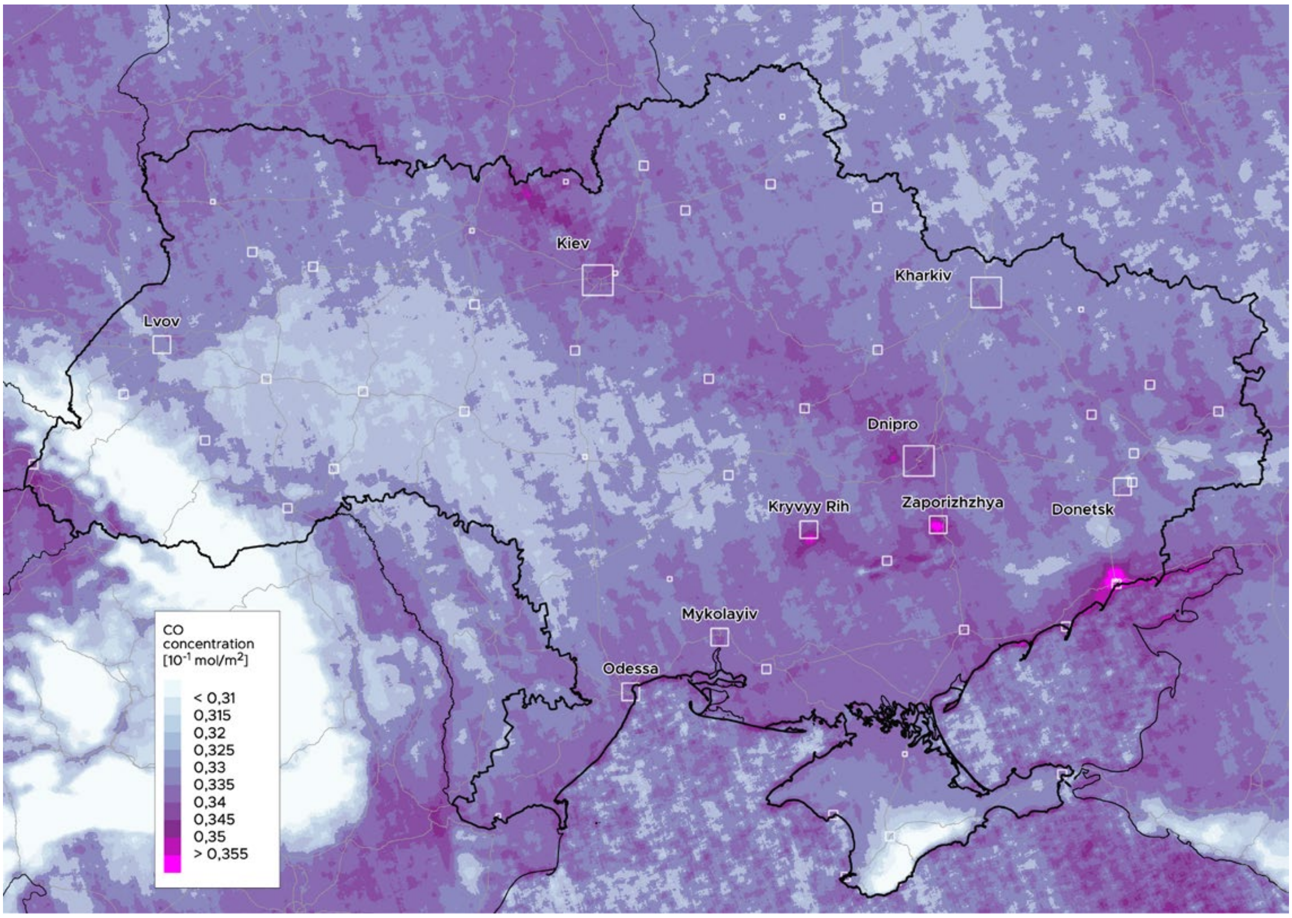


**Fig. 8:** *Average concentrations of CO in Ukraine between May 2018 and April 2020.*

## Carbon monoxide

There are two maps that are important for understanding carbon monoxide concentrations over Ukraine. Figure 8 shows the distribution of the average CO concentrations between May 2018 and April 2020 and Figure 9 displays the terrain elevation. From these two images, the natural high negative correlation between CO concentrations and elevation can be spotted. Thus, the lowest concentrations of CO follow the Carpathian mountain range and Crimean mountains, while the highest concentrations can be found in the Dnieper Lowland and Black Sea-Azov Lowland. This is mostly caused by the natural cycle of CO in the air. However, the human impact on concentration is visible within the lowlands, where the major steel production centres, including Mariupol, Zaporizhia, Kryvyi Rih, and Kamianske (formerly Dniprodzerzhynsk) are located. Furthermore, higher concentrations are found in and around the Chernobyl Nuclear Power Plant Zone of Alienation and south-west of the Carpathian Mountains, near the border with Slovakia and Hungary.

**THE MOST AFFECTED REGIONS**

- Kherson region
- Kyiv city
- Zaporizhia region
- Dnipropetrovsk region

The regions with the highest CO concentrations were Kherson, the city of Kyiv, and the Zaporizhia and Dnipropetrovsk regions. While the average nationwide concentration of CO reached a value of 0.332 * $10^{-1}$ mol/$m^2$, these regions were characterized by average concentrations of 0.340, 0.339, 0.339, and 0.339 * $10^{-1}$ mol/$m^2$ respectively. On the other hand, the regions with the lowest average concentrations were the Ivano-Frankivsk (0.315 * $10^{-1}$ mol/$m^2$), Zakarpattia (0.319 * $10^{-1}$ mol/$m^2$), and Chernivtsi (0.324 * $10^{-1}$ mol/$m^2$) regions. Among districts, the highest concentrations were observed in the Mariupol (0.361 * $10^{-1}$ mol/$m^2$), Zaporizhia (0.351 * $10^{-1}$ mol/$m^2$), Manhush (the former Pershotravnevyi) (0.349 * $10^{-1}$ mol/$m^2$), Dnipro (0.345 * $10^{-1}$ mol/$m^2$), and Kryvyi Rih (0.344 * $10^{-1}$ mol/$m^2$) districts. It means that the differences between the

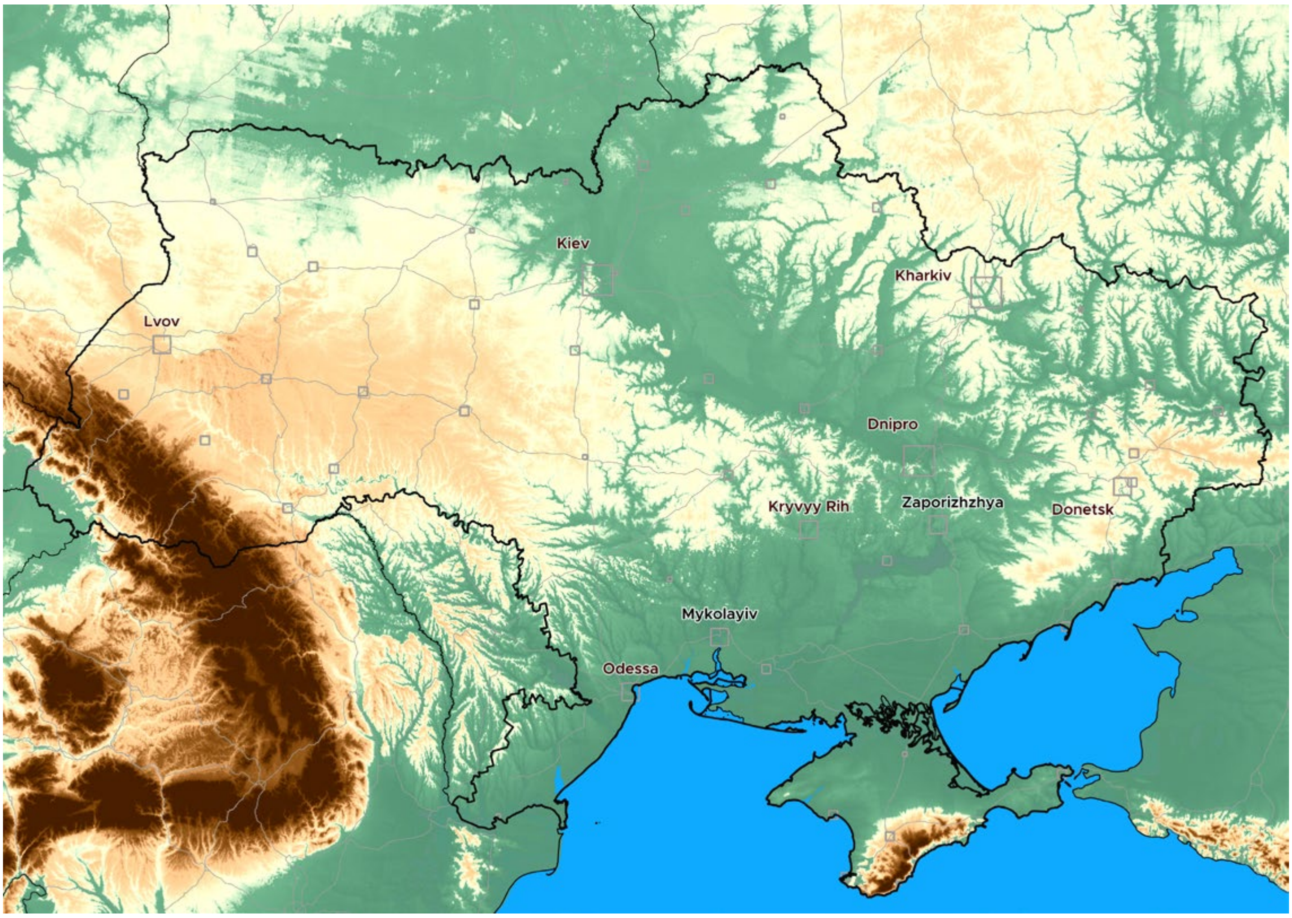


**Figure 9:** *Physical map of Ukraine. Source: SRTM DEM (https://dds.cr.usgs.gov/srtm/)*

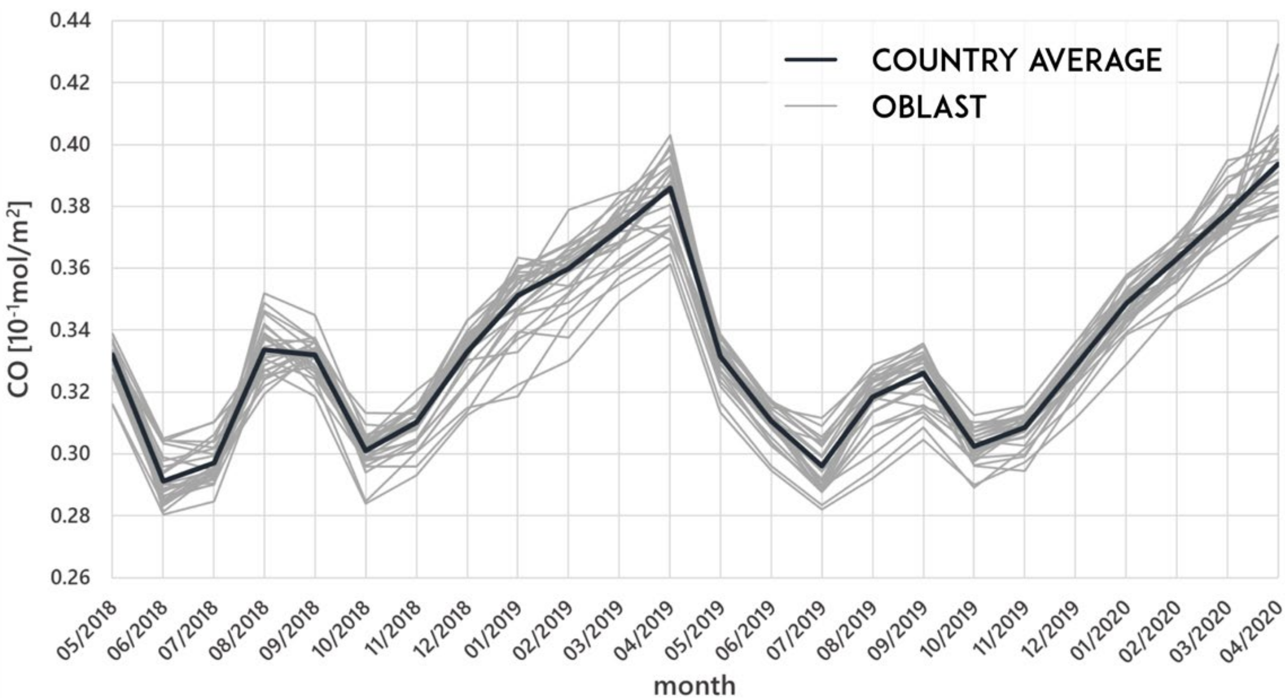


**Fig. 10:** *Average monthly concentrations of CO in Ukraine and its regions between May 2018 and April 2020.*

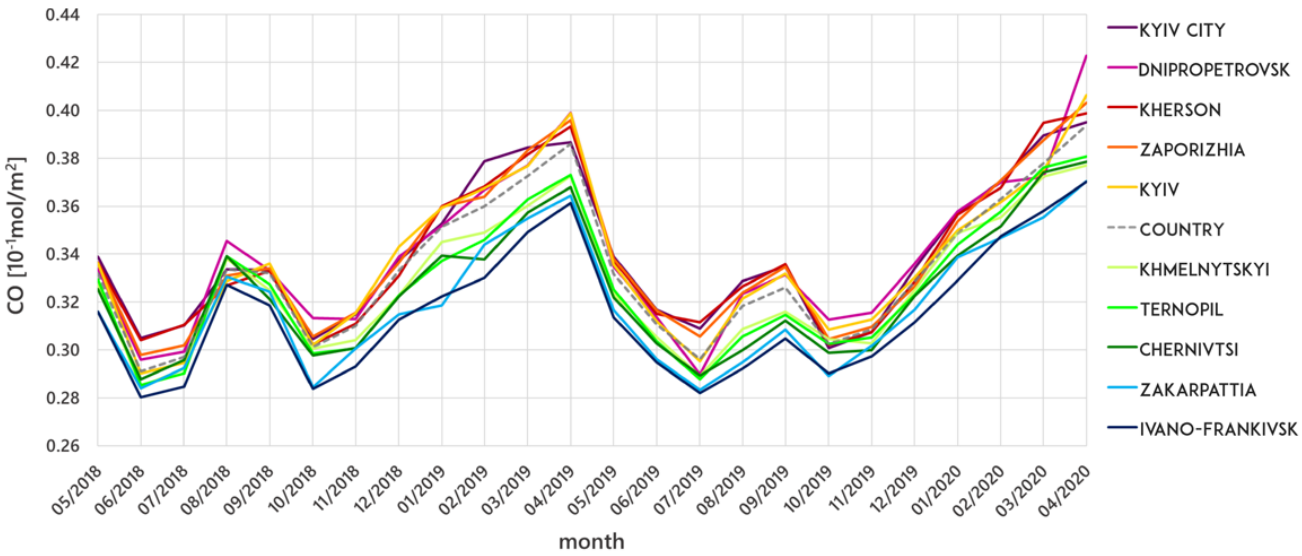


**Fig 11:** *Development of the average concentrations of CO in the selected regions of Ukraine between May 2018 and April 2020. The five regions with the highest overall concentrations and the five regions with the lowest overall concentrations have been selected for the display.*

most polluted and the least polluted areas are about 30% of the concentrations.

Human impact on CO concentrations is visible within the lowlands, where the major steel production centres, including Mariupol, Zaporizhia, Kryvyi Rih, and Kamianske (formerly Dniprodzerzhynsk) are located.

The development of monthly average concentrations of CO is shown in Figures 10 and 11. The concentrations rise in the winter and early spring months, reaching their highest values in April, followed by a sharp decline. The lowest concentrations in both years were reached in July. This trend follows a general yearly cycle of CO concentrations in the atmosphere of the Northern Hemisphere.

## Sulphur dioxide

The median sulphur dioxide ($SO_2$) concentration over Ukraine between May 2018 and April 2020 was **0.43 * $10^{-3}$ mol/m²**. This value represents a relatively low level of pollution in comparison to the global hotspots. However, there are differences on a local level. As can be seen in the map of average $SO_2$ concentrations, higher concentrations are located around urban areas and especially in the eastern part of the country, with active coal mines and heavy industry.

This observation is also confirmed by the analysis of the $SO_2$ dataset provided by CAMS (Figure 13). It confirms the main polluted area; however, it puts more focus on other urban areas as well.

The seasonality of $SO_2$ values is clear (Figures 14 and 15), with concentrations peaking strongly between November and January, with values that are five times higher. This trend is probably a result of both natural and human factors,[28] including: 1) lower winter levels of $SO_2$ deposition as a result of the absence of vegetation and lower levels of precipitation; and 2) higher levels of emissions from the (central) thermal heating of houses in residential areas. On the other hand, average monthly concentrations in all regions are very similar to the national average during the summer.

> *The seasonality of $SO_2$ values is clear, with concentrations peaking between November and January.*

**THE MOST AFFECTED REGIONS**

- Donetsk region
- Kyiv (city)
- Dnipropetrovsk region
- Zaporizhia region

28 https://www.researchgate.net/publication/265250018_Changes_in_sulphur_dioxide_concentrations_in_the_atmospheric_air_assessed_during_short-term_measurements_in_the_vicinity_of_Olsztyn_Poland

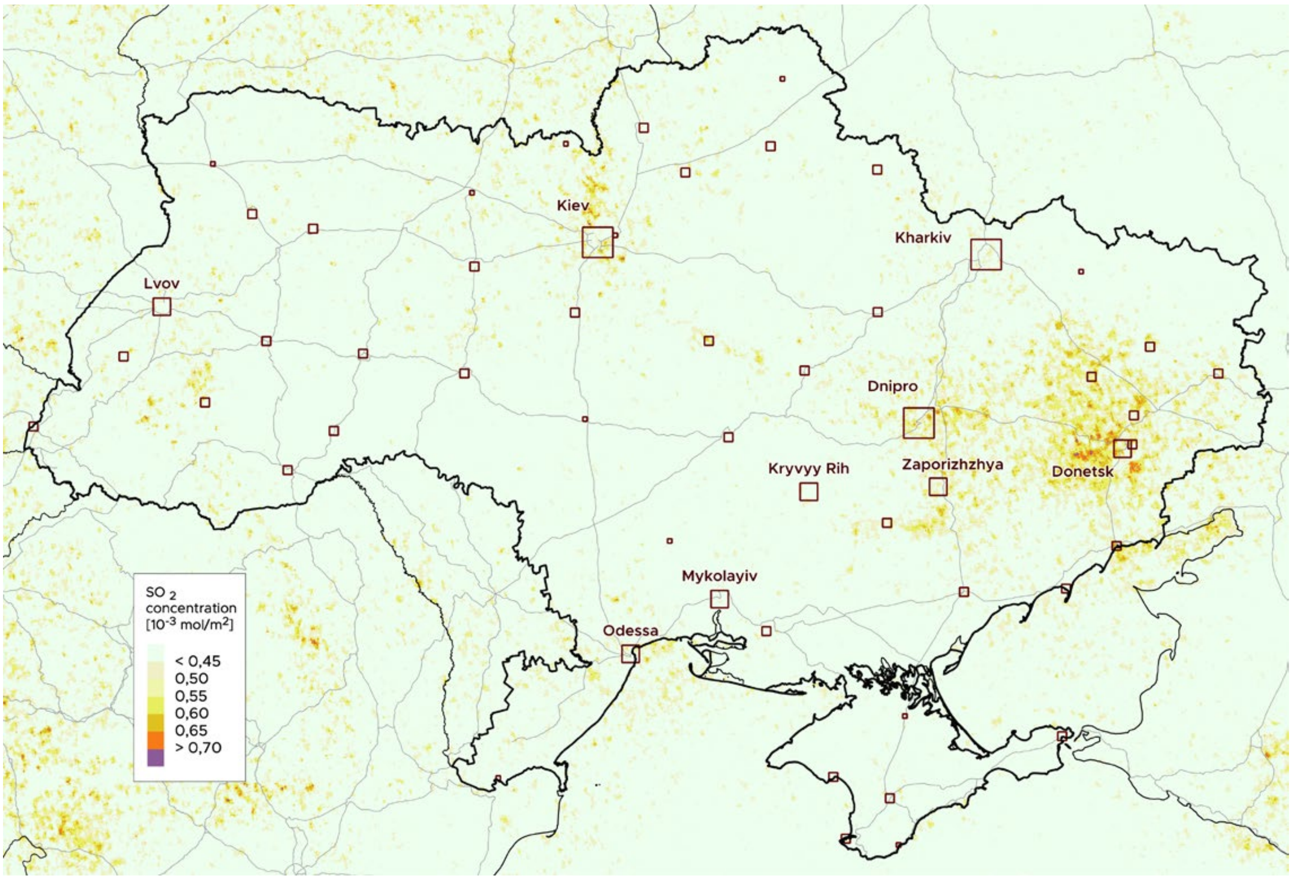


**Fig. 12:** *Median concentrations of $SO_2$ in Ukraine between May 2018 and April 2020 based on Sentinel 5p.*

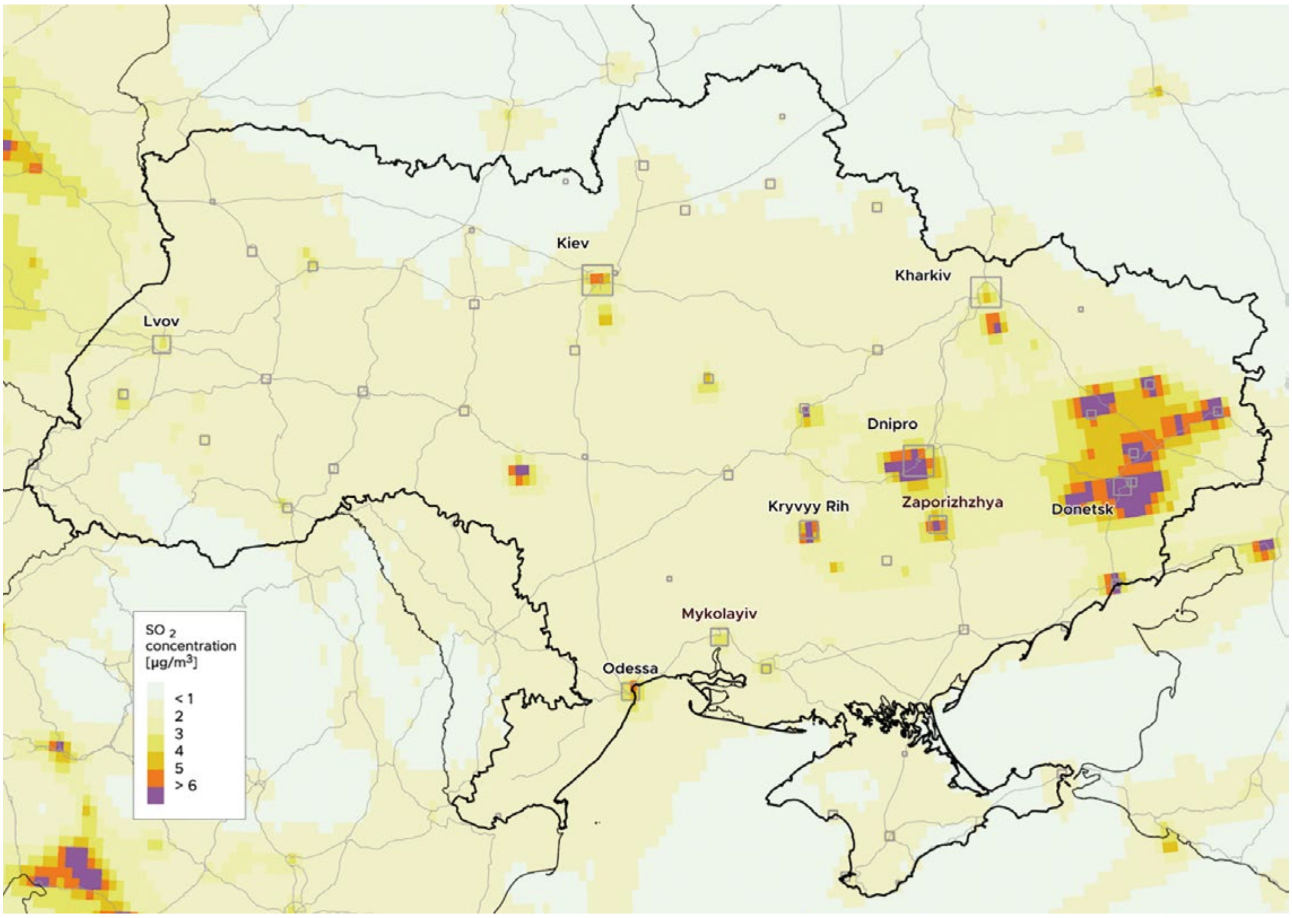


**Fig. 13:** *Median concentrations of $SO_2$ in Ukraine between July 2017 and July 2020 based on CAMS.*

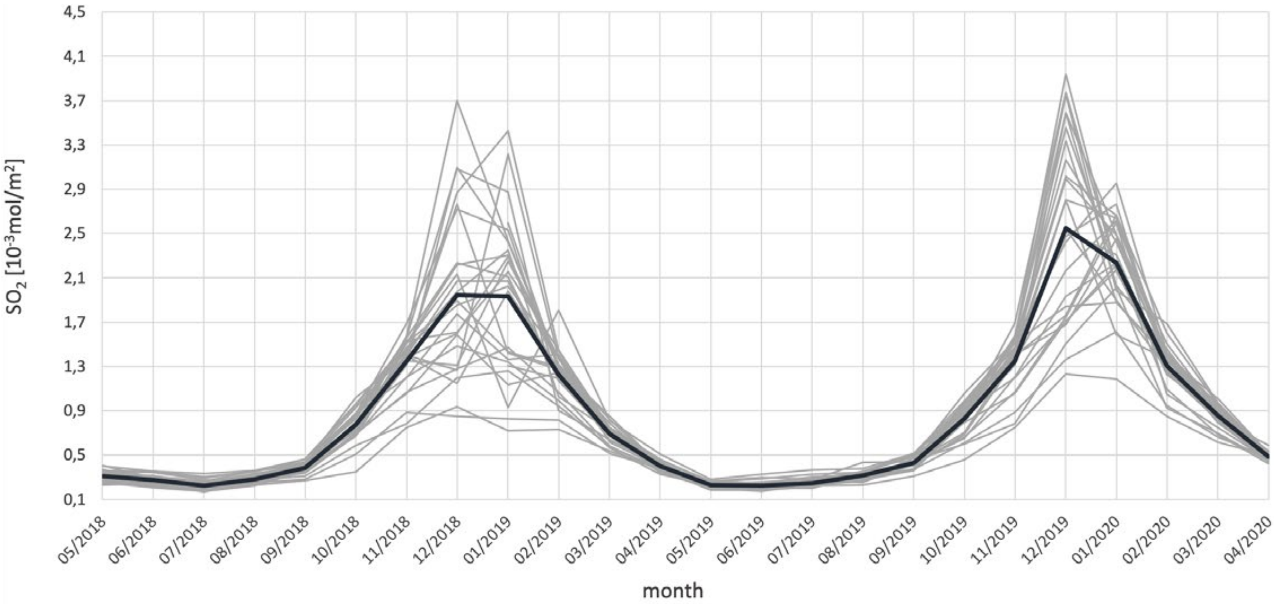


**Fig. 14:** *Average monthly concentrations of $SO_2$ in Ukraine and its regions between May 2018 and April 2020.*

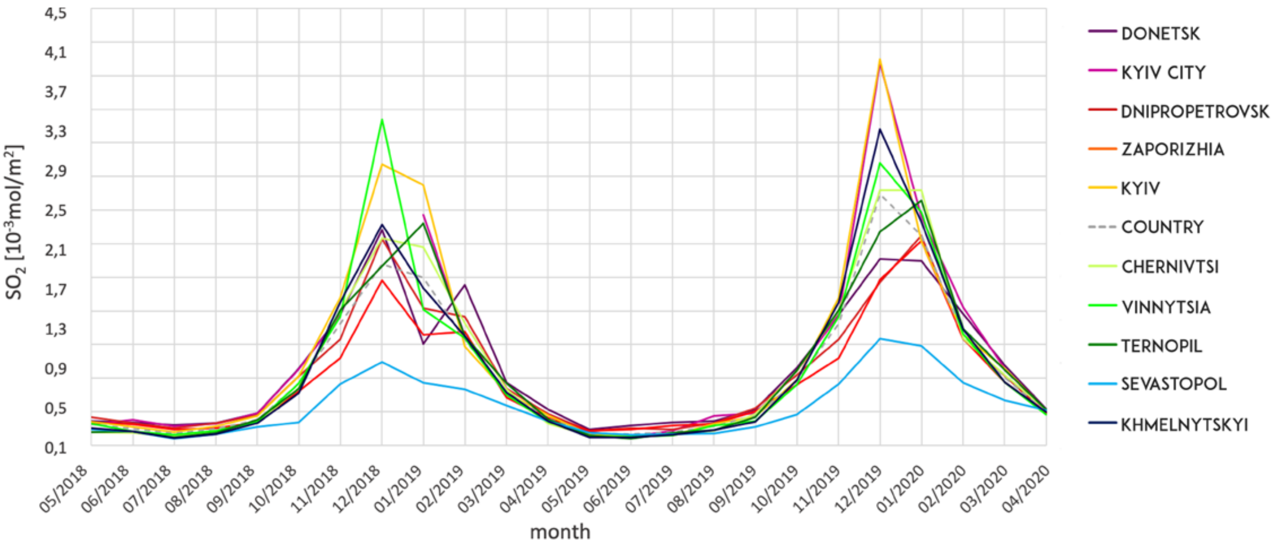


**Fig 15:** *Development of the average concentrations of $SO_2$ in the selected regions of Ukraine between May 2018 and April 2020. The five regions with the highest overall concentrations and the five regions with the lowest overall concentrations have been selected for the display.*

# Formaldehyde

The average values of HCHO for the territory of Ukraine are very similar throughout the country, as can be seen in Figure 16. The average concentration over Ukraine between May 2018 and April 2020 reached a value of **1.47 * $10^{-4}$ mol/m²**. Notwithstanding this, the eastern part of Ukraine and the area of the capital city, Kyiv, include some hotspots where HCHO concentrations are higher. Since the main anthropogenic sources of HCHO in the atmosphere include vehicle emissions, industrial emissions, and coal combustion, this can be attributed to the heavy industry, to coal-mining activities in the Donetsk basin, and to higher mobility in large urban areas.

The eastern part of Ukraine and the area of the capital city, Kyiv, include some hotspots where HCHO concentrations are higher.

Figures 17 and 18 show the development of HCHO concentrations between May 2018 and April 2020.

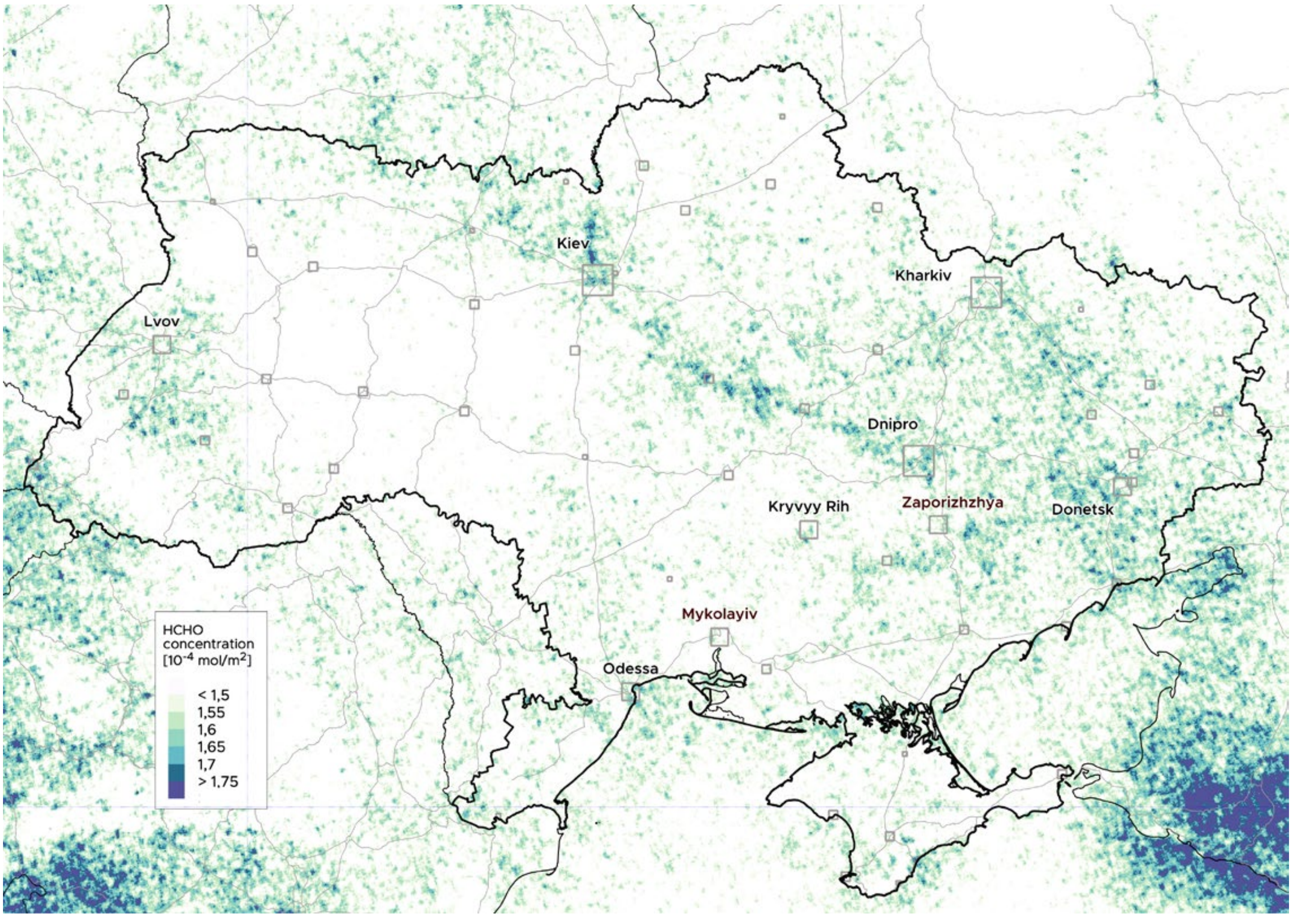


**Fig. 16:** *Average monthly concentrations of HCHO in Ukraine and its regions between May 2018 and April 2020.*

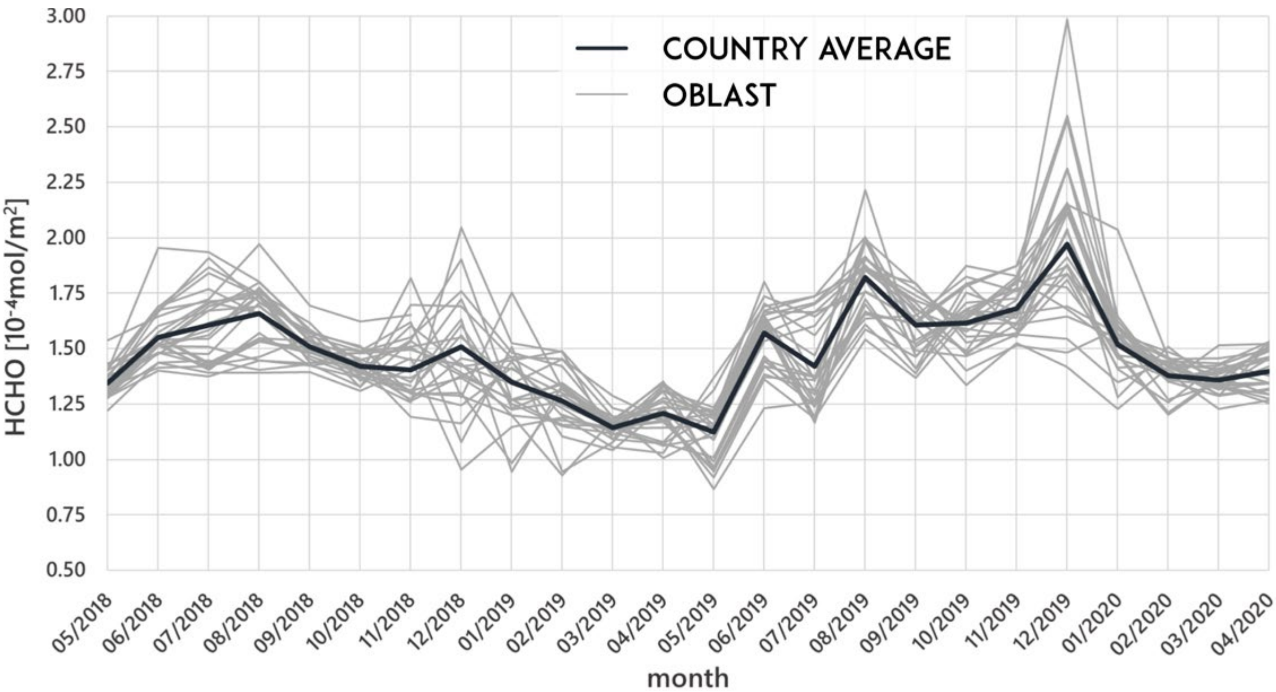


**Fig. 17:** *Average monthly concentrations of HCHO in Ukraine and its regions between May 2018 and April 2020.*

On average, **the values range from 1.25 to 1.75 * $10^{-4}$ mol/m$^2$,** but some peaks can be observed. The seasonal variations in the distribution of formaldehyde are principally related to temperature changes, fire events, and changes in anthropogenic activities.

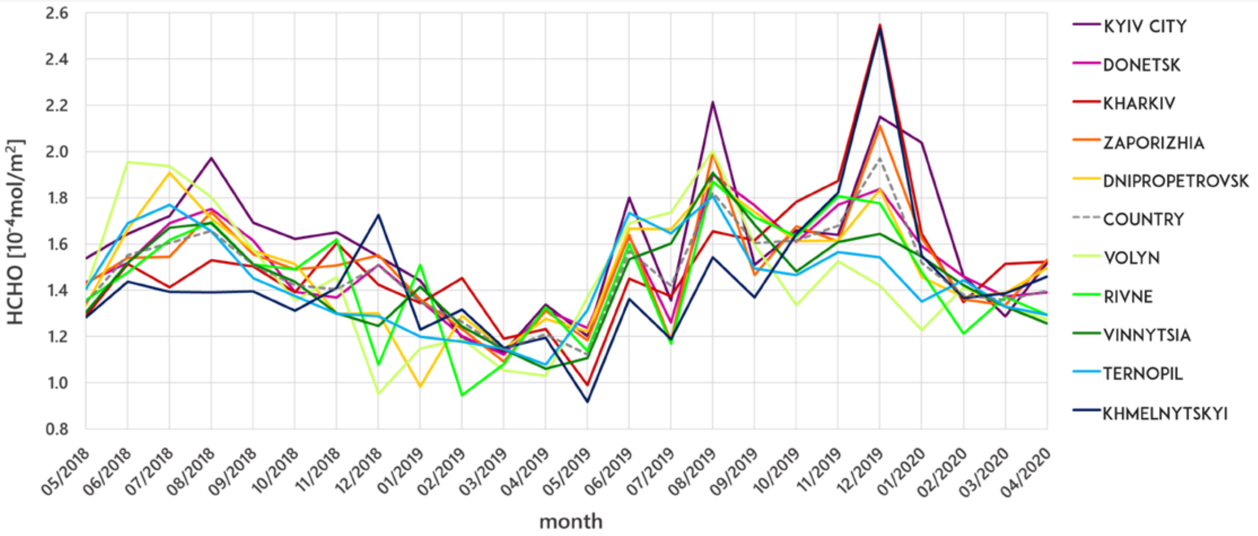


**Fig 18:** *Development of the average concentrations of HCHO in the selected regions of Ukraine between May 2018 and April 2020. The five regions with the highest overall concentrations and the five regions with the lowest overall concentrations have been selected for the display.*

## Particulate matter $PM_{2.5}$

The average $PM_{2,5}$ concentration reached a value of **9.02 μg/m³**. The average distribution is shown in Figure 19. The amount of particulate matter decreases from the south to the north of the country, with the highest concentrations located in the industrial region of eastern Ukraine. Generally, the Donetsk region (11.85 μg/m³), Dnipropetrovsk region (10.88 μg/m³), Kyiv (city) region (10.76 μg/m³), and Zaporizhia (10.15 μg/m³) are among the most affected regions with regard to long-term $PM_{2.5}$ exposure.

**THE MOST AFFECTED REGIONS**
- Donetsk region
- Dnipropetrovsk region
- Kyiv city region
- Zaporizhia region

In several districts, $PM_{2.5}$ concentrations do not comply with the guideline level of 10 μg/m³ indicated by the WHO. There are 127 such districts (see Annex 2), half of which are located within the Donetsk region, 31 within the Dnipropetrovsk region, nine within the city of Kyiv, 16 within the Luhansk region, and within the Zakarpattia and the Chernivtsi regions. Furthermore, the limiting values were exceeded in the cities of Zaporizhia (16.10 μg/m³), Odessa (12.02 μg/m³), and Uzhhorod (11.03 μg/m³). The highest average concentrations were reached in the cities of Mariupol (25.65 μg/m³), Kryvyi Rih (18.93 μg/m³), Manhush (17.51 μg/m³), and Dnipro (16.64 μg/m³). Even the country average was over the limit in March 2018, between November 2018 and February 2019, in November 2019, and in January 2020 and March 2020.

> *“Concentrations of $PM_{2,5}$ exceed the WHO limits in 135 districts. Even the country average was over the limit in March 2017, November 2018, and February 2019.*

On average, $PM_{2.5}$ values in Ukraine are in the range of 5-11 μg/m³. The peaks of the concentrations are reached in late autumn and during the winter period (Figures 20, 21). A decrease in values generally occurs during the summer season and at the beginning of autumn.

The development of average $PM_{2.5}$ concentrations in the regions of Ukraine can be observed in Figure 21. In the Donetsk, Dnipropetrovsk, and Kyiv city regions a significant proportion of values can be seen above the 10 μg/m³ threshold between the late autumn of 2018 and the winter season in 2019. Values are generally higher than in the rest of the country in the Donetsk region. The level even reached over 22 μg/m³ on average between August 2019 and October 2019. The highest concentrations

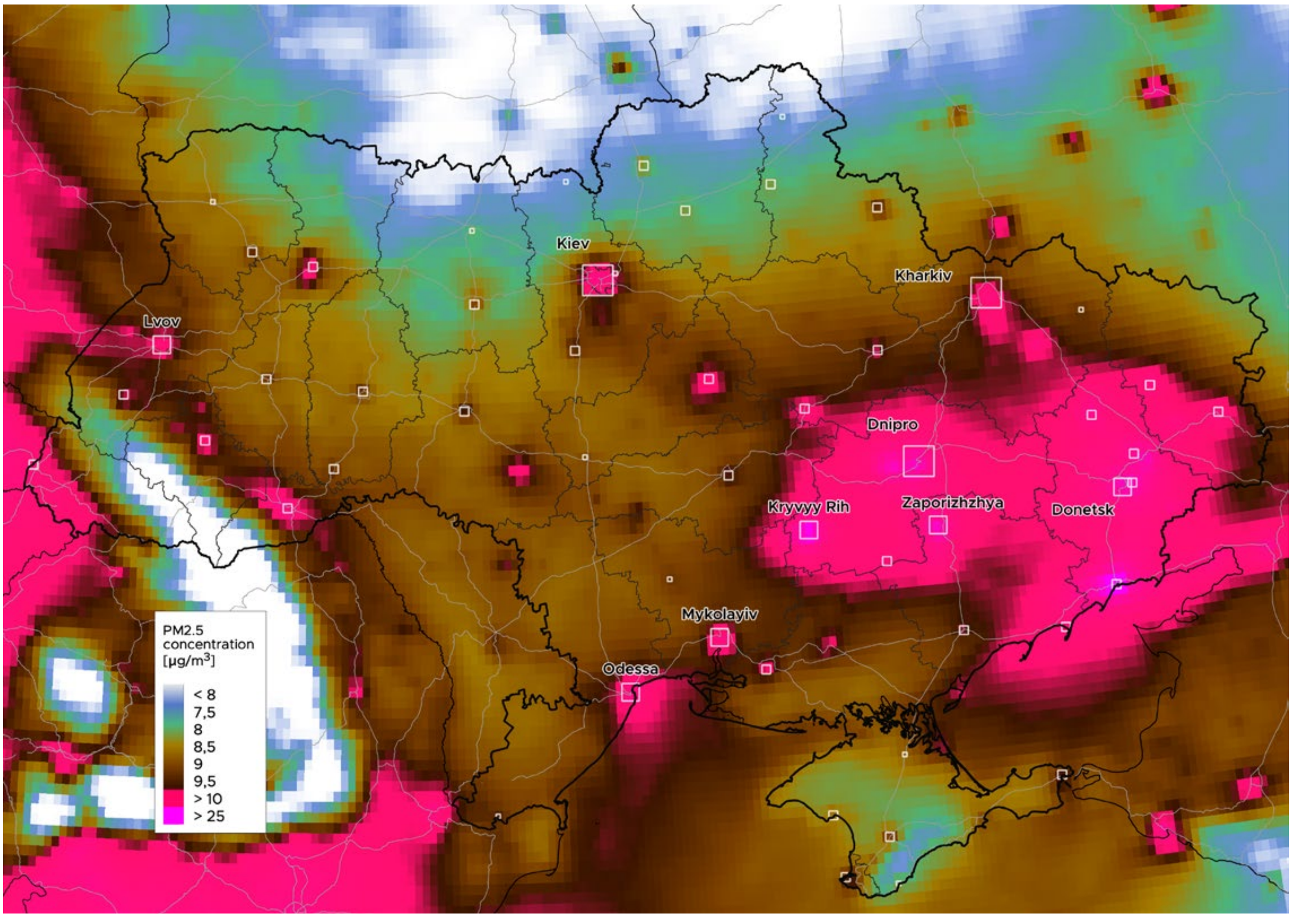


**Fig. 19:** *Average concentrations of $PM_{2.5}$ in Ukraine between July 2017 and July 2020.*

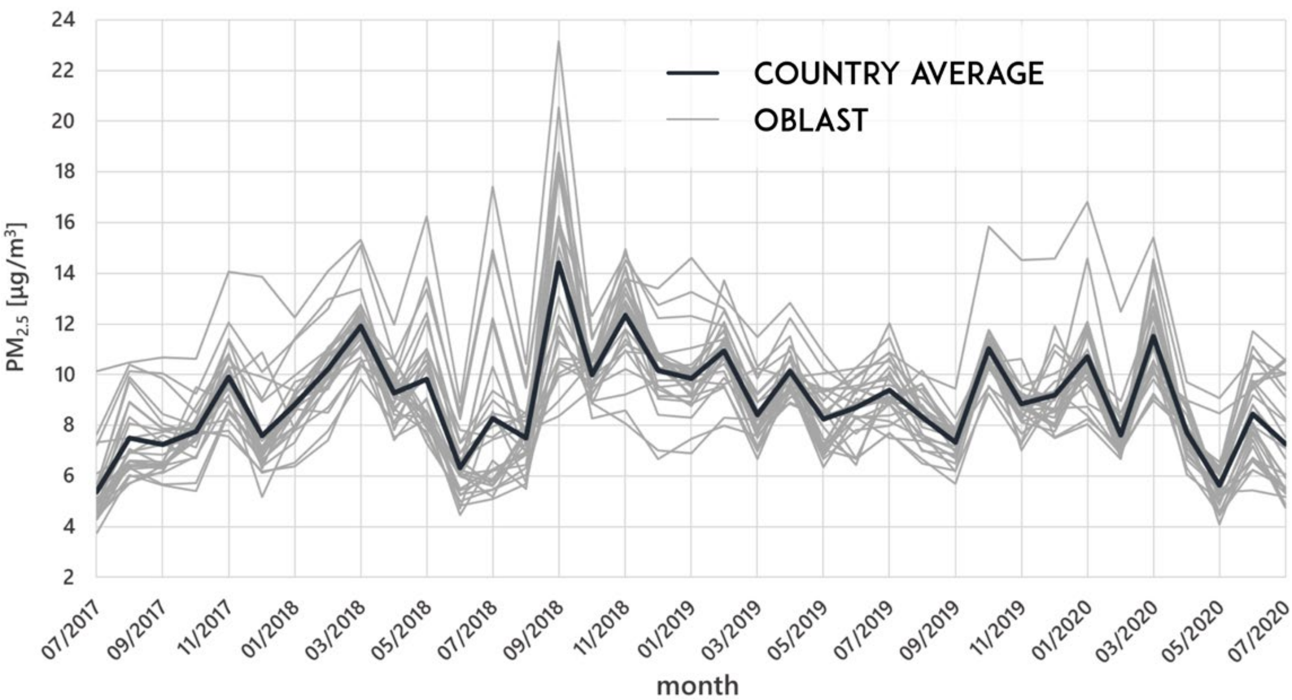


**Fig. 20:** *Average monthly concentrations of $PM_{2.5}$ in Ukraine and its regions between July 2017 and July 2020.*

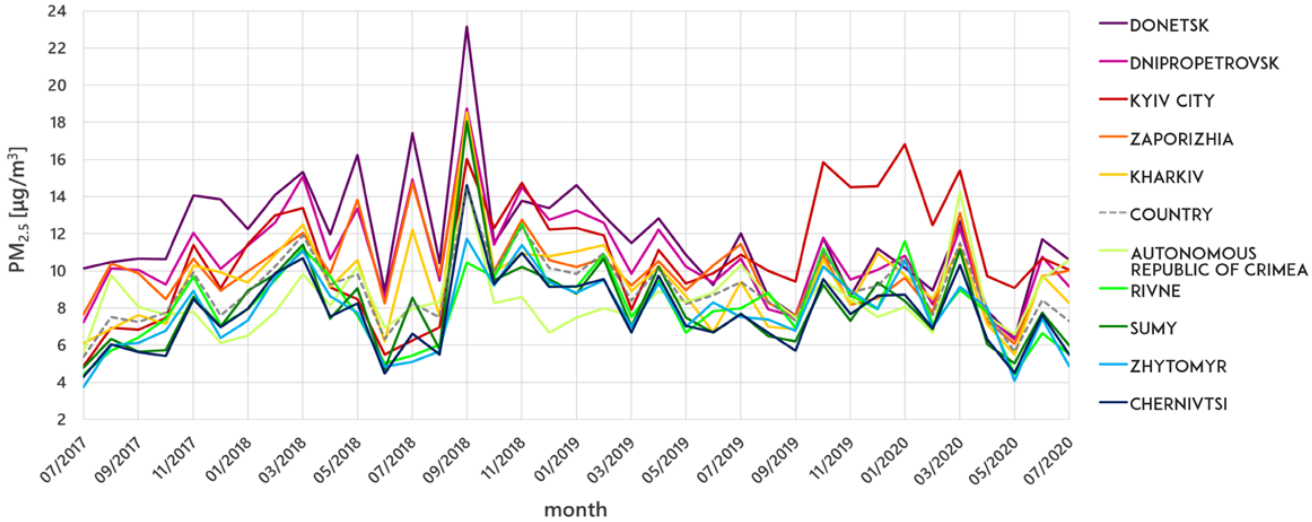


**Fig. 21:** *Development of the average concentrations of $PM_{2.5}$ in Ukrainian regions between July 2017 and July 2017. The five regions with the highest overall concentrations and the five regions with the lowest overall concentrations have been selected for the display.*

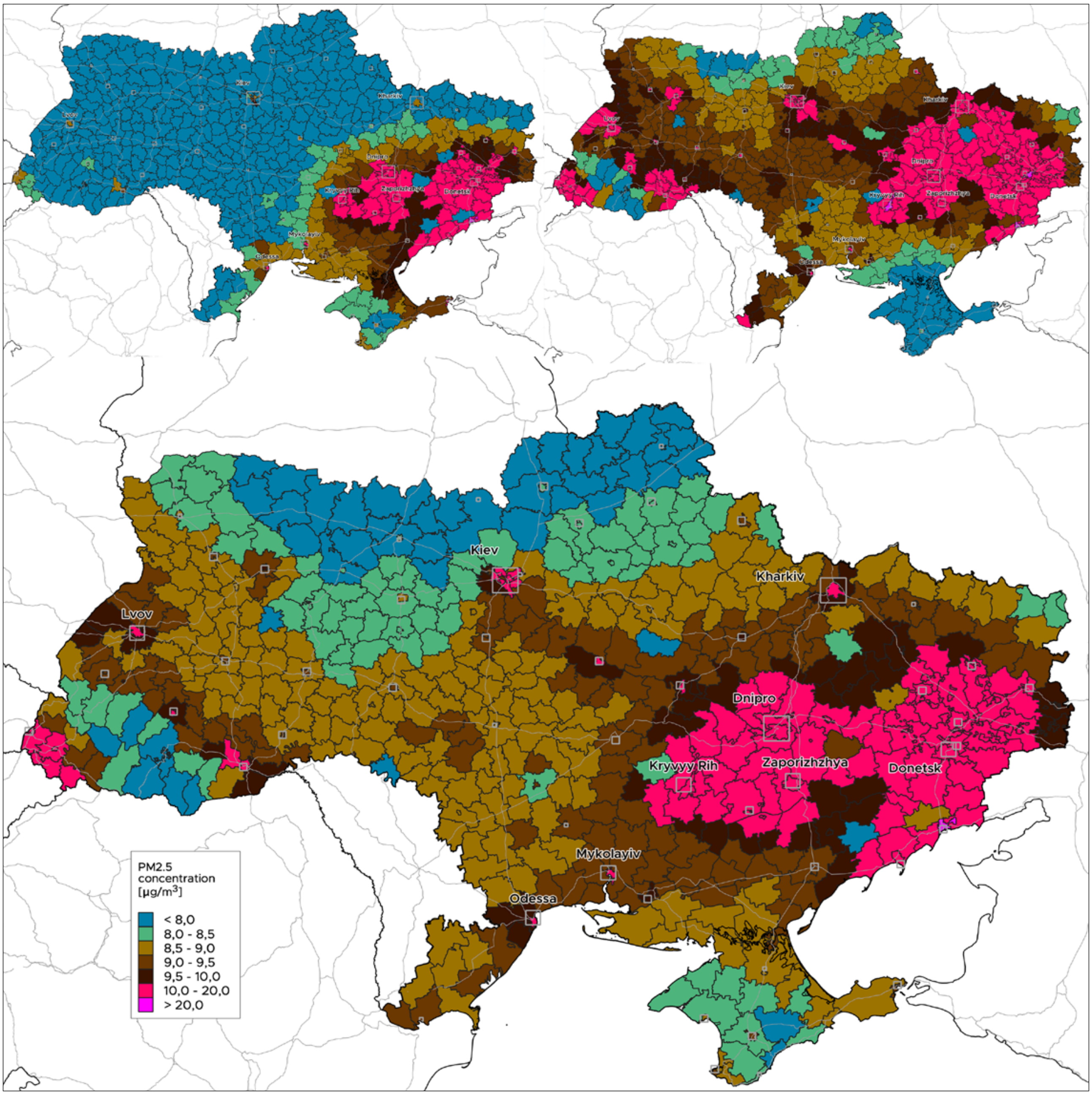


**Fig. 22:** *Average concentrations of $PM_{2.5}$ in districts of Ukraine; between July 2017 and July 20170 (bottom), summer season (left) and winter season (right)*

were also reached in the Kyiv city region between the autumn of 2019 and the winter season in 2020. The lowest values are in the Sumy, Chernivtsi, and Zhytomyr regions, which are located in the north of the country.

Figure 22 compares $PM_{2.5}$ concentrations in the regions of Ukraine in the winter and summer seasons. Pollution decreases in most of the regions during the summer season, as values are cut down to a level of 8 µg/m³. An exception is the Crimea region, where values are higher in summer than in winter. $PM_{2.5}$ values also fall significantly in the city of Kyiv during the summer; nevertheless, there is a significant increase in values throughout the country in the winter months.

Year-round high values are found in the districts of Dnipro, Mariupol, Kryvyi Rih, Zaporizhia, and Kamianske (Dniprodzerzhynsk). In Mariupol average concentrations of 29.41 µg/m³ were observed in the winter seasons; this is almost twice the WHO guideline level for $PM_{2.5}$.

## Particulate matter $PM_{10}$

The **average concentration over Ukraine reaches 11.79 µg/m³** for the period that was monitored. As in the case of $PM_{2.5}$, the amount of $PM_{10}$ decreases from the south to the north of Ukraine (Figure 23). There are five cities where the values exceed the WHO guideline annual mean values for coarse particulates (20 µg/m³). In Mariupol, average values even exceed the WHO guideline for 24h mean values (50 µg/m³). The limiting annual mean value was also exceeded in certain parts of four cities – Kryvyi Rih, Dnipro, Zaporizhia, and Donetsk, all of which are located in south-eastern Ukraine. Together with the capital city, Kyiv, and the city of Kharkiv, the Dniester river valley also achieves high concentrations of $PM_{10}$.

On the other side, together with the northern part of the Ukrainian border, the Carpathian mountain range shows the lowest values. Some other hotspots can be observed, for example the city of Ladyzhyn, which has a relatively low population density and would not be considered a typical urban area, but is where the Ladyzhyn thermal power station is located. Increased

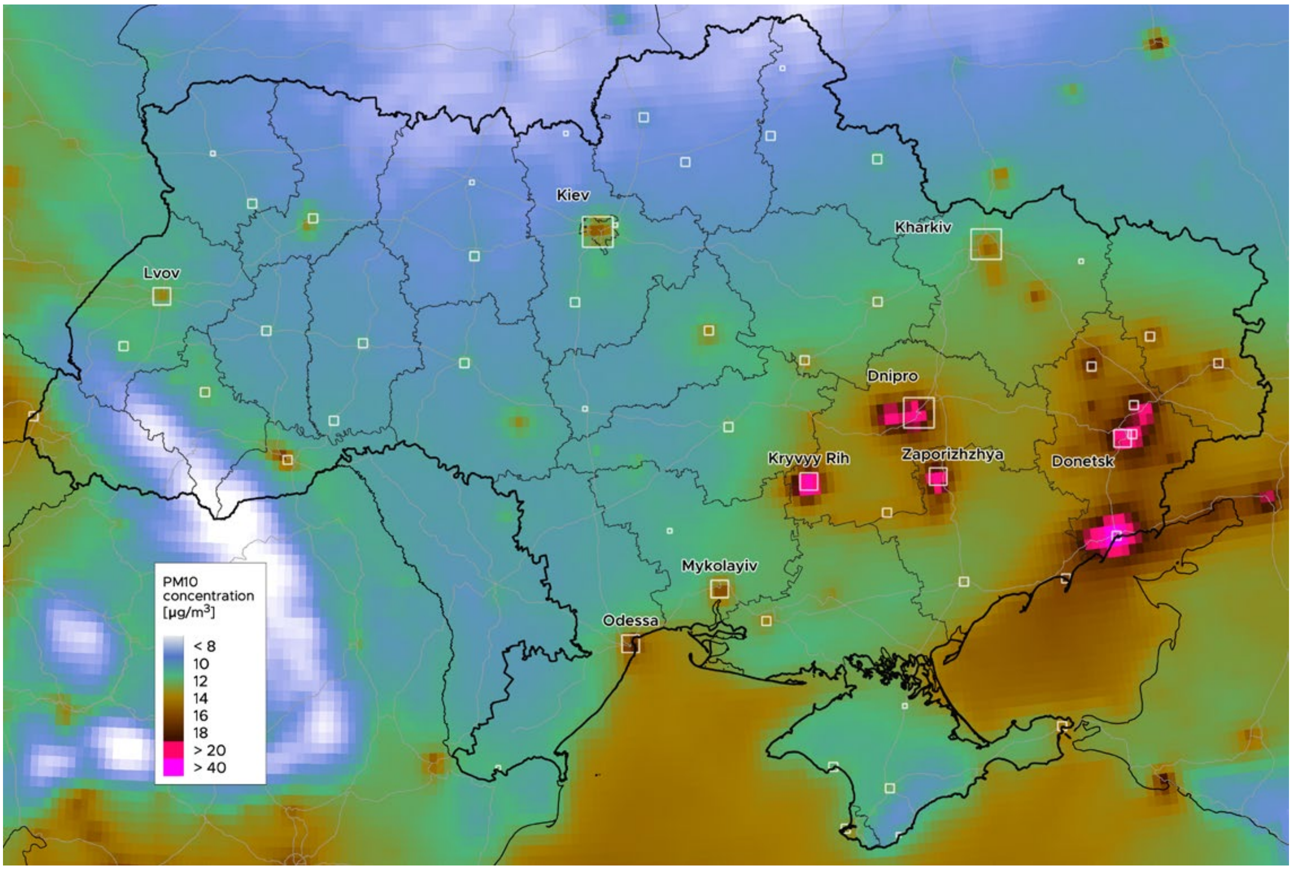


***Fig. 23:*** *Average concentrations of $PM_{10}$ in Ukraine between July 2017 and July 2020.*

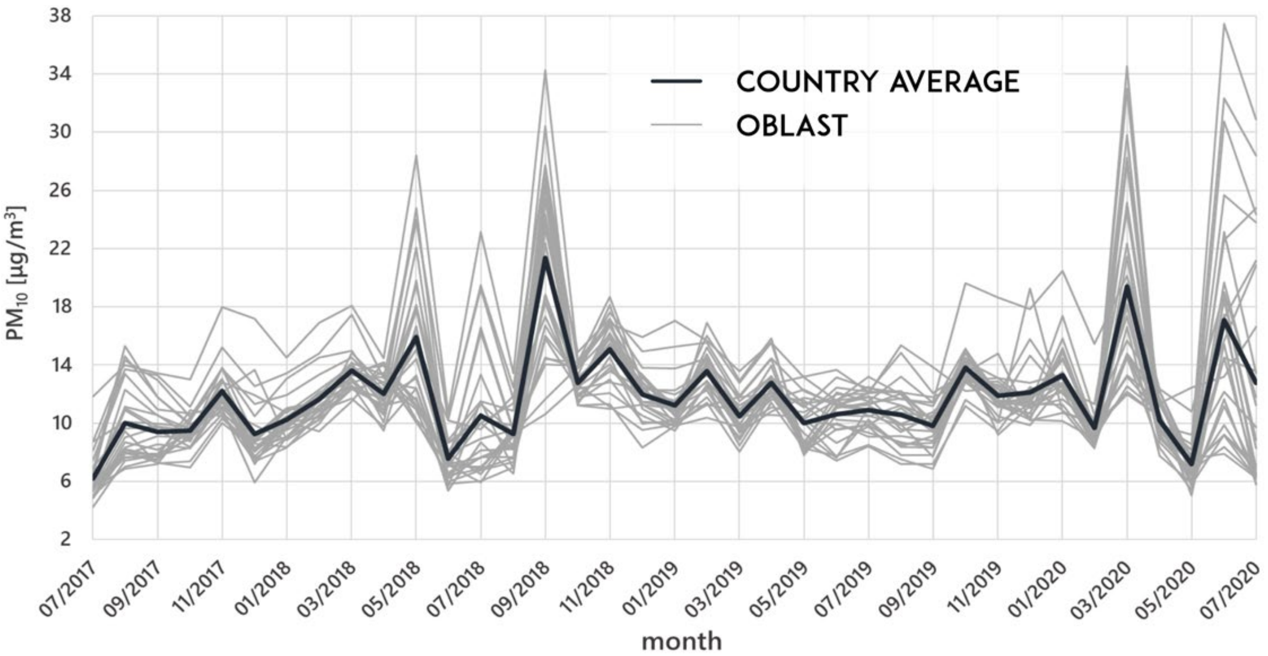


**Fig. 24:** *Average monthly concentrations of $PM_{10}$ in Ukraine and its regions between July 2017 and July 2020.*

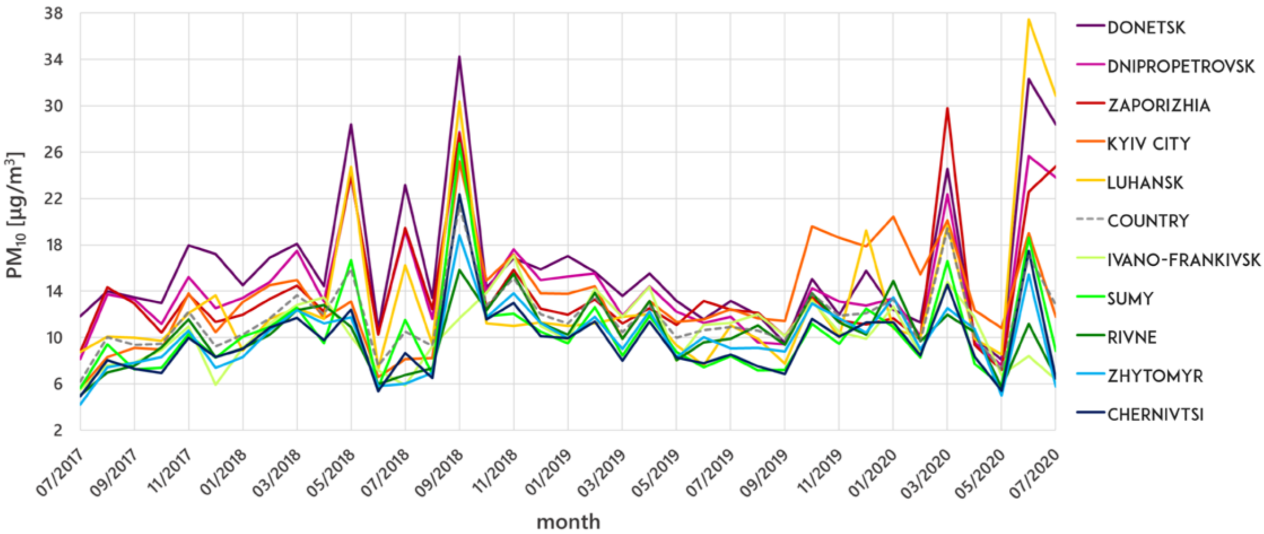


**Fig. 25:** *Development of the average concentrations of $PM_{10}$ in Ukrainian regions between May 2018 and April 2020. The five regions with the highest overall concentrations and the five regions with the lowest overall concentrations have been selected for the display.*

pollution around this city is also indicated by other pollutants ($NO_2$, $PM_{2.5}$). The spatial distribution of $PM_{10}$ concentrations follows the assumption that significantly high values would be observed over the Black Sea and Sea of Azov off the coast of Ukraine, as natural sources (including the evaporation of seawater) represent a significant part of the intake of particulate matter into the air.

> *Limiting values for PM10 were exceeded in certain parts of four cities – Kryvyi Rih, Dnipro, Zaporizhia, and Mariupol.*

## THE MOST AFFECTED REGIONS

- Donetsk region
- Dnipropetrovsk region
- Zaporizhia region

$PM_{10}$ values for different regions generally achieve lower intra-regional variability than for $PM_{25}$; as can be observed in Figure 24, most of the values approach the country average**.** On average, monthly values of $PM_{10}$ in Ukraine are in the range of 6-14 μg/m³**.** There were only two months when the country average reached the WHO limit annual mean values for coarse particulates (September 2018 and March 2020).

# Recommendations

Air quality is considered to be one of the most important health and environmental factors nowadays. In order to improve the quality of life and the environment in Ukraine, coordinated action is necessary on the national, regional and municipal, industry, and citizen level. Moreover, reducing air pollution will directly contribute to fulfilling the UN Sustainable Development goals, as well as the goals of the UNFCCC Paris Agreement on climate change. Air and industrial pollution are also mentioned as one of the environmental priorities in the Association Agreement with the European Union from 2017, which provides for gradual approximation of Ukrainian legislation in accordance with EU environmental rules, policies, and standards, and the development of sector strategies.

Public policies supporting the improvement of air quality should focus on four key areas:

## Monitoring approach

Producing real data and evidence and their use must be a priority for achieving real improvements in air quality while also maintaining cost-effectiveness. Therefore, the connection of all existing ground monitoring systems and extension of the network is a necessity, especially in places that have been identified as air pollution hotspots. According to the experience of the EU countries, building a unified system operated by one authority on a national level, which also performs validation of data, seems to be the best option. This system should also be independent of external and political influences. It is advisable to use all available data on air quality, including public air monitoring systems and the results of independent scientific research, after their additional evaluation.

Ground measurements will provide more insights into the origin of pollution on a local level and precise measurements of pollution levels in places with a high population density. Satellite monitoring and CAMS data should be used on a regular basis for monitoring overall progress and changes in spatial and temporal distribution on a country/regional level. The accessibility of the data by the wide public (open data, a website with the database, analysis, and interpretation) should be obvious in the 21st century.

The results of air quality monitoring should affect government systems at different levels:

- state standards of ecological safety,
- procedures for issuing legal permits for pollutant emissions;
- state regulatory policy.

The monitoring of real pollution levels should be supplemented by the Pollution Release and Transfer Register (PRTR) presenting summary releases of pollutants from individual large industrial facilities – and thus enabling major pollution sources to be identified.

## Emission inventories and plans

(Local) governments use emission inventories to help determine significant sources of air pollutants and to target the steps they take. Methods to determine emissions include continuous monitoring at a specific source, short-term measurements that are extrapolated to a longer time period, and the use of emission factors. Understanding and quantifying local sources of air pollution allows actors to identify key sectors for rapid and cost-effective mitigation.

Especially for industrial centres and/or urban areas, conducting emission inventories should precede the planning of individual measures. Clean air plans on municipal and regional levels based on up-to-date inventories are used as the most effective tool for long-term air quality improvements in cities and regions around the world. Announcing smog alerts and restrictions on transport, industrial operations, and public life should be part of such plans.

## Changes in management practices

Many sectors provide opportunities for ~improving air quality. Out of them, transport, heavy industry, mining, heating, energy production, public procurement, and building retrofitting are among the most targeted and efficient. Targeted funding to improve air quality (the state, regional or local subsidies for new boilers, retrofitting, etc.) is used for both the commercial sector and individuals.

Concerning the major industrial polluters, the state should implement progressive legislation and adopt the EU standards. Compliance with permitted pollution limits should then be enforced by the state authorities. The state, international organizations, and intergovernmental bodies should motivate the industries to perform essential modernization and investments in the best available techniques (BAT), as many existing industrial facilities are outdated.

## Public involvement

Awareness-raising and communication campaigns are essential to increase public understanding of the serious consequences of air pollution for human health. It is crucial to ensure that citizens have access to information – data from the state air quality monitoring, timely warnings during smog situations, details on the operation of the major pollution sources, etc. The state should involve the public in decision making – such as spatial planning, approval of clean air plans on the municipal and regional levels, and EIAs and other permitting procedures for the operation of industrial facilities. Public involvement – besides its other positive effects – also helps to overcome potential public, political, or commercial opposition to planned measures.

Public awareness campaigns should also bring improvements based on changes in individual behaviour (transport, heating in private houses, energy saving, burning of biomass, etc.).

# ANNEX

## Annex 1: Average concentrations in the regions

**Tab. 1:** *Average concentrations of $NO_2$, CO, $SO_2$, and HCHO in the regions ("oblasti") of Ukraine between 1 May 2018 and 30 April 2020 and average concentrations of $PM_{2.5}$, and $PM_{10}$ in the regions of Ukraine between 15 July 2017 and 14 July 2020. Concentrations exceeding the WHO guideline values are displayed in bold.*

| pollutant/region | $NO_2$ [mol * $10^{-4}$ /m²] | CO [mol * $10^{-1}$ /m²] | $SO_2$ [mol * $10^{-3}$ /m²] | HCHO [mol * $10^{-4}$ /m²] | $PM_{2.5}$ [µg/m³] | $PM_{10}$ [µg/m³] |
|---|---|---|---|---|---|---|
| **Aut. Rep. of Crimea** | 0.215 | 0.332 | 0.414 | 1.46 | 8.47 | 12.23 |
| **Cherkasy** | 0.261 | 0.333 | 0.413 | 1.55 | 8.95 | 11.36 |
| **Chernihiv** | 0.244 | 0.335 | 0.436 | 1.49 | 7.74 | 9.77 |
| **Chernivtsi** | 0.244 | 0.324 | 0.404 | 1.45 | 8.87 | 10.97 |
| **Dnipropetrovsk** | 0.335 | 0.339 | 0.471 | 1.48 | **10.88** | 14.50 |
| **Donetsk** | 0.402 | 0.337 | 0.520 | 1.51 | **11.85** | 16.20 |
| **Ivano-Frankivsk** | 0.250 | 0.315 | 0.442 | 1.46 | 8.40 | 10.40 |
| **Kharkiv** | 0.291 | 0.334 | 0.447 | 1.48 | 9.37 | 12.70 |
| **Kherson** | 0.246 | 0.340 | 0.419 | 1.51 | 9.13 | 12.67 |
| **Khmelnytskyi** | 0.253 | 0.327 | 0.391 | 1.47 | 8.49 | 10.76 |
| **Kirovohrad** | 0.257 | 0.333 | 0.412 | 1.37 | 9.15 | 11.87 |
| **Kyiv (region)** | 0.304 | 0.337 | 0.448 | 1.46 | 8.53 | 10.76 |
| **Kyiv (city)** | 0.633 | 0.339 | 0.493 | 1.48 | **10.76** | 13.34 |
| **Luhansk** | 0.291 | 0.335 | 0.434 | 1.57 | 9.38 | 13.30 |
| **Lviv** | 0.274 | 0.328 | 0.433 | 1.49 | 9.02 | 11.36 |
| **Mykolaiv** | 0.255 | 0.337 | 0.417 | 1.48 | 9.18 | 12.10 |
| **Odessa** | 0.250 | 0.336 | 0.436 | 1.45 | 8.94 | 11.55 |
| **Poltava** | 0.276 | 0.337 | 0.423 | 1.48 | 9.04 | 11.78 |
| **Rivne** | 0.252 | 0.334 | 0.423 | 1.50 | 8.11 | 10.28 |
| **Sevastopol (city)** | 0.260 | 0.330 | 0.392 | 1.43 | 8.79 | 12.42 |
| **Sumy** | 0.236 | 0.333 | 0.414 | 1.47 | 8.10 | 10.40 |
| **Ternopil** | 0.272 | 0.327 | 0.398 | 1.45 | 8.69 | 10.94 |
| **Vinnytsia** | 0.251 | 0.329 | 0.399 | 1.40 | 8.70 | 11.01 |
| **Volyn** | 0.273 | 0.335 | 0.414 | 1.40 | 8.40 | 10.69 |
| **Zakarpattia** | 0.208 | 0.319 | 0.414 | 1.43 | 8.73 | 10.90 |
| **Zaporizhia** | 0.284 | 0.339 | 0.464 | 1.45 | **10.15** | 13.98 |
| **Zhytomyr** | 0.243 | 0.332 | 0.430 | 1.51 | 7.83 | 10.00 |
| **country average** | **0.280** | **0.332** | **0.432** | **1.47** | **9.02** | **11.79** |

# Annex 2: List of districts with excessive concentrations of $PM_{2,5}$

*Districts (raions) where PM2.5 concentrations do not comply with the guideline level of 10 µg/m3 indicated by the WHO.*

| Region | Territory of the administrative unit | | Average | | Average all time |
|---|---|---|---|---|---|
| | Type | Name | Average summer | Average winter | |
| **Donetsk** | **City/town** | **Mariupol** | 20.83 | 29.41 | 25.65 |
| **Dnipropetrovsk** | **City/town** | **Kryvyi Rih** | 14.72 | 22.81 | 18.93 |
| **Donetsk** | **District** | **Manhush** | 15.18 | 19.34 | 17.51 |
| **Dnipropetrovsk** | **City/town** | **Dnipro** | 13.43 | 19.31 | 16.64 |
| **Donetsk** | **City/town** | **Yenakiieve** | 12.98 | 20.34 | 16.56 |
| **Donetsk** | **City/town** | **Makiivka** | 13.54 | 19.55 | 16.54 |
| **Zaporizhia** | **City/town** | **Zaporizhia** | 13.50 | 18.45 | 16.10 |
| **Dnipropetrovsk** | **City/town** | **Dnipro** | 12.60 | 15.72 | 14.62 |
| **Donetsk** | **City/town** | **Donetsk** | 13.09 | 15.36 | 14.34 |
| **Donetsk** | **City/town** | **Khartsyzk** | 11.79 | 15.96 | 14.03 |
| **Donetsk** | **City/town** | **Yasynuvata** | 11.47 | 15.60 | 13.34 |
| **Donetsk** | **City/town** | **Horlivka** | 11.16 | 15.32 | 13.18 |
| **Dnipropetrovsk** | **District** | **Kryvyi Rih** | 11.08 | 14.69 | 13.13 |
| **Donetsk** | **District** | **Yasynuvata** | 11.23 | 14.59 | 12.89 |
| **Dnipropetrovsk** | **District** | **Dnipro** | 11.15 | 14.04 | 12.86 |
| **Donetsk** | **District** | **Nikolske** | 11.81 | 13.37 | 12.85 |
| **Donetsk** | **City/town** | **Zhdanivka** | 10.99 | 13.60 | 12.54 |
| **Dnipropetrovsk** | **District** | **Petrykivka** | 10.01 | 14.38 | 12.47 |
| **Donetsk** | **City/town** | **Kramatorsk** | 10.81 | 13.61 | 12.40 |
| **Kyiv City** | **District** | **Shevchenkivskyi** | 9.36 | 14.22 | 12.16 |
| **Kyiv City** | **District** | **Pecherskyi** | 9.24 | 14.30 | 12.11 |
| **Odessa** | **City/town** | **Odessa** | 11.44 | 11.86 | 12.02 |
| **Donetsk** | **District** | **Novoazovsk** | 11.83 | 11.46 | 11.95 |
| **Donetsk** | **City/town** | **Vuhledar** | 10.83 | 12.49 | 11.91 |
| **Kyiv City** | **District** | **Solomianskyi** | 9.16 | 13.86 | 11.91 |
| **Donetsk** | **City/town** | **Sloviansk** | 10.37 | 12.95 | 11.83 |
| **Donetsk** | **City/town** | **Toretsk** | 10.46 | 13.11 | 11.83 |
| **Dnipropetrovsk** | **District** | **Krynychky** | 10.36 | 12.57 | 11.82 |
| **Donetsk** | **City/town** | **Khrestivka** | 10.73 | 12.40 | 11.82 |
| **Donetsk** | **City/town** | **Selydove** | 11.41 | 11.85 | 11.76 |

| Region | Territory of the administrative unit | | Average | | Average all time |
|---|---|---|---|---|---|
| | Type | Name | Average summer | Average winter | |
| Donetsk | District | Boykivske | 11.42 | 11.58 | 11.76 |
| Zaporizhia | District | Zaporizhia | 11.11 | 12.18 | 11.74 |
| Donetsk | District | Starobesheve | 11.43 | 11.38 | 11.65 |
| Dnipropetrovsk | District | Shyroke | 10.64 | 12.09 | 11.65 |
| Luhansk | City/town | Sieverodonetsk | 10.05 | 12.78 | 11.63 |
| Chernivtsi | City/town | Chernivtsi | 9.07 | 14.26 | 11.55 |
| Donetsk | City/town | Shakhtarsk | 10.55 | 12.10 | 11.53 |
| Donetsk | District | Amvrosiivka | 11.09 | 11.53 | 11.52 |
| Luhansk | City/town | Alchevsk | 10.29 | 12.21 | 11.51 |
| Kyiv City | District | Dniprovskyi | 8.71 | 13.58 | 11.49 |
| Donetsk | District | Kostiantynivka | 10.26 | 12.20 | 11.36 |
| Luhansk | City/town | Lysychansk | 9.78 | 12.43 | 11.33 |
| Kyiv City | District | Kamianets-Podilskyi | 8.67 | 13.18 | 11.32 |
| Donetsk | District | Marinka | 11.20 | 11.19 | 11.32 |
| Zaporizhia | District | Berdyansk | 11.20 | 10.86 | 11.32 |
| Donetsk | City/town | Novohrodivka | 10.87 | 11.55 | 11.30 |
| Luhansk | City/town | Krasnolutskyi | 10.19 | 11.87 | 11.27 |
| Donetsk | City/town | Kostiantynivka | 10.06 | 12.11 | 11.24 |
| Donetsk | District | Shakhtarsk | 10.46 | 11.60 | 11.23 |
| Mykolayiv | City/town | Mykolayiv | 10.13 | 11.38 | 11.19 |
| Luhansk | City/town | Luhansk | 10.26 | 11.37 | 11.18 |
| Luhansk | District | Perevalsk | 10.17 | 11.56 | 11.14 |
| Donetsk | District | Pokrovsk | 10.69 | 11.32 | 11.13 |
| Zaporizhia | City/town | Berdiansk | 11.55 | 9.87 | 11.09 |
| Zaporizhia | District | Vilnianskyi | 10.31 | 11.46 | 11.09 |
| Luhansk | City/town | Kadiivka | 10.10 | 11.65 | 11.08 |
| Donetsk | City/town | Krasnolymanska | 9.86 | 12.00 | 11.08 |
| Donetsk | City/town | Pokrovsk | 10.59 | 11.31 | 11.06 |
| Dnipropetrovsk | City/town | Novomoskovska | 9.58 | 12.05 | 11.05 |
| Donetsk | District | Volnovakha | 10.97 | 10.84 | 11.03 |
| Zakarpattia | City/town | Uzhhorod | 8.74 | 13.64 | 11.03 |
| Dnipropetrovsk | District | Solone | 10.38 | 11.28 | 11.02 |
| Donetsk | District | Bakhmut | 9.89 | 11.83 | 11.01 |

| Region | Territory of the administrative unit | | Average | | Average all time |
|---|---|---|---|---|---|
| | Type | Name | Average summer | Average winter | |
| Chernivtsi | District | Kitsman | 8.52 | 13.14 | 10.97 |
| Donetsk | City/town | Toretsk | 10.21 | 11.33 | 10.91 |
| Donetsk | City/town | Bakhmut | 9.82 | 11.76 | 10.90 |
| Kharkiv | City/town | Kharkiv | 8.64 | 12.88 | 10.89 |
| Donetsk | District | Sloviansk | 9.64 | 11.61 | 10.87 |
| Dnipropetrovsk | District | Verkhnodniprovsk | 9.49 | 11.32 | 10.86 |
| Dnipropetrovsk | District | Tomakivka | 10.47 | 10.61 | 10.76 |
| Dnipropetrovsk | City/town | Nikopol | 11.13 | 10.06 | 10.75 |
| Lviv | City/town | Lviv | 8.69 | 11.84 | 10.72 |
| Luhansk | District | Popasna | 9.71 | 11.23 | 10.72 |
| Dnipropetrovsk | City/town | Marhanets | 10.64 | 10.30 | 10.70 |
| Zakarpattia | District | Uzhhorod | 8.51 | 12.98 | 10.67 |
| Cherkasy | City/town | Cherkasy | 8.84 | 11.57 | 10.64 |
| Donetsk | City/town | Snizhne | 9.98 | 10.93 | 10.62 |
| Zakarpattia | City/town | Mukachevo | 8.33 | 12.95 | 10.60 |
| Dnipropetrovsk | District | Synelnykove | 10.12 | 10.48 | 10.60 |
| Donetsk | City/town | Dobropillia | 10.01 | 10.81 | 10.59 |
| Kyiv City | District | Desnianskyi | 7.98 | 12.47 | 10.59 |
| Donetsk | District | Velyka Novosilka | 10.57 | 10.19 | 10.57 |
| Kyiv City | District | Sviatoshynskyi | 8.16 | 11.90 | 10.55 |
| Luhansk | City/town | Brianka | 9.88 | 10.77 | 10.55 |
| Donetsk | District | Dobropillia | 10.00 | 10.70 | 10.55 |
| Zaporizhia | City/town | Enerhodar | 10.77 | 9.79 | 10.54 |
| Dnipropetrovsk | District | Apostolove | 10.36 | 10.08 | 10.54 |
| Luhansk | City/town | Rubizhne | 9.03 | 11.60 | 10.53 |
| Dnipropetrovsk | City/town | Synelnykove | 10.12 | 10.29 | 10.52 |
| Luhansk | City/town | Holubivka | 9.60 | 11.06 | 10.52 |
| Dnipropetrovsk | City/town | Pokrovske | 10.51 | 9.95 | 10.51 |
| Dnipropetrovsk | District | Nikopol | 10.46 | 9.90 | 10.46 |
| Dnipropetrovsk | District | Sofiivka | 9.57 | 10.59 | 10.46 |
| Dnipropetrovsk | City/town | Zhovti Vody | 9.21 | 11.12 | 10.43 |
| Dnipropetrovsk | District | Novomoskovsk | 9.21 | 11.16 | 10.42 |
| Poltava | City/town | Kremenchuk | 8.97 | 10.85 | 10.40 |

| Region | Territory of the administrative unit | | Average | | Average all time |
|---|---|---|---|---|---|
| | Type | Name | Average summer | Average winter | |
| Kyiv City | District | Holosiivskyi | 7.94 | 11.90 | 10.38 |
| Zakarpattia | District | Berehove | 8.24 | 12.72 | 10.38 |
| Kyiv City | District | Darnytskyi | 7.78 | 12.18 | 10.36 |
| Zaporizhia | District | Rozivka | 10.41 | 10.10 | 10.33 |
| Kirovohrad | District | Petrove | 9.21 | 10.96 | 10.33 |
| Dnipropetrovsk | City/town | Pavlograd | 9.57 | 10.38 | 10.32 |
| Dnipropetrovsk | District | Tsarychanka | 8.64 | 11.17 | 10.31 |
| Mykolayiv | District | Kazanka | 9.47 | 10.18 | 10.29 |
| Donetsk | District | Oleksandrivka | 9.49 | 10.50 | 10.28 |
| Dnipropetrovsk | District | Piatykhatky | 9.10 | 10.70 | 10.28 |
| Kyiv City | District | Obolonskyi | 7.87 | 11.80 | 10.27 |
| Dnipropetrovsk | District | Mezhova | 10.00 | 10.06 | 10.26 |
| Zakarpattia | District | Mykhailivka | 8.11 | 12.37 | 10.26 |
| Zaporizhia | District | Vasylivka | 10.46 | 9.72 | 10.26 |
| Zaporizhia | District | Bilmak | 10.29 | 9.85 | 10.25 |
| Luhansk | District | Lutuhyne | 9.67 | 10.11 | 10.23 |
| Zaporizhia | District | Kamianka-Dniprovska | 10.47 | 9.44 | 10.21 |
| Luhansk | District | Antratsyt | 9.70 | 10.17 | 10.21 |
| Dnipropetrovsk | District | Mahdalynivka | 8.64 | 11.16 | 10.20 |
| Luhansk | District | Slovianoserbsk | 9.29 | 10.51 | 10.19 |
| Dnipropetrovsk | District | Pokrov | 10.03 | 9.80 | 10.19 |
| Zaporizhia | District | Prymorsk | 10.49 | 9.21 | 10.19 |
| Luhansk | City/town | Antratsyt | 9.70 | 10.18 | 10.18 |
| Zakarpattia | District | Vynohradiv | 8.08 | 12.49 | 10.17 |
| Dnipropetrovsk | District | Pavlohrad | 9.46 | 10.13 | 10.13 |
| Dnipropetrovsk | District | Vasylkivka | 9.76 | 9.83 | 10.11 |
| Dnipropetrovsk | District | Petropavlivka | 9.64 | 10.02 | 10.10 |
| Zaporizhia | District | Novomykolaivka | 9.82 | 9.70 | 10.08 |
| Donetsk | District | Lyman | 8.89 | 10.88 | 10.07 |
| Ivano-Frankivsk | City/town | Ivano-Frankivsk | 8.22 | 11.03 | 10.06 |
| Odessa | District | Ovidiopol | 9.29 | 9.63 | 10.00 |

**Kryvyi Rih**: *The city is a coal mining and metallurgy centre of Kryvbas. The biggest polluter of its environment is the global steelworking corporation ArcelorMittal. Photo: Stanislav Krupar / Arnika*

**Mariupol:** *Air pollution is caused by the Azovstal and Ilyich steelworks, owned by the Metinvest Group of Rinat Akhmetov; these plants are one of the largest steel producers in Ukraine. Photo: Stanislav Krupar / Arnika*

**Zaporizhia:** *Air pollution is caused by the Azovstal and Ilyich steelworks, owned by the Metinvest Group of Rinat Akhmetov; these plants are one of the largest steel producers in Ukraine. Photo: Stanislav Krupar / Arnika*

**Mariupol:** *Large demonstrations by the civic initiative "Let us breathe!" pushed the steelworks to make environmental investments and caused some of the activists to gain places in the city council. Photo: Archive of Let us breathe!*

**Arnika** is uniting people seeking a better environment. We believe that natural wealth is not only a gift, but also an obligation to save it for the future. Since its foundation, Arnika has become one of the most important environmental organizations in the Czech Republic. We base our activities on three pillars: engaging the public, professional arguments, and communication. Since the beginning, we have led public campaigns both in the Czech Republic and internationally. The organization focuses on nature conservation, toxics and waste, access to information, and public participation in decision-making.

**Clean Air for Ukraine** is a joint project of Arnika and an informal network of local non-governmental organizations from the industrial regions of Ukraine. Our objective is to improve access to information and strengthen public participation in decision-making. A public monitoring network of air pollution, analysis of soil, river sediments, and foodstuffs in five regions, and capacity building programmes for the civil society are some of our main achievements. We bring the experience of transformation of the Czech Republic, involve scientists and experts in public campaigns, publish analyses, and suggest solutions.

**World from Space** is a Czech company bringing the benefits of space technology to sustainable society. Our key technology domains are Earth Observation and geospatial and big data analysis, especially in the urban, environmental, and agricultural domains. We focus on advanced data analysis and machine learning by means of satellite imagery and data from the Copernicus services. The company's flagship product DynaCrop API provides global crop monitoring for agriculture software. Let us know about your ideas and check out our website: www.worldfrom.space

**More information: www.cleanair.org.ua**