# Air Pollution in Belarus from space

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

**Prague - Minsk, 2020**

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# Air Pollution in Belarus from Space

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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.**

According to our analysis, both satellite and modelled data sources show **generally low concentrations of the pollutants that we studied over Belarus**. However, low average regional values don't mean that there are not local hotspots where the pollution levels might be significantly higher. Moreover, pollutants other than the ones we studied could have severe effects on human health. Only local spot measurements are able to unveil such pollution.

**From a city perspective, there should be a focus on four key urban areas, Brest, Homyel, Hrodna, and Minsk**, which have higher overall concentrations of pollutants than the rest of the country.

There are generally low levels of $SO_2$ and formaldehyde. A hotspot of higher formaldehyde values can be observed in the North of Belarus over the town of Novopolock, where a major oil refinery is located.

**The significant transport of cross-border $NO_2$ and PM pollution from Poland is present in south-west Belarus, especially in the winter months.**

The amount of $PM_{2.5}$ and $PM_{10}$ decreases from the south-west to the north-east of Belarus. **Hrodna is the only city where the concentrations of $PM_{2.5}$ exceed the guideline level indicated by the WHO**. No city or region exceeds the limit for $PM_{10}$.

Public policies supporting air quality improvements should focus on four main areas: improving air quality monitoring, supporting emissions inventories and plans, conducting changes in management practices in key sectors, and including the public into the process.

# Introduction

With the rapid increase of the world's population and its high consumer demand, the problem of air pollution is growing. 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.

> *"7 million people die every year from exposure to polluted air."* 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,[1] with ambient (i.e. outdoor) pollution alone causing about 4.2 millions premature deaths every year, mainly from heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections in children.[2]

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).

According to the WHO, Belarus has entered the list of the countries with the highest incidence of annual deaths from air pollution per 100,000 inhabitants. The total number of deaths caused by air pollution in Belarus is estimated at 9,450. The total volume of deaths from air pollution may not necessarily be related to only air quality influenced by the pollutants we investigated ($O_3$, $NO_2$, $SO_2$, CO and particulate matter). This discrepancy can be linked with the Chernobyl catastrophe, which has been influencing Belarus's environment for decades.[3]

The aim of this analysis is to assess the current state of air pollution in Belarus. The concentration of six pollutants in the atmosphere has been observed using both the 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,[4] more than 60% of the $NO_2$ in European cities comes from motor vehicle exhausts. Other sources of $NO_2$ are oil and metal refining, electricity generation (especially from coal-fired power

1 https://www.who.int/news-room/air-pollution
2 https://www.who.int/airpollution/ambient/health-impacts/en/
3 https://belarusdigest.com/story/environmental-protection-in-belarus-are-the-rankings-misleading/
4 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.

stations), other manufacturing industries, and food processing. The natural sources of the gas are 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,[5] 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, 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 exhausts**
- **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 as 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, degradation of vegetation and animals, and forest fires**, and 60% comes from **fossil fuel consumption, waste incineration, tobacco smoke, and charcoal fires.[6]** 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 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"*[7] Source: WHO

While CO accumulates in the atmosphere during winter, it is depleted rapidly as a result of natural reactions in spring. Thus, in the northern

5 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)

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

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

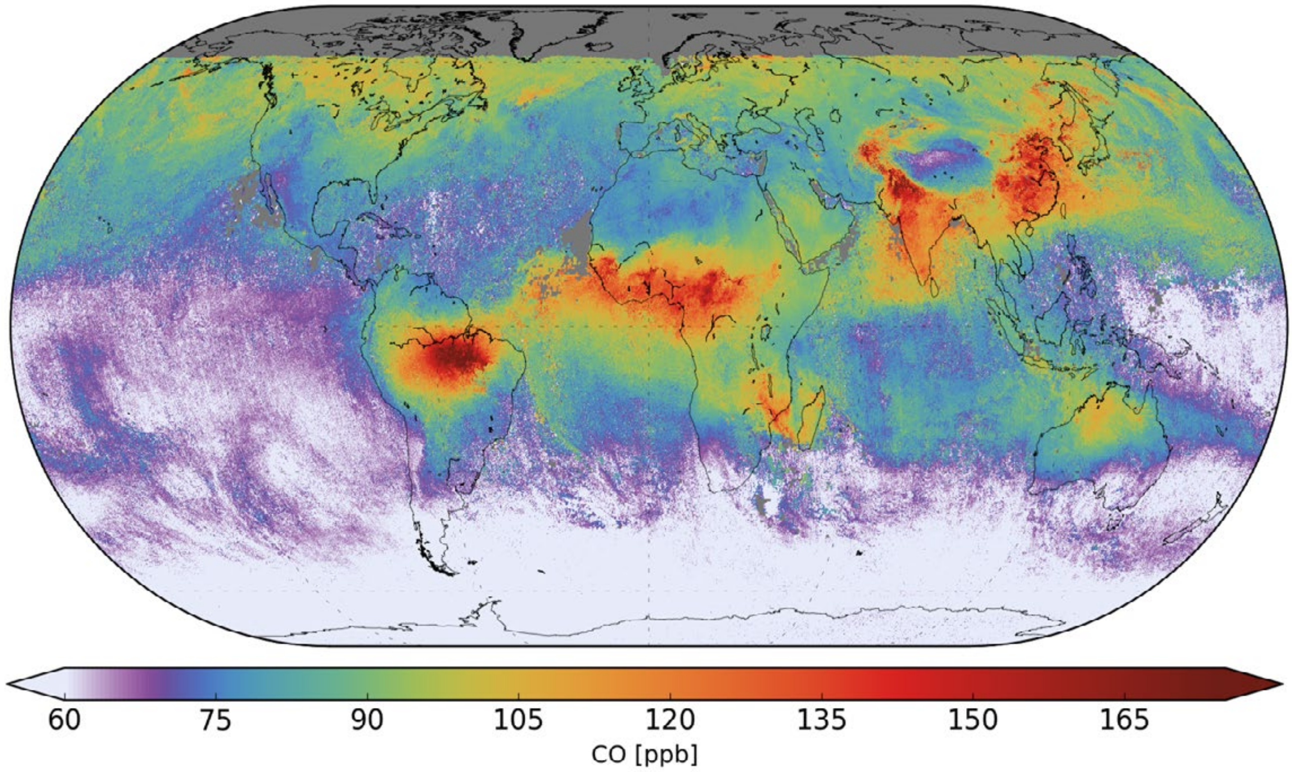


**Fig. 1:** *The global CO total column mixing ratio average concentration created with TROPOMI L2 data (13-19 November 2017), The data clearly shows CO enhancement by wildfires in Brazil, Africa, Madagascar, and Australia, as well as anthropogenic air pollution in India and China; http://www.tropomi.eu/data-products/carbon-monoxide*

hemisphere, CO concentrations are generally lowest in June, July, and August. [8]

## 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 emitted $SO_2$ 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,[9] "$SO_2$ 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, and 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 form the main component of acid rain. The S5P satellite is limited in 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**

## 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 the oxidation chains of non-methane volatile organic compounds (NMVOC); its column

8 https://sos.noaa.gov/datasets/carbon-monoxide-2008-2011/
9 https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

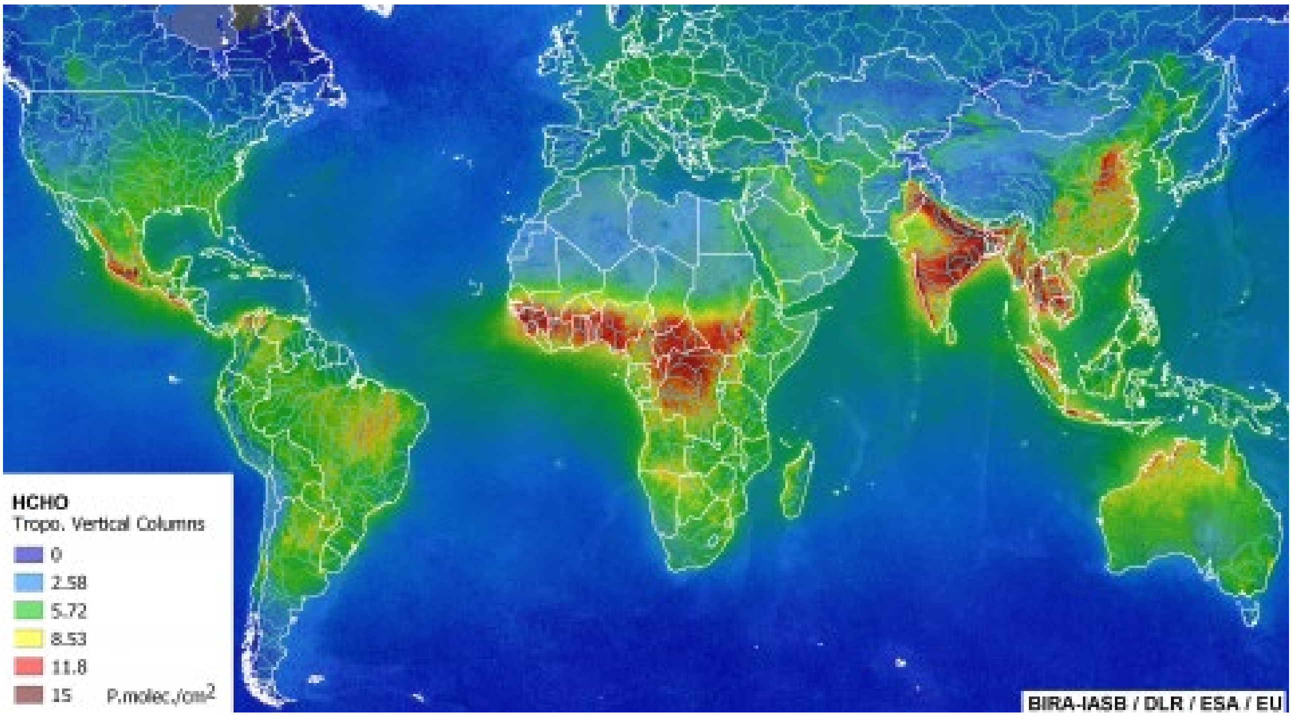


***Fig. 2:*** *The global HCHO concentrations created with TROPOMI L2 data (November 2017-June 2018), http://www.tropomi.eu/data-products/formaldehyde,*

is composed of different sorts of volatile organic compounds. As its lifetime in the atmosphere is only a few hours, monitoring of 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."*[10] 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.[11]

> *"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*[12]

**MAIN HUMAN SOURCES**

- **petrochemical industrial sources**
- **industrial processes**
- **heating**

## Particulate matter ($PM_{2.5}$ and $PM_{10}$)

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.

10 https://www.bbc.com/news/science-environment-44550091

11 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

12 https://www.who.int/ipcs/publications/cicad/en/cicad40.pdf

On the basis of size, particulate matter is often divided into two main groups: the coarse fraction contains the larger particles with a size ranging from 2.5 to 10 µm ($PM_{2.5}$ - $PM_{10}$) and 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 $PM_{2.5}$."*[13] Source: WHO

There is a direct negative effect of particulate matter concentrations 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 catalysts for chemical reactions on their 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's why WHO experts recommend values that determine the minimum risk to public health.

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 the 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.[14] The short-term level of pollution should not exceed 25 µg/m³ ($PM_{2.5}$) and 50 µg/m³ ($PM_{10}$) as a 24-hour mean.[15] 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 $PM_{2.5}$."*[16]

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

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

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

16 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 sulfur 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 adductforming 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 atmosphere monitoring launched in October 2017 as a part of the EU Copernicus Programme. It carries a spectrometer TROPOMI (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 and primary pre-processed to 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 below 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 (from May 2018 to April 2020) are obtained via SH.

> *"The distribution of satellite-measured air pollution does not take into account the 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[17] (tropospheric column). CO clear sky TROPOMI observations provide total CO columns with sensitivity to the tropospheric boundary layer.[18] The HCHO and $SO_2$ observations give the total atmospheric column between the surface and the tropopause.[19] Because of several identified error satellite images, 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.[20]

## Quality flags and observation frequency

It is important to take into account that the quality of 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 Belarus) is more than once a day. There are scanning overlaps at higher latitudes because 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

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

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** 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 done on a 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) in order to get a 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),[21] which 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.[22] 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 present analysis, the surface level concentrations of $PM_{2.5}$ and $PM_{10}$ have been 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 (what is called a rolling archive), our analysis of $PM_{2.5}$ and $PM_{10}$ concentrations covers the period from July 15 2017 to July 14 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. January 1 2018 until April 30 2020.

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

21 https://www.ecmwf.int/

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

# Results

## Nitrogen dioxide

From our analysis, there is a relatively low **average concentration of $NO_2$ over Belarus, 0.24 * $10^{-4}$ mol/m²**. In general, the lowest concentrations of $NO_2$ can be found in the north of Belarus. Several hotspots have significantly higher values, including the urban area of the capital city, Minsk, where $NO_2$ exceeds **0.50 * $10^{-4}$ mol/m²** (more than two times higher than a country average**).** The important industrial cities of Hrodna, Brest, and Homyel (as can be seen in Figure 3) are also higher than average (over 0.3 * $10^{-4}$ mol/m²)**.**

The highest levels of $NO_2$ were reached in the late autumn of 2019 and the winter season in 2020 (Figure 4), while the lowest concentrations were observed in the summer months (2018, 2019). The nitrogen dioxide concentration for different regions generally achieves lower variability in the summer season; however, significant differences between regions can be observed in the wintertime. The decrease in January 2019 is due to lower pixel density in this month for the whole of Belarus.[23]

> *The capital city, Minsk, has $NO_2$ pollution more than two times higher than the country average.*

Compelling transport of cross-border $NO_2$ pollution occurs in Belarus in the winter months. As can be seen in Figure 6, there is a significant increase in concentrations at the border with Poland. As there is no large city on Polish territory near the border, it can be expected that the source of pollution can be from the large Lublin Coal Basin, which is located in the east of Poland, close to the borders with Belarus and Ukraine. The Bogdanka coal mine (located in the basin) is one of the leading coal producers in Poland and its impact on pollution and environment is not negligible.[24] Black coal is also used for operation by the near Kozienice Power Station, the second largest thermal power plant in Poland.[25] Because of the low-lying and rugged terrain and prevailing westerly wind flows,[26] it may be the reason for the increased concentrations in western Belarus during the winter season.

The Brest region, located in proximity to the coal basin, reached a concentration for the winter months (0.37 * $10^{-4}$ mol/m²) that is twice as high as for the summer season (0.18 * $10^{-4}$ mol/m²).

In a more detailed look, the highest average concentrations are reached in districts close to the border of Poland in the direction of the basin. These are the districts of Brest (0.49 * $10^{-4}$ mol/m²), Kamenets (0.44 * $10^{-4}$ mol/m²), Zhabinka (0.47 * $10^{-4}$ mol/m²), Malorita (0.44 * $10^{-4}$ mol/m²), and Kobrin (0.43 * $10^{-4}$ mol/m²). In all these districts the summer concentration of $NO_2$ is around 0.20 * $10^{-4}$ mol/m² (total concentration around 0.25 * $10^{-4}$ mol/m²). Thus, a significant decrease in air quality is observed in these districts during the winter.

A significant increase in $NO_2$ values at the border with Poland is observed in both Belarus and Ukraine. As mentioned above, the decrease in concentrations in January 2019 happened as a result of the lower pixel density for the month.

In general, there is a pattern in seasonality; low $NO_2$ concentrations over the whole Belarus can be seen in summer, whereas an increase in$NO_2$ concentra-

23 Generally, there are more pixels below the limit "qa_value" of 0.75 (and are filtered out) during winter seasons, mainly because of poorer weather conditions.

24 https://euracoal.eu/library/archive/poland/

25 https://www.power-technology.com/projects/kozienice-coal-fired-power-station-unit-11/

26 https://nerc.ukri.org/planetearth/stories/881/

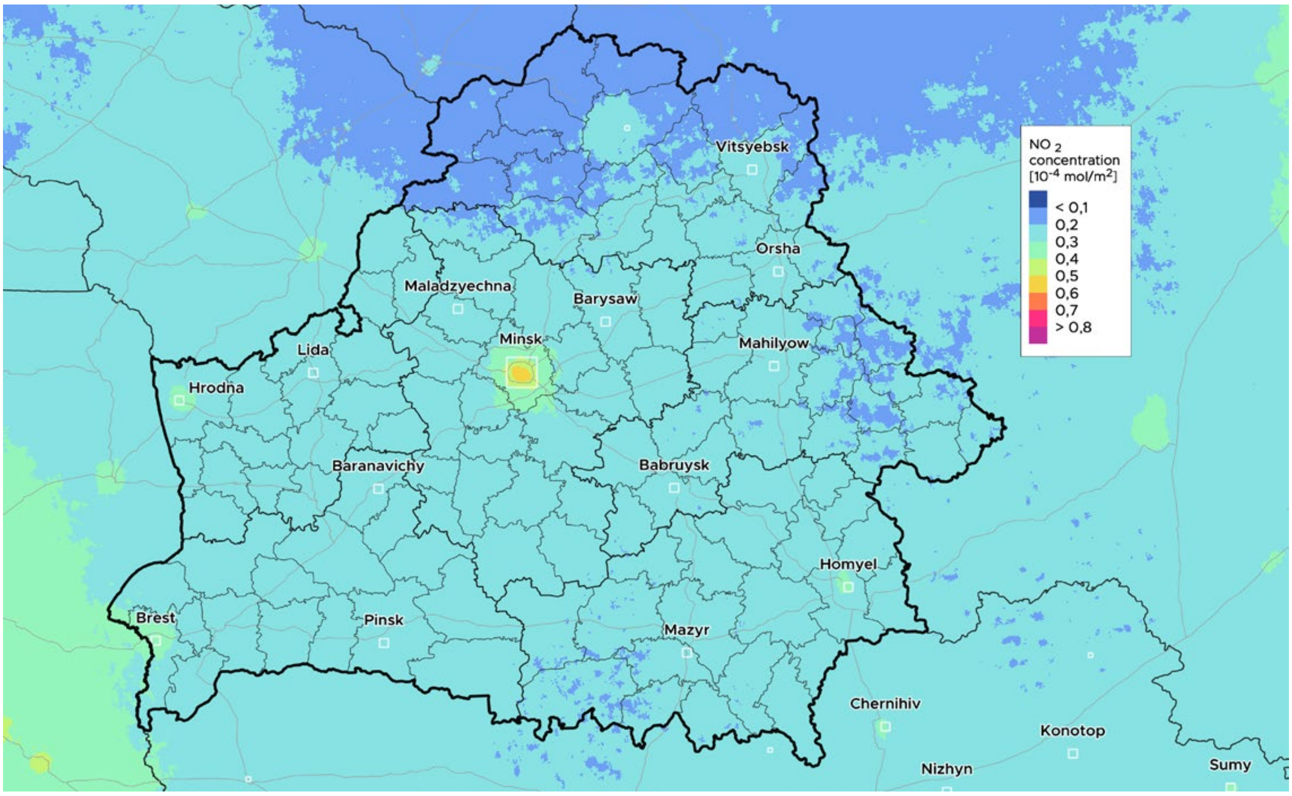


***Fig. 3:*** *Average concentrations of NO2 in Belarus between May 2018 and April 2020. Major cities are displayed as dark red squares, classified by their population. a*

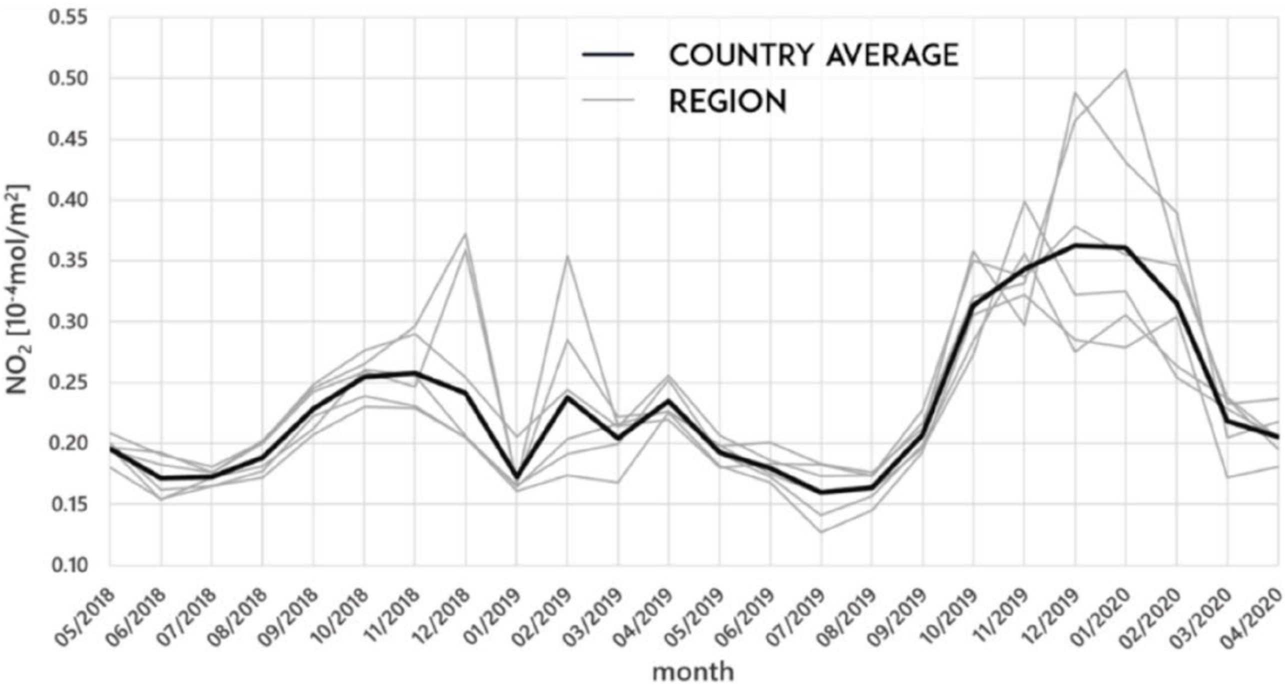


***Fig. 4:*** *Average monthly concentrations of $NO_2$ in Belarus and its regions between May 2018 and April 2020.*

tions can be observed from the west to the east of Belarus. In the Minsk city district there are higher average concentrations throughout the whole year - 0.35* $10^{-4}$ mol/$m^2$ (summer months - 0.26 * $10^{-4}$ mol/$m^2$, winter months - 0.42 * $10^{-4}$ mol/$m^2$).

> *A compelling transport of cross-border $NO_2$ pollution from Poland occurs in Belarus in the winter months.*

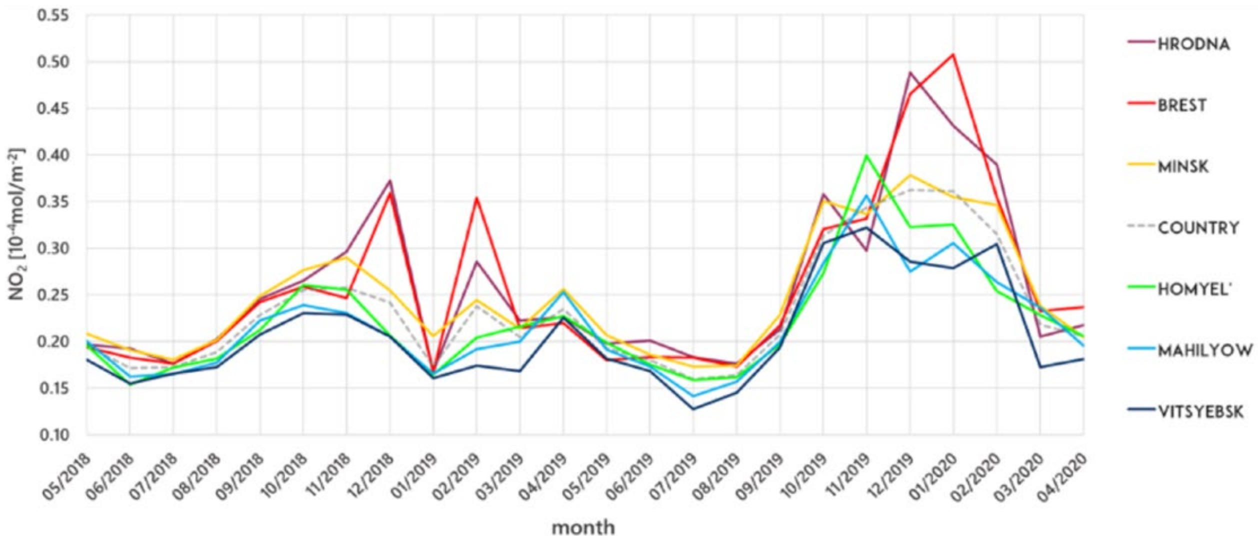


***Fig. 5:*** *Development of the average concentrations of $NO_2$ in regions of Belarus between May 2018 and April 2020.*

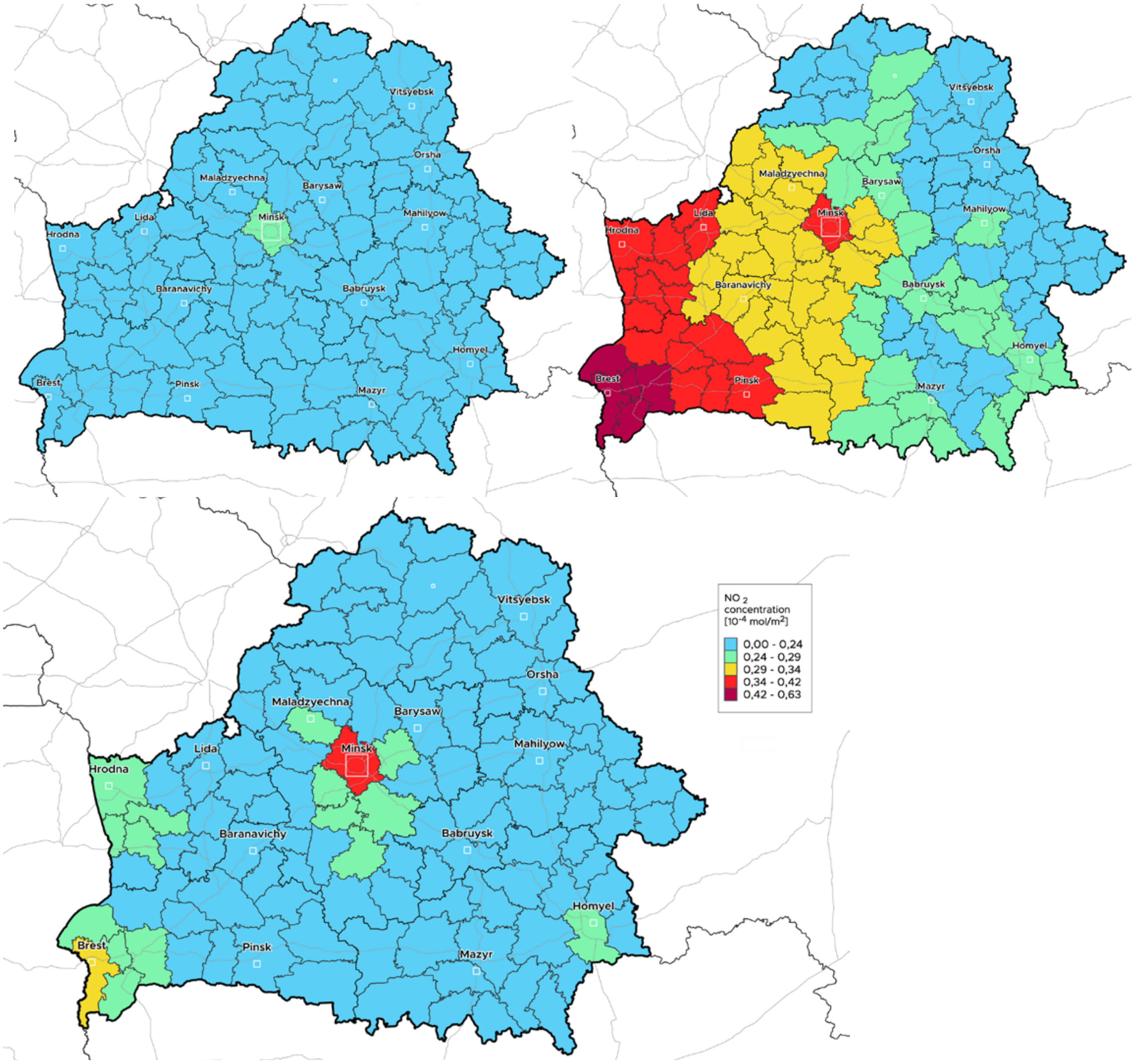


***Fig.6:*** *Average concentrations of $NO_2$ in Belarus between May 2018 and April 2020. Major cities are displayed as dark red squares, classified by their population.*

## Carbon monoxide

There are two maps important for understanding carbon monoxide concentrations over Belarus. Figure 7 shows the distribution of the average CO concentrations in Belarus between May 2018 and April 2020 and Figure 8 displays the terrain elevation in Belarus. Despite the fact that Belarus is generally a flat country, from these two images, a natural high negative correlation between CO concentrations and elevation can be spotted. Thus, the lowest concentration of CO follows the Belarusian Ridge, while the highest concentration

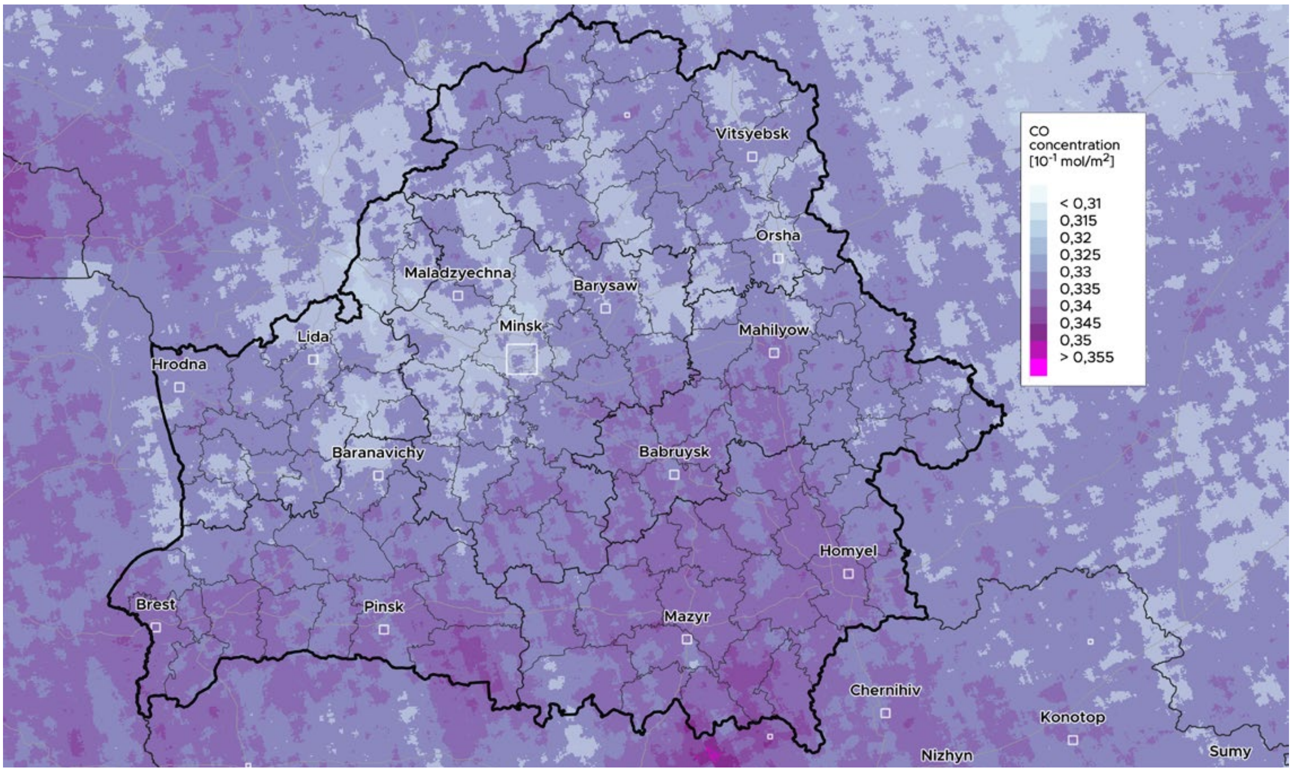


***Fig. 7:*** *Average concentrations of CO in Belarus between May 2018 and April 2020.*

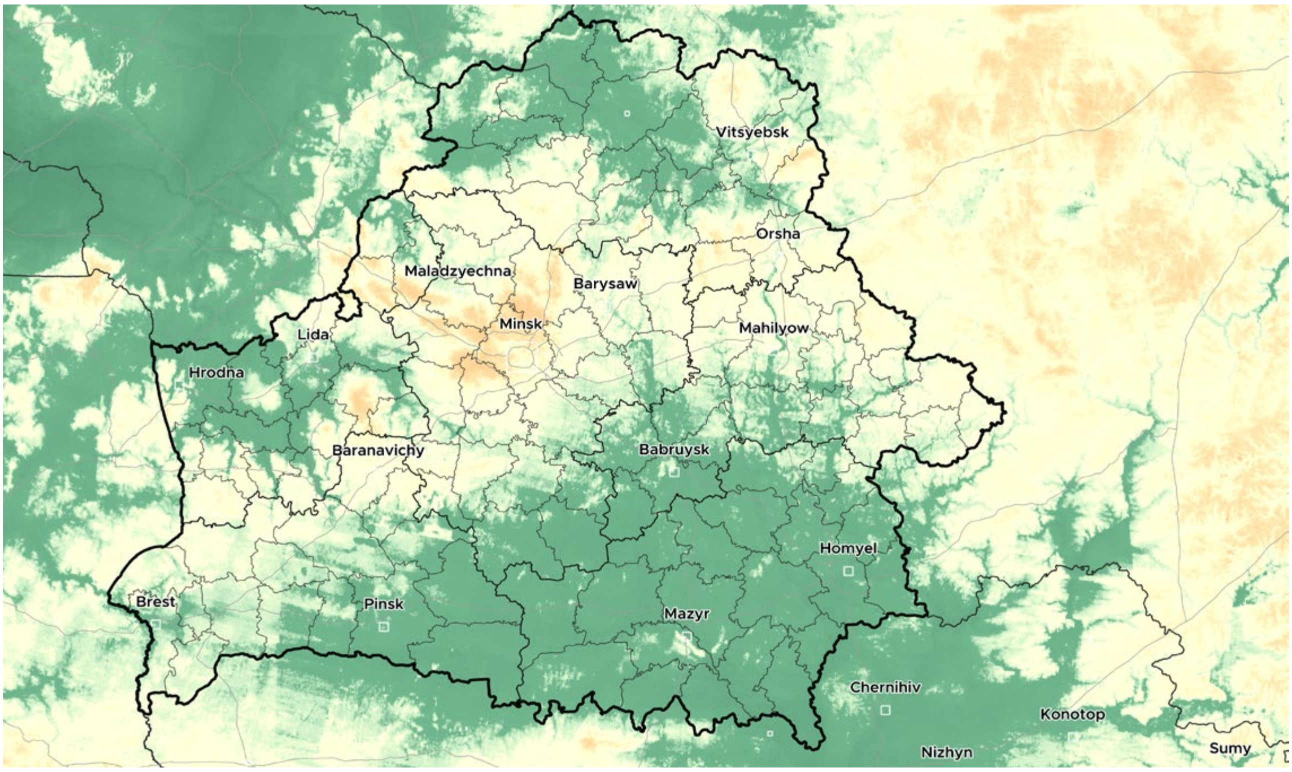


***Fig. 8:*** *Physical map of Belarus. Source: SRTM DEM (https://dds.cr.usgs.gov/srtm/)*

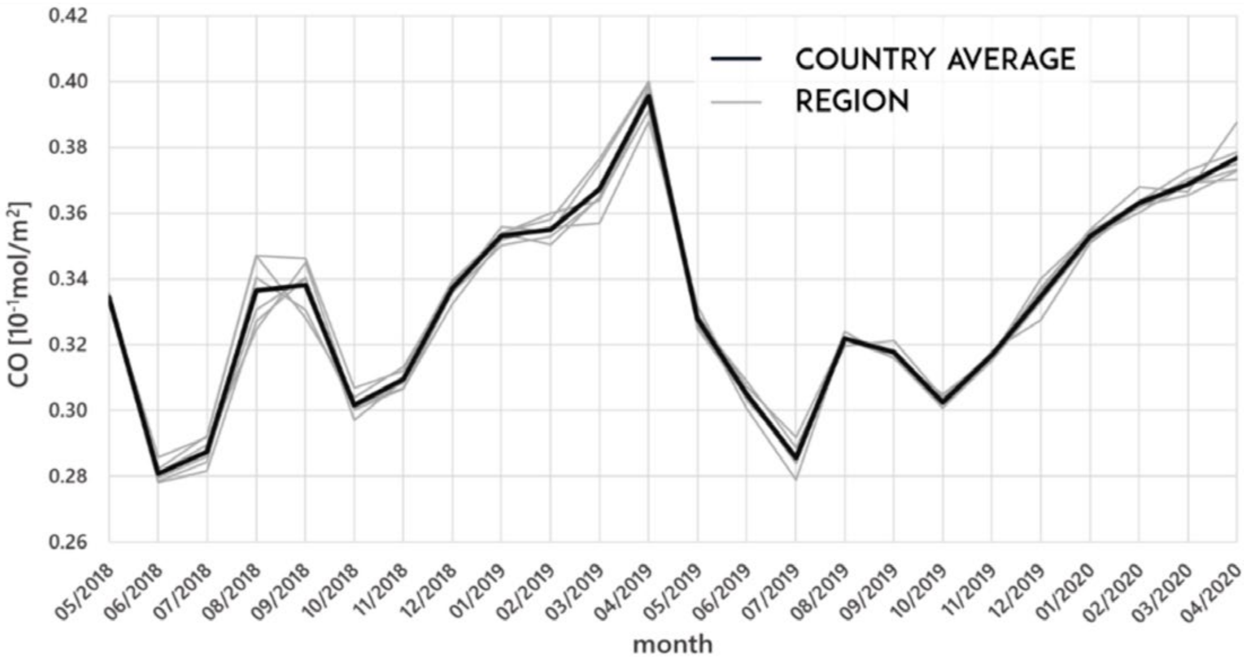


***Fig 9:*** *Average monthly concentrations of CO in Belarus and its regions between May 2018 and April 2020.*

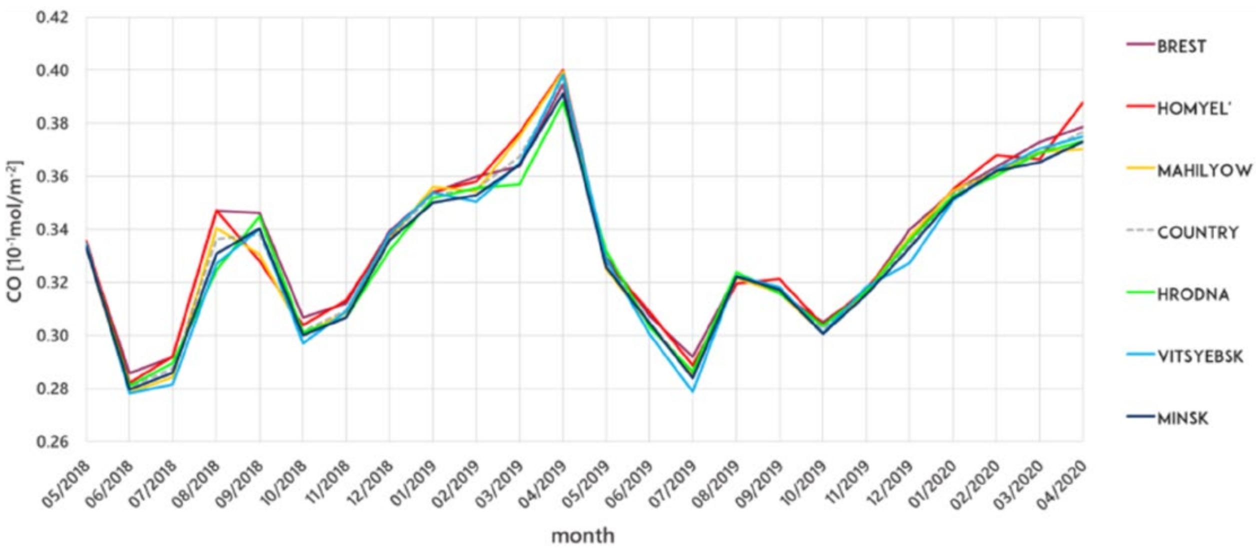


***Fig 10:*** *Development of the average concentrations of CO in selected regions of Belarus between May 2018 and April 2020. The regions are sorted by the highest and lowest values.*

can be found in the south of the country, where lowlands are located. This is mostly caused by the natural cycle of CO in the air. The average CO concentration over Belarus between May 2018 and April 2020 was **0.332 * $10^{-1}$ mol/m²**. The regions with the highest CO concentrations were Brest (0.335 * $10^{-1}$ mol/m²) and Homyel (0.335 * $10^{-1}$ mol/m²). But it is important to take into account the fact that the intra-regional variability between the lowest and the highest concentrations is very low. The two districts with the highest concentrations are Khoyniki (0.339 * $10^{-1}$ mol/m²) and Naroulia (0.338 * $10^{-1}$ mol/m²), both located in the Homyel region. The lowest concentrations, on the other hand, are detected in the Ashmayana (0.326 * $10^{-1}$ mol/m²) and Navahradak districts (0.328 * $10^{-1}$ mol/m²).

Figure 9 displays the development of monthly average concentrations. The values 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 the general yearly cycle of CO concentrations in the atmosphere of the Northern Hemisphere. The curve also confirms the fact that the average concentration in all regions is very similar to the national average throughout the whole period.

# Sulphur dioxide

The median sulphur dioxide ($SO_2$) concentration over Belarus between May 2018 and April 2020 reached a generally low value of 0.469 * $10^{-3}$ mol/$m^2$. Within the state of Belarus, the highest concentrations are in the Minsk (0.485 * $10^{-3}$ mol/$m^2$), Vitsyebsk (0.487 * $10^{-3}$ mol/$m^2$), and Mahilyow (0.465 * $10^{-3}$ mol/$m^2$) regions, as can be seen on Figure 11. This partly corresponds with the $SO_2$ values analysed from the CAMS data (Figure 12), which shows higher concentrations in the western part of the country and around the main urban centres.

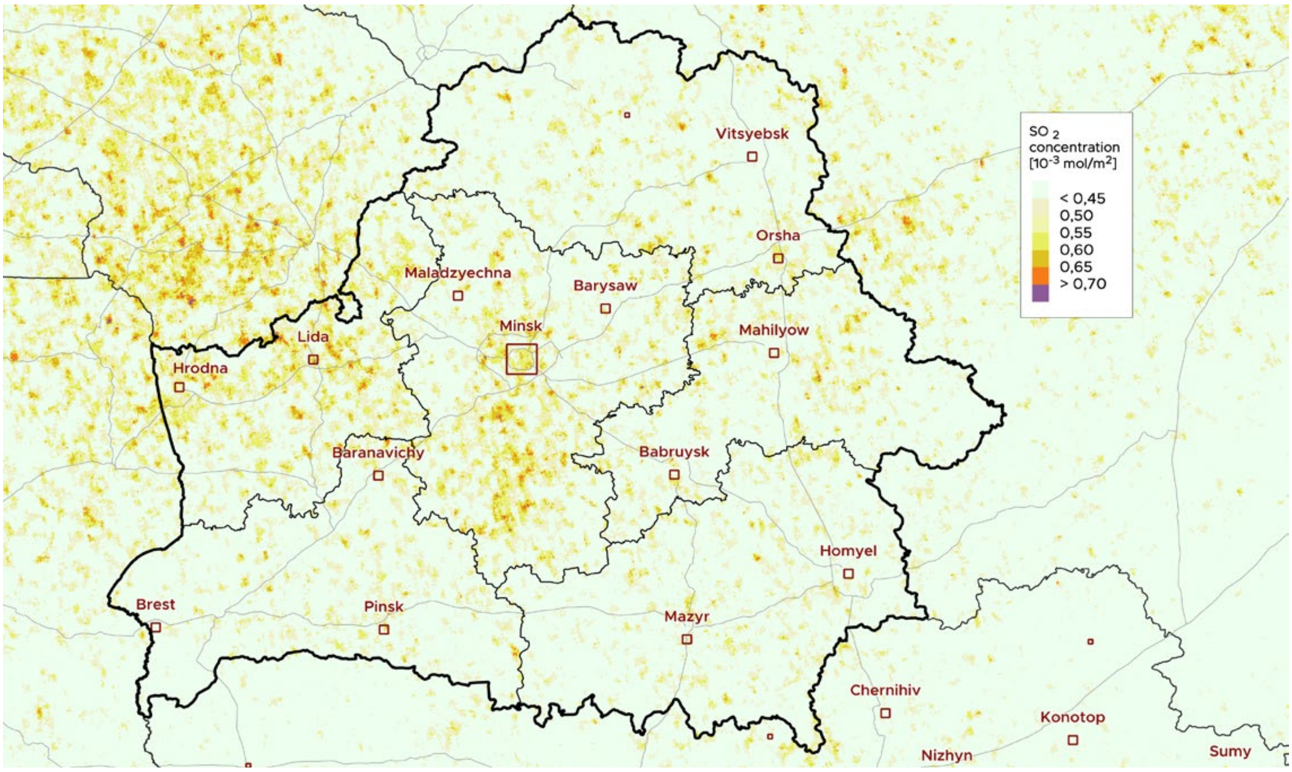


*Fig. 11: Median concentrations of $SO_2$ in Belarus between May 2018 and April 2020, based on Sentinel 5p*

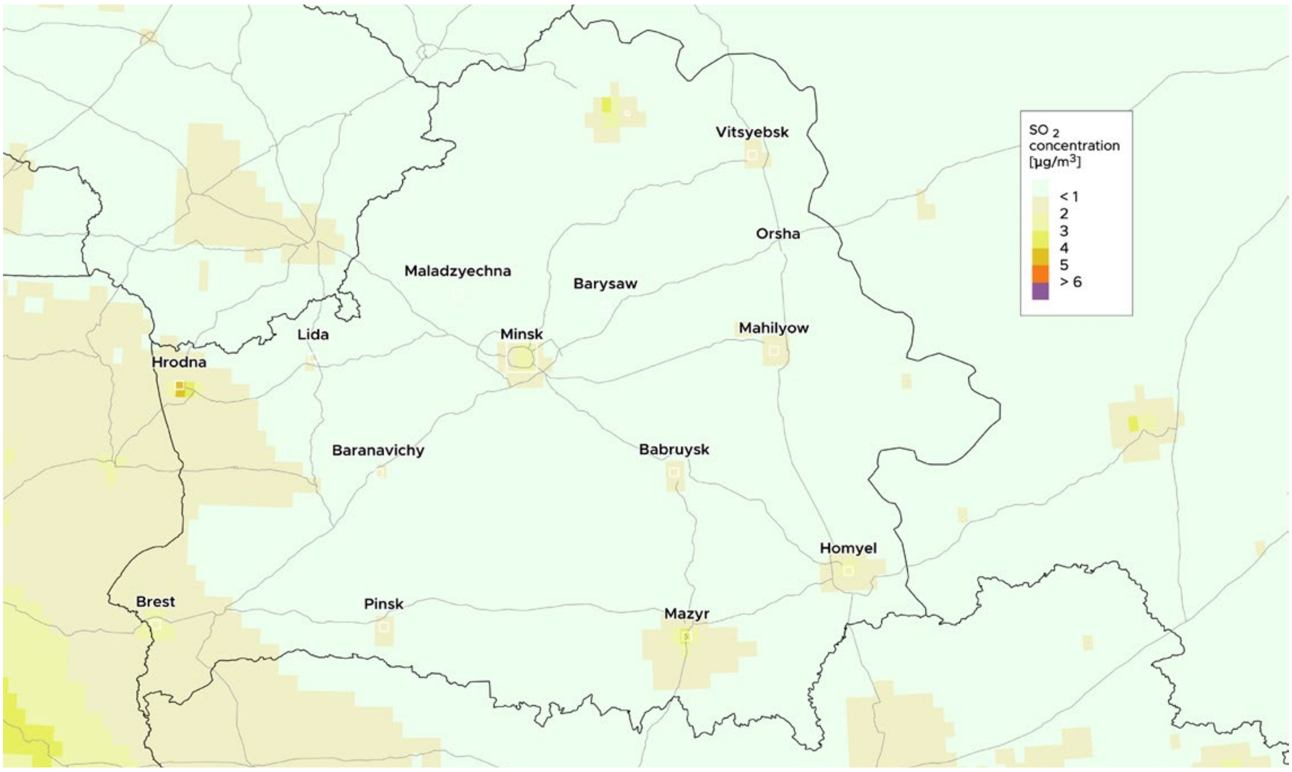


*Fig. 12: Median concentrations of $SO_2$ in Belarus between July 2017 and July 2020, based on CAMS.*

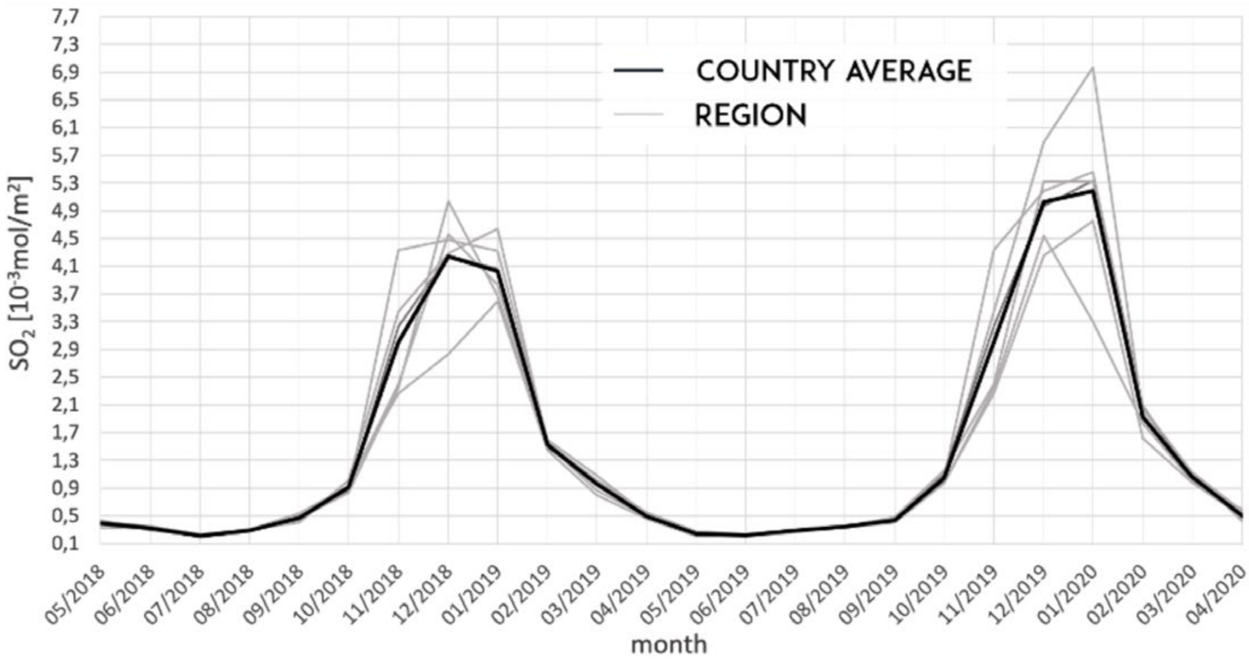


***Fig. 13:*** *Average monthly concentrations of $SO_2$ in Belarus and its regions between July 2017 and July 2020.*

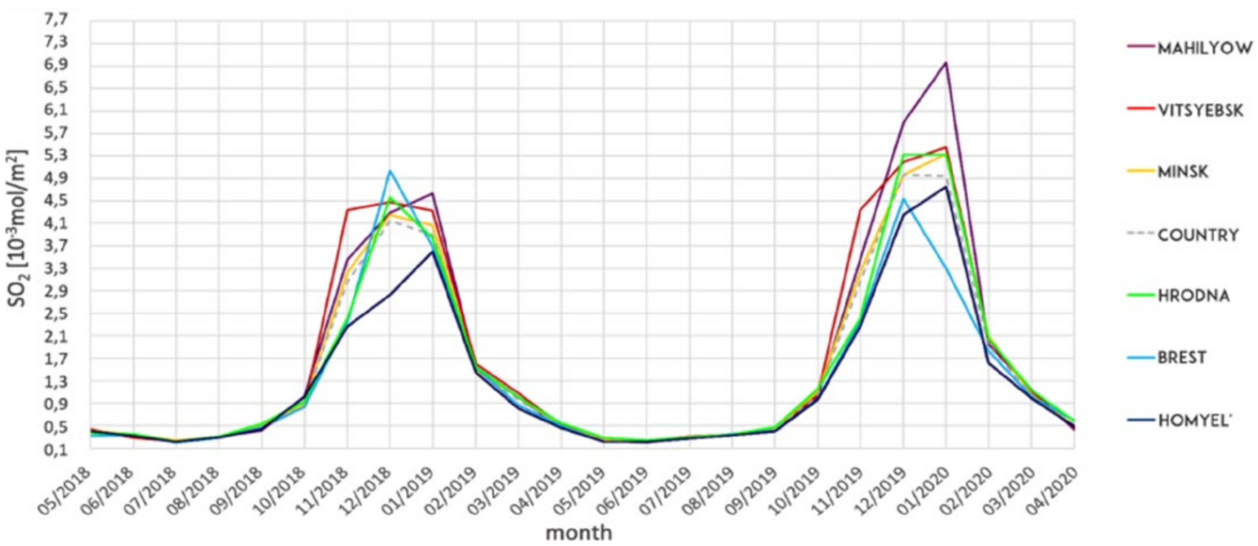


***Fig 14:*** *Development of the average concentrations of $SO_2$ in selected regions of Belarus between May 2018 and April 2020. The regions are sorted by the highest and lowest values.*

The seasonality of $SO_2$ values is clear (Figures 13 and 14), with concentrations strongly peaking between November and January, with values that are around ten times higher. This trend is probably a result of both natural and human factors,[27] including: 1) lower winter levels of $SO_2$ deposition as a result of the absence of vegetation and lower amounts of precipitation; and 2) higher emissions from the thermal heating of houses in residential areas. On the other hand, the average monthly concentrations in all regions are very similar to the national average during the summer.

27 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

## Formaldehyde

The averages of HCHO for the territory of Belarus are very similar throughout the country, as can be seen in Figure 15. The average concentration over Belarus between May 2018 and April 2020 reached a generally very low value of **1.51 * $10^{-4}$ mol/m²**. The intra-regional variability between the lowest and the highest concentrations is also quite low. As the petrochemical industry is one of the sources of HCHO, a hotspot of higher values can be observed in the north of Belarus over the town of Novopolock, where a major oil refinery is located. Otherwise, the influence of anthropogenic sources on the distribution of higher values has not been observed.

The development of HCHO concentrations between May 2018 and April 2020 can be seen in Figure 16. On average, **the values range from**

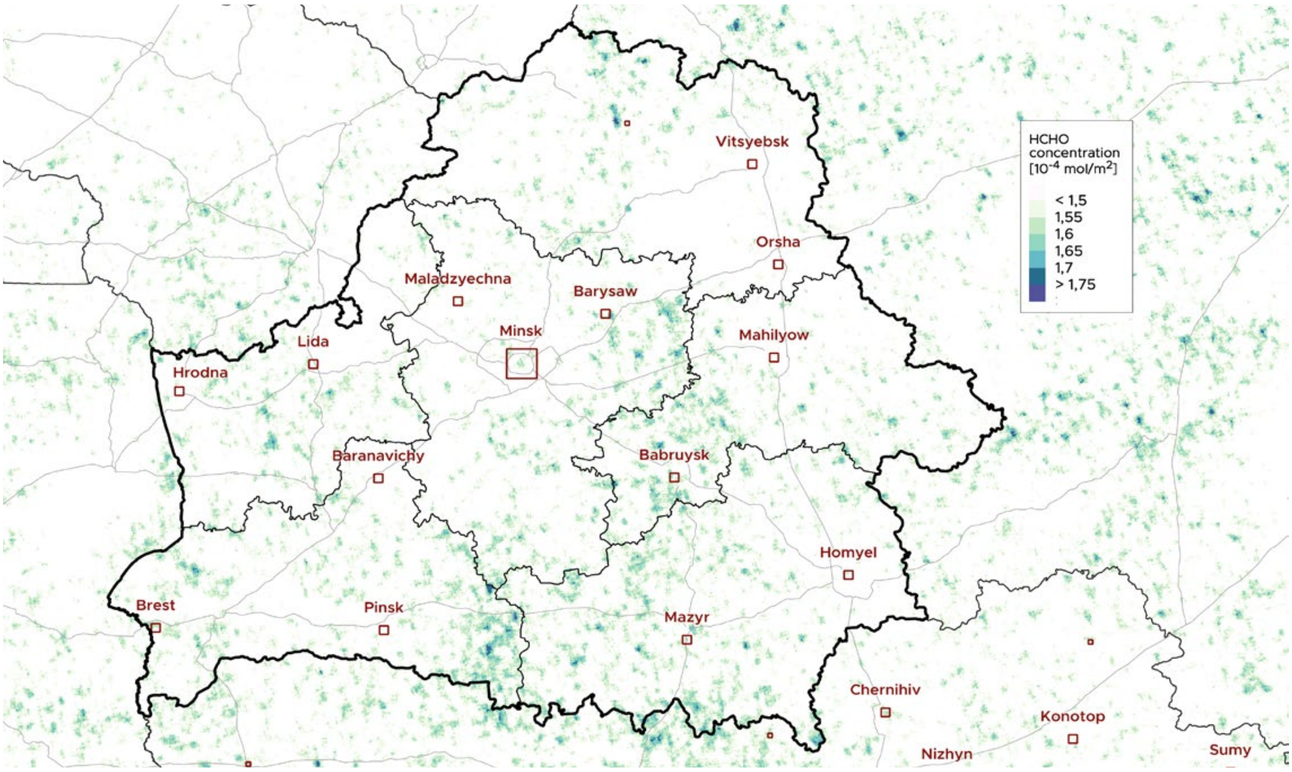


***Fig. 15:*** *Average concentrations of HCHO in Belarus between May 2018 and April 2020.*

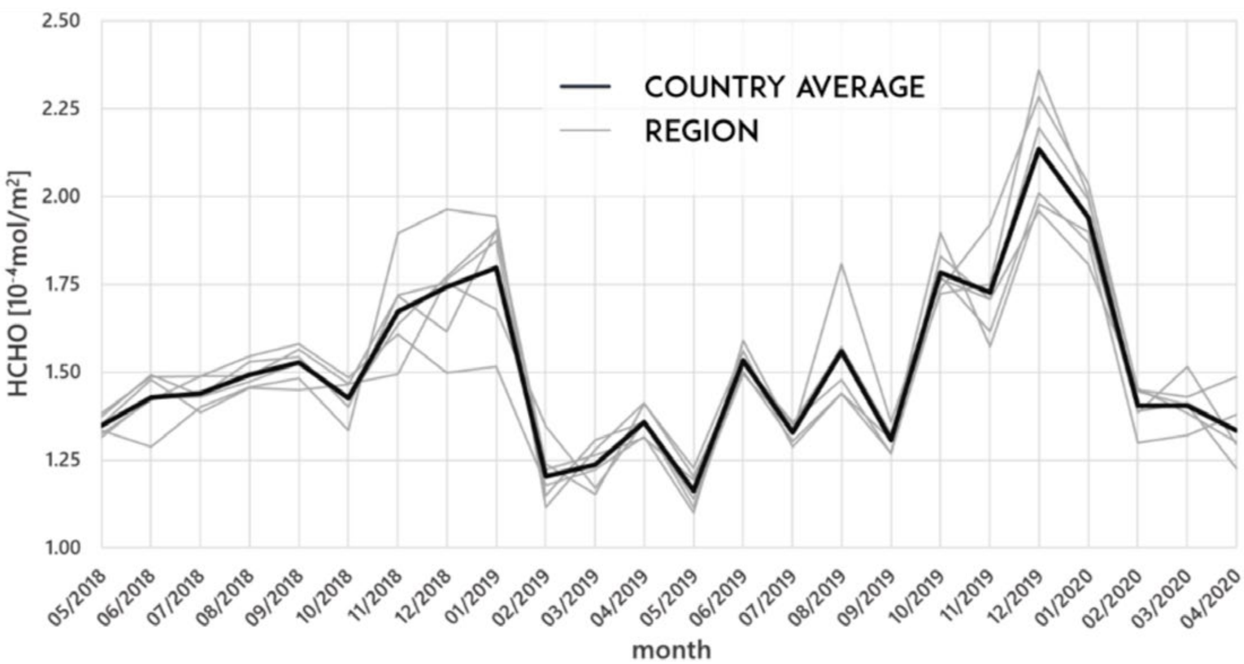


***Fig. 16:*** *Average monthly concentrations of HCHO in Belarus and its regions between July 2017 and July 2020.*

**1.25 - 1.80 * $10^{-4}$ mol/m²** but some peaks can be observed. The seasonal variations of the formaldehyde distribution are principally related to temperature changes and fire events.

*A hotspot of higher values can be observed in the north of Belarus over the town of Novopolock, where a major oil refinery is located*

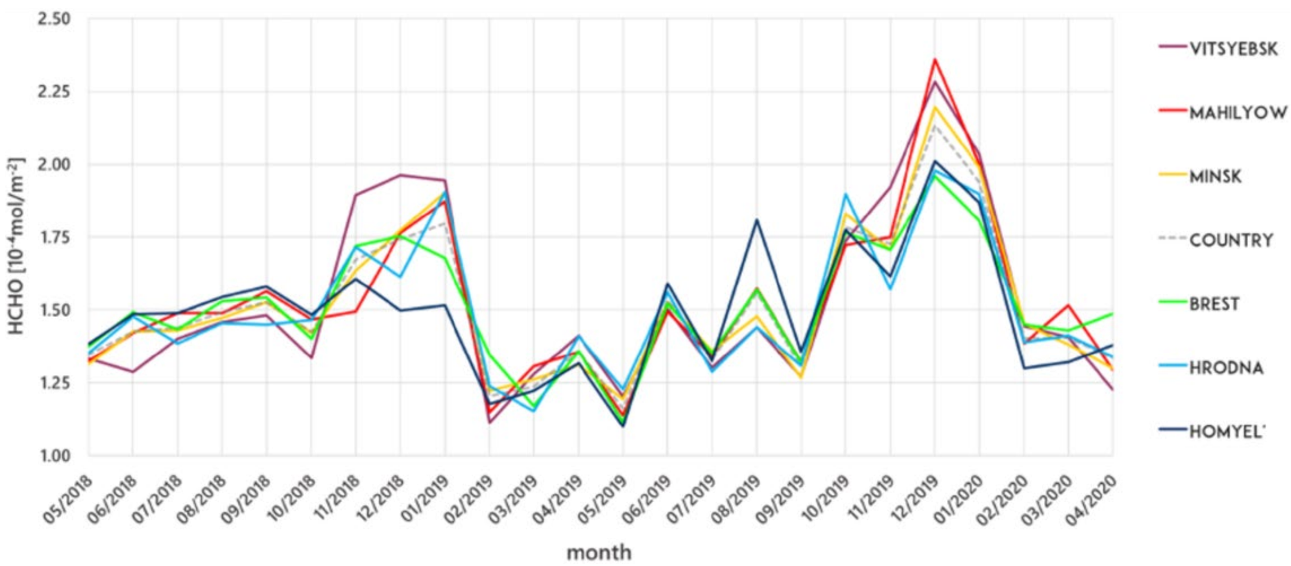


***Fig 17:*** *Development of the average concentrations of HCHO in the regions of Belarus between May 2018 and April 2020.*

## Particulate matter $PM_{2.5}$

The average $PM_{2.5}$ concentration over Belarus between July 2017 and July 2020 reached a value of 7,11 µg/m³ (Figure 18). The amount decreases from the south to the north of Belarus. The highest concentrations can be found in the urban area of Hrodna, a large industrial city located in the western part of Belarus. At the same time, Hrodna is the only city inBelarus where concentrations of $PM_{2.5}$ exceed the guideline level of 10 µg/m³ indicated by the WHO. In some other hotspots reaching higher values of $PM_{2.5}$, related industries can be found. These are the city of Novopolock, the leading producer in the refining and chemical industry, located in the north of Belarus, and Homyel, considered to be one of the industrial centres in Belarus, located in the south-east of the country. A significant increase in concentrations can also be seen at the border with Poland, in the Brest region. In general, the highest average concentration is reached in the raions of Brest (8.71 µg/m³), Hrodna (8.60 µg/m³), Malaryta (8.45 µg/m³), and Zhabinka (8.43 µg/m³); most of these belong to the Brest region, which has the highest concentrations of $PM_{2.5}$ in Belarus. The higher concentrations of $PM_{2.5}$ in the south-west of the country might also be directly affected by the transboundary transport of pollution from Poland.[28]

*Hrodna is the only city where the concentrations of $PM_{2.5}$ exceed the guideline level indicated by the WHO.*

Figure 19 shows the average monthly concentrations of $PM_{2.5}$ in Belarus. On average, $PM_{2.5}$ values in Belarus are in the range of 5-8 µg/m³. The peaks of the concentrations are reached in late autumn and during the winter period. A decrease in the values generally occurs during the summer and at the beginning of the autumn.

28 Check the NO2 results chapter for more detail.

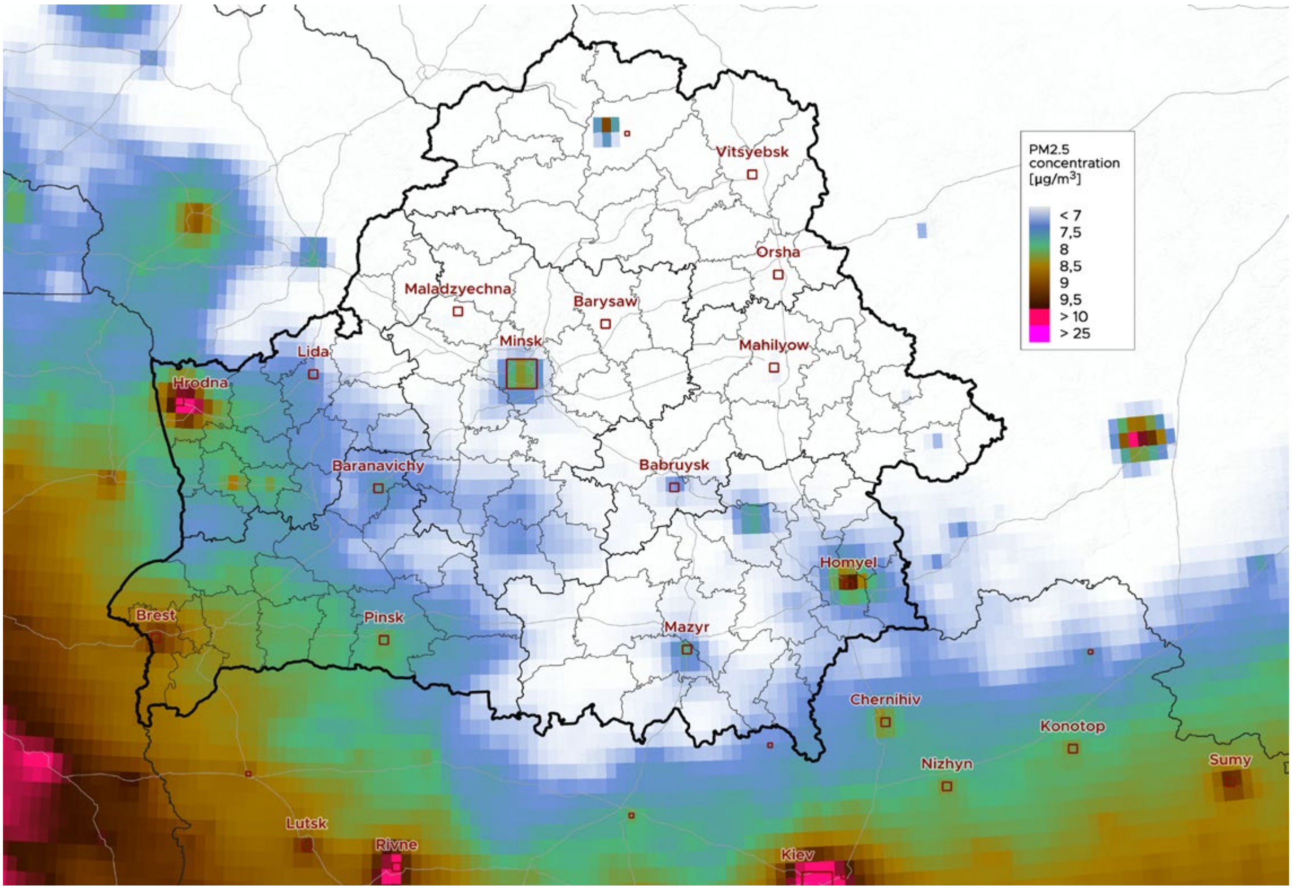


***Fig. 18:*** *Average concentrations of $PM_{2.5}$ in Belarus between July 2017 and July 2020.*

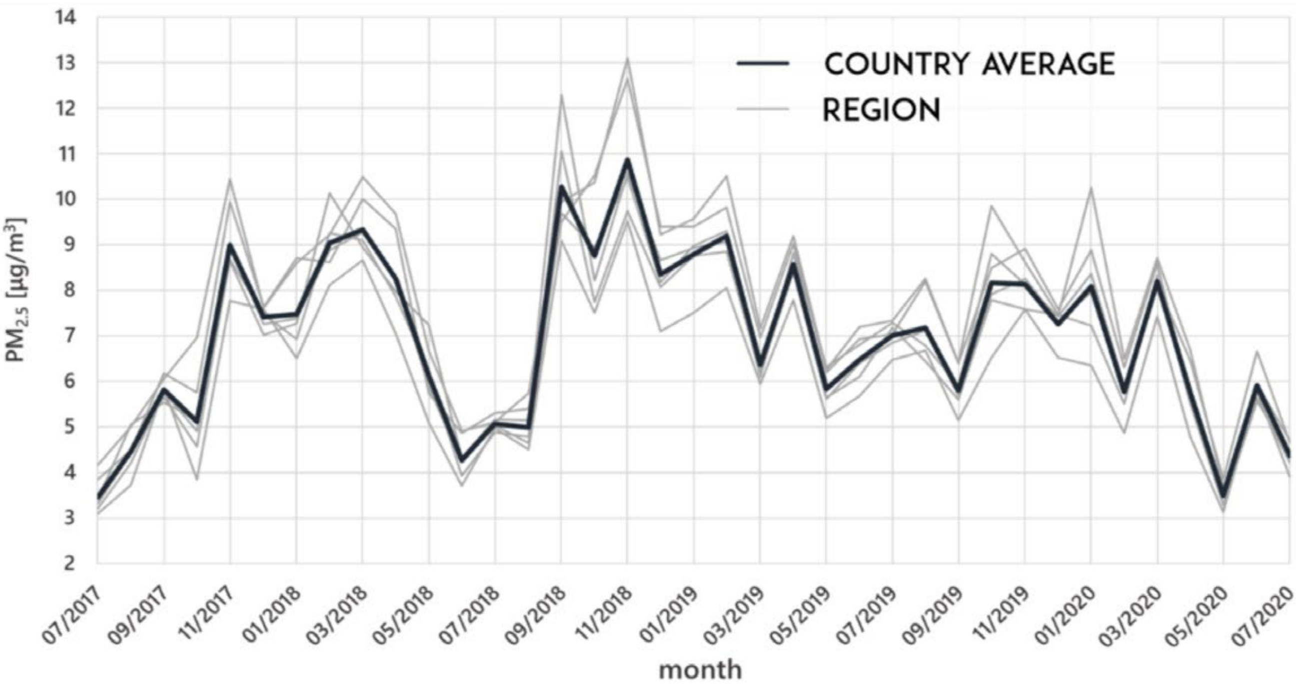


***Fig. 19:*** *Average monthly concentrations of $PM_{2.5}$ in Belarus and its regions between July 2017 and July 2020.v*


***Fig. 20:*** *Development of the average concentrations of $PM_{2.5}$ in regions of Belarus between May 2018 and April 2020.*

## Particulate matter $PM_{10}$

The average concentration over Belarus is shown in Figure 21. It reaches 9.00 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-west to the north-east of Belarus. There are no cities where the values exceed the WHO guideline annual mean values for coarse particulates (20 µg/m³). The highest concentrations are observed in the region of Brest (10.04 µg/m³). In the Brest region, the highest average concentrations are reached in the districts of Brest (11.24 µg/m³), Zhabinka (10.78 µg/m³), and Malaryta (10.77 µg/m³).

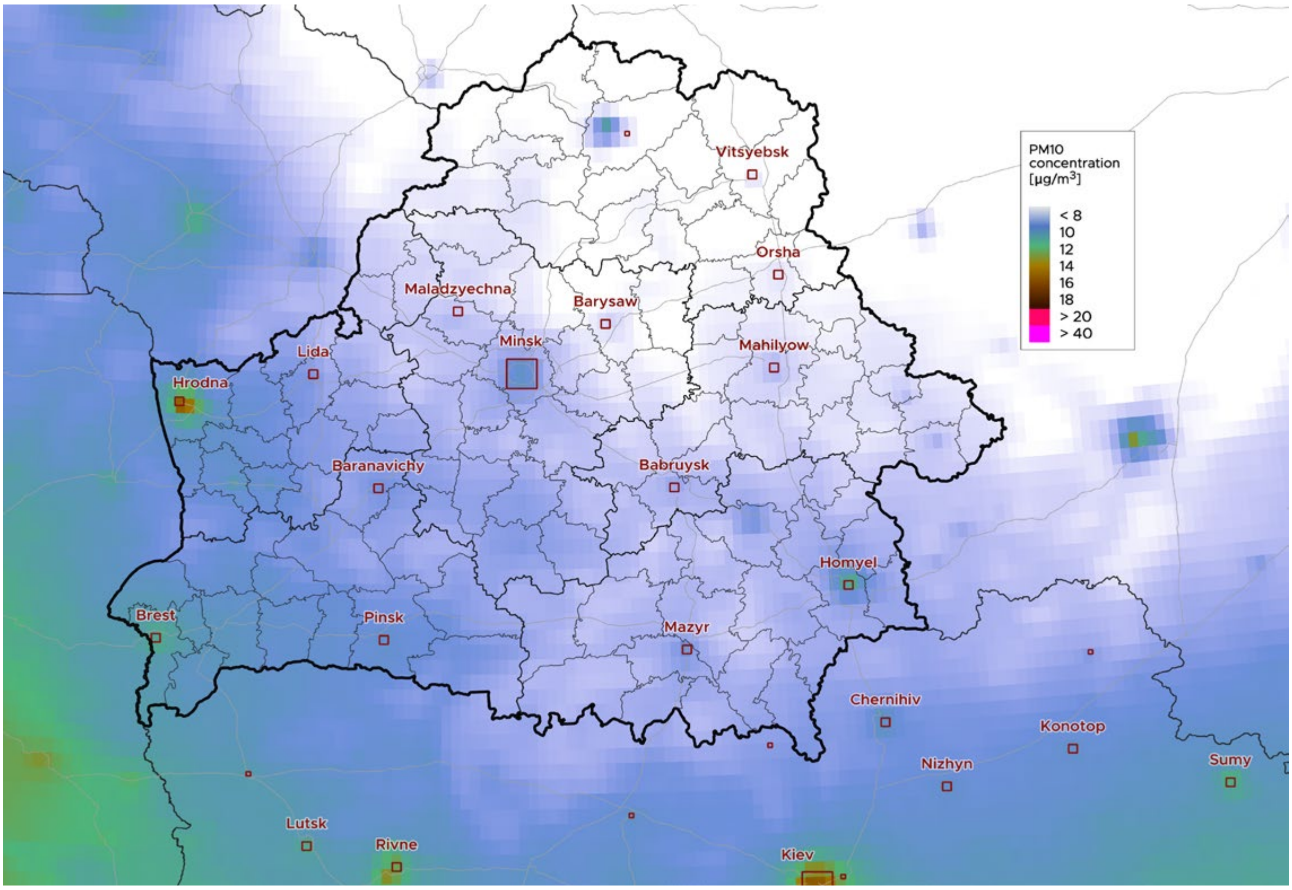


***Fig. 21:*** *Average concentrations of $PM_{10}$ in Belarus between July 2017 and July 2020.*

The $PM_{10}$ values for different regions generally show similar intra-regional and seasonal variability to those for $PM_{2,5}$. Figure 22 shows that the most of the values vary around the country average**.** The monthly values of $PM_{10}$ in Belarus are in the range of 4-15 µg/m$^3$**.** The highest increase in concentrations occurs in the autumn. In September 2018, the concentration reached its highest observed values - a country average of 15.31 µg/m$^3$ and in Homyel 18.66 µg/m$^3$**.**

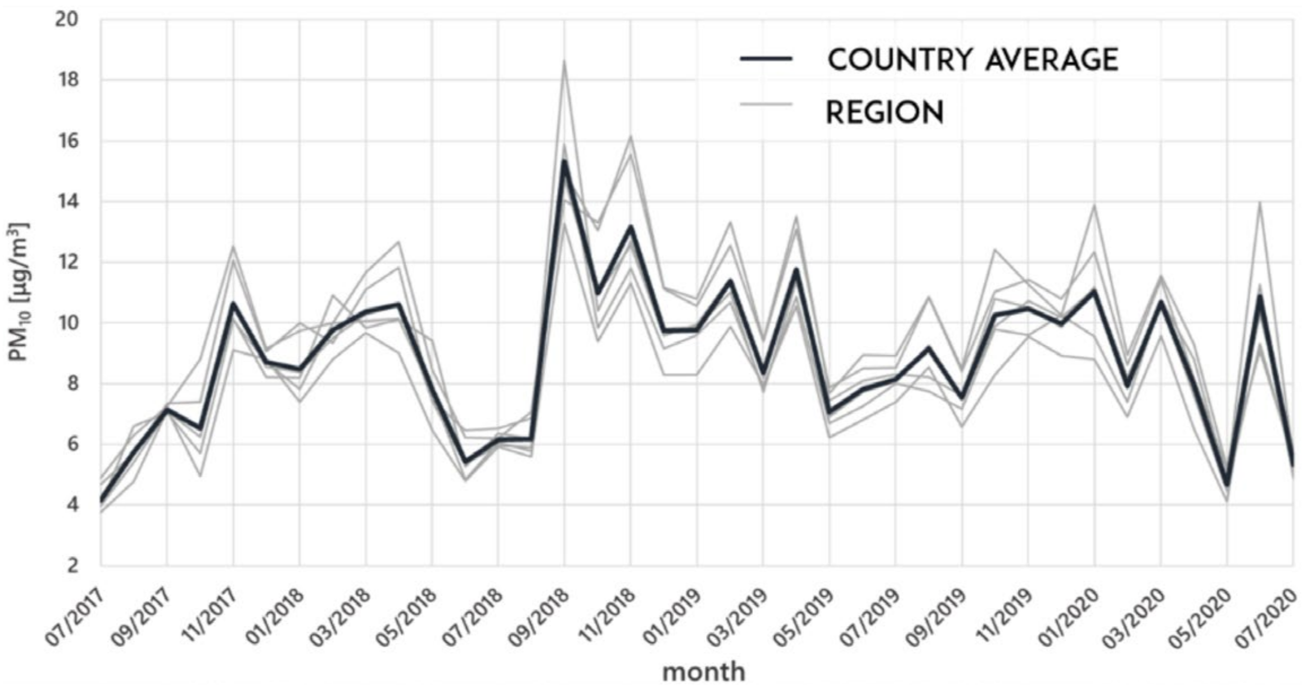


***Fig. 22:*** *Average monthly concentrations of $PM_{10}$ in Belarus and its regions between July 2017 and July 2020.*


***Fig. 23:*** *Development of the average concentrations of $PM_{10}$ in regions of Belarus between May 2018 and April 2020.*

# Recommendations

Air quality is considered to be one of the most important health and environmental factors nowadays. In order to increase the quality of life and environment in Belarus, coordinated action is necessary on the national, regional and municipal, industry, and citizen level. Moreover, decreasing 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. Public policies supporting improvements in 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[29] 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 the 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 density of population. Satellite monitoring and CAMS data should be used on a regular basis for the monitoring of overall progress and changes in spatial and temporal distribution on a country/regional level. The accessibility of the data by the general public (open data, a website with a 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,
- the procedure for issuing legal permits for pollutant emissions;
- state regulatory policy.

Monitoring of real pollution levels should be supplemented by a Pollution Release and Transfer Register (PRTR) presenting summary releases of pollutants from individual large industrial facilities - and thus enabling major sources of pollution 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 of a specific source, short-term measurements that are extrapolated to a longer time period, or the use of emissions factors.

29 E.g. starting from 2019, a local air quality monitoring project - AirMQ - has been conducting monitoring of particulate matter in Minsk and six other cities inBelarus. The project utilizes commercially available laser-scattering sensors capable of measuring PM1, PM2.5, and PM10. Data is collected with one-minute resolution.

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 the 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.

## Change in management practices

Many sectors provide opportunities for improving air quality. Out of these, 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 (state, regional, or local subsidies for new boilers, retrofitting, etc.) is being 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 undertake essential modernization and investments in the best available techniques (BAT), as many of the 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 sources of pollution, etc. The state should involve the public in decision making - such as spatial planning, approval of clean air plans on municipal and regional levels, EIAs and other permit procedures for the operation of industrial facilities. Public involvement - besides 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 ("voblast") of Belarus between 1 May 2018 and 30 April 2020 and average concentrations of $PM_{2.5}$ and $PM_{10}$ in the regions of Belarus between 15 July 2017 and 14 July 2020.*

| 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] |
|---|---|---|---|---|---|---|
| **Brest** | 0.258 | 0.335 | 0.457 | 1.51 | 7.86 | 10.04 |
| **Homyel** | 0.223 | 0.335 | 0.459 | 1.49 | 7.24 | 9.13 |
| **Hrodna** | 0.259 | 0.331 | 0.461 | 1.50 | 7.54 | 9.65 |
| **Mahilyow** | 0.216 | 0.332 | 0.465 | 1.52 | 6.83 | 8.52 |
| **Minsk** | 0.248 | 0.330 | 0.485 | 1.52 | 6.95 | 8.78 |
| **Vityebsk** | 0.206 | 0.330 | 0.487 | 1.53 | 6.26 | 7.89 |
| **country average** | **0.235** | **0.332** | **0.469** | **1.51** | **7.11** | **9.00** |

## Annex 2: Photos

***photo 1:*** *Cellulose production plant in Svetlahorsk*

***photo 2:*** *Power plant in Minsk*

***photo 3:*** *Kronospan wood-based panels manufacture company in Smorgon*

**Arnika** (Czech Republic) is uniting people seeking a better environment. We believe that natural wealth represents 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.

**Ecohome** (Belarus) is based on the principles of democracy and sustainable development, striving to create harmonious relationships between us and around us - at home, in the country, and around the world. The goal of the organization is to promote an environmentally responsible way of life. Thematically, it focuses on organic farming, permaculture, alternatives to nuclear energy, education for sustainable development, and what is called eco-art - art that promotes ecological values and awakens the public from its lethargy. Ecohome promotes public involvement in decision-making processes.

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